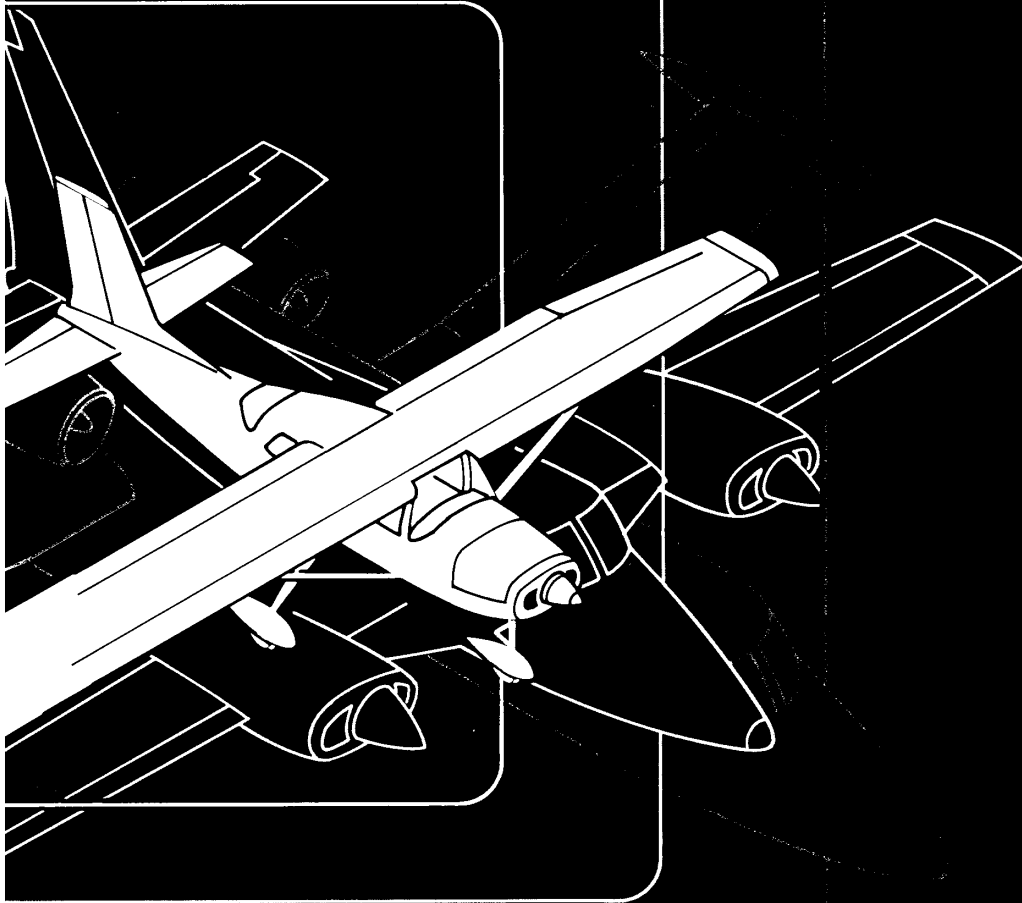


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FOREWORD

Purpose

The purpose of this document is to provide in compact form recommendations and technical reasons for the selection, design and application of aircraft electric power systems and electrically-actuated load equipment, without going into specific detailed designs. It forms a fitting companion reference document to the "Design Manual on Aircraft Electrical Installations" put out by the Aircraft Industries Association, in that the latter stresses specific application and installation practices with a minimum of technical explanation.

Form

This standard was originally published in 1960 as AIEE 750 in the form of a series of pamphlets in order to allow for more convenient revision and addition of sections as available without necessitating a reprint of the entire guide.

Sections of this guide are :

- 000 — Introduction
- 100 — Criteria for the Electric System
- 131 — Characteristics of Alternating-Current Generators Affecting Their Application
- 132 — Distribution System Design
- 133 — Symmetrical Components
- 200 — Principal Subdivisions of Electric System
- 300 — Selection of the System
- 400 — Installation Practices
- 500 — Equipment Characteristics
- 800 — Electric System Design Procedures

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IEEE Guide for Aircraft Electric Systems

000—INTRODUCTION

010 GENERAL

Preparation of material incorporated in this report has been undertaken in the belief that it will materially aid in the realization of better aircraft electric systems. This conviction is confirmed by opinions expressed in joint meetings, including representation from NASA, SAE, NEMA, the U. S. Air Force Systems Command, and the U. S. Naval Air Systems Command.

020 QUALITY ATTAINMENT

Superior quality of performance in an aircraft electric system can be obtained as a result of:

- a. Improved device performance
- b. Better application and installation techniques.

Improved device performance is the result of more effective utilization of material, the incorporation of ingenious design features, or better manufacturing in a particular device, while better application technique is concerned with selecting the most appropriate combination of devices and coordinating them in the most effective manner so as to realize the best overall results in a composite functional system.

030 SCOPE

Material comprising this report is directed primarily at the *attainment of improved application technique*—the attainment of the highest possible quality of performance from a combination of particular devices to perform a given function. The performance qualities exhibited by a composite system composed of numerous devices will be influenced by the character of devices which are selected to work together and the manner in which they are interconnected or correlated. The extent to which such composite systems may be benefited by proper application technique is great.

Realization of the stated objective involves comprehensive treatment of the following character expressed quantitatively in simple compact form.

- a. An explanation of the fundamental electrical problems involved.
- b. Typical characteristic performance data of the various elements and devices of which the system is composed, which shall define inherent limitations as well as meritorious qualities.
- c. Methods of analysis or test by which the qualities and limitations of a particular composite system may be evaluated.

- d. Formulation of particular application practices which experience and judgment confirm as assuring good performance.
- e. Formulation of a general analysis procedure outlining the various factors which must be examined or checked.

Although this report will refrain from defining or dictating specific characteristics of particular devices, it is quite possible that desirable features brought out by application considerations may assist other groups in creating new devices or improving existing ones.

Electrical applications in aircraft assume many peculiar aspects. Weight and space are of great importance, and reductions in these quantities deserve infinitely greater consideration than in equipment for land service. Equipment must be capable of successful operation in the presence of wide variations in ambient temperature, humidity, and altitude. In general, equipment must be capable of withstanding severe vibration in the member which supports it and it may be subjected to intense acoustic energy. Apart from these considerations which are peculiar to aircraft service, all knowledge accumulated through years of industrial experience should be used to the fullest advantage in bettering the performance of aircraft electric systems.

Aircraft electric systems have grown over the years from the early nonessential automobile-type systems to the present-day general-purpose systems which perform many vital functions. Installed capacities have grown also, to an extent that more attention to system protection is necessary for safety. This has occurred during a period when the electrical divisions of the aircraft manufacturers have been expanding in size. In fact, much of the engineering expansion has resulted from the increased dependence upon the aircraft electric system and the consequent growth in system size and complexity. In view of the influx of new engineering talent into these organizations it is apparent that immense benefits can result from a comprehensive summary of good application principles which are founded on sound engineering fundamentals. The unprecedented expansion of size and number of aircraft with ever-increasing electric system capacities which has occurred since 1941, principally for military service, has resulted in the accumulation of much knowledge and experience relative to good electrical application practice. It is important that this vast reservoir of knowledge be tapped, coordinated, and compiled in the form of a permanent record.

In the final analysis, the resulting benefits will be measurable in terms of:

- a. Improved reliability; fewer outages, less maintenance
- b. Lighter weight
- c. Simplification of installation, operation, maintenance
- d. Greater safety to personnel, the aircraft and electric equipment

- e. Lower monetary cost of aircraft electric service
- f. Better quality of electric service, such as voltage and frequency regulation.

100—CRITERIA FOR THE ELECTRIC SYSTEM

110 BASIC FACTOR

The purpose of the electric system is to supply the load equipment with electric power for sufficiently reliable and effective operation of that equipment.

120 GENERATOR CAPACITY

The first step in the development of an electric power system is to determine the electrical requirements of the loads. From these the necessary electrical source capacity may be determined. To establish that criterion, a load analysis for the aircraft should be made. The methods used for making the load analysis divide the load requirements into three categories to correlate with short-time overload, intermediate-time overload, and continuous capacities of generators. It is advisable to review the load analyses carefully to determine if the generators as affected by altitude, temperature, revolutions per minute, cooling air etc., will supply adequate power over the various time periods and operating conditions of the aircraft. Advantage can be taken of the overload capacity of the generator for short periods. Overload ratings are discussed in Section 514.1. Methods of analyzing electric loads are discussed in Section 810.

130 SYSTEM CAPACITY

The feeders from the source to the main bus should be capable of handling the full output of the power sources even if the generator capacity is much greater than that required by the loads. This will enable further growth of the system and also permit full use of remaining generator capacity after a loss of one or more generators.

131 Characteristics of Alternating-Current Generators Affecting Their Application

The design of alternating-current generators, their voltage regulators and various types of excitation systems is discussed in Sections 000 through 120, 140 through 500, and 800. Provided the generator and regulator are furnished as a matched design, the electric system engineer is primarily concerned with performance characteristics of this combination. The process of optimizing these designs by synchronous machine analysis is accomplished by a team comprised of a machine designer and a regulator designer. In some cases, this method of analysis is of interest to the system designer so he can see that the available equipment is used to its best advantage.

Other features of alternating-current generators in which system engineers are interested are the steady-state and transient ratings, and the type of operation resulting from abnormal system conditions such as short circuits, faults, and low input speeds.

Therefore, this section is devoted to the following subjects:

1. Synchronous machine analysis
2. Machine ratings
3. Effect of abnormal operating conditions

The first of these subjects, synchronous machine analysis is outlined herein.

It has been found that alternating-current machines can be described by various resistances, reactances and time constants. These data plus the time constants and saturation curves of the exciter describe the system with which regulator designers and system designers are concerned.

Note: In this discussion, the effect of machine resistances are neglected.

The usual method of analyzing an alternating-current generator consists of first, determining the action of the alternating-current end, then modifying this analysis with the action of the excitation system and voltage regulator. The simplest conception of the alternating-current machine is that of a voltage in series with an inductive reactance. In other words, the terminal voltage equals a generated voltage minus a drop due to reactance. This reactance differs according to previous history and the particular instant of time that we are considering. For steady-state conditions, this reactance is ordinarily considered to be a linear function of field current and is known as the synchronous reactance. For calculation of alternating-current components during transient conditions, the series reactance values differ from those during steady state. They are commonly called transient or sub-transient reactances.

Studying the steady-state condition first, the synchronous reactance can be described in the following fashion, using wound rotor theory for simplification.

In Figure I-1 let ϕ be the flux which results from direct current flowing in the alternator field. E_a , which is the voltage rise in the armature caused by that flux, lags the flux by 90 degrees on the vector diagram. At no load, since there are no voltage drops caused by armature current flowing through the armature windings, the terminal voltage V_t equals E_a . Also since ϕ is proportional to ampere turns in the field and since the field resistance is constant, E_a is proportional to the excitation voltage impressed across the field.

Now, as shown in Figure I-2, if a load is connected to the generator there will be a voltage drop across the armature proportional to the current times the leakage reactance of the armature. This requires more main field flux to keep the terminal voltage constant. However, the action of the armature current produces an armature reaction magnetomotive force across the airgap in phase with the current. In order to counteract this effect, which actually subtracts vectorially from the main magnetomotive force more excitation is required from the main field to keep the terminal voltage constant. Since the fictitious voltage caused by the armature reaction magnetomotive force is in quadrature with the current, it may be added to

the drop due to leakage reactance thus requiring the generated voltage E_a . The total of leakage reactance and the foregoing is termed synchronous reactance.

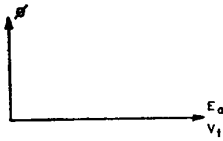


Figure I-1 Alternating-Current Generator Field Flux and Armature Voltage Vectors—No Load.

Present aircraft alternating-current generators are salient-pole machines. Due to their rotor construction, the magnetic reluctance is higher in the axis between the poles, the quadrature axis, than in the axis in line with the poles, the direct axis. It becomes necessary then to separate the armature reaction into two components. Figure I-3 shows the armature current divided into direct- and quadrature-axis components and the voltage drop due to armature current also divided into two components $i_d x_d$ and $i_q x_q$. Both x_d and x_q are comprised of a leakage component and an armature reaction component.

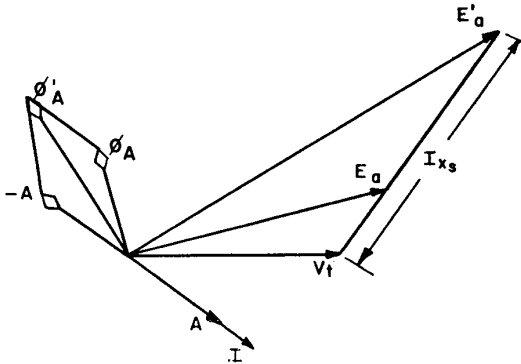


Figure I-2 Alternating-Current Generator Field Flux and Armature Voltage Vectors—Wound Rotor Machine with Load.

Figure I-3 also shows another item of interest, the angle between E_a and V_t . It is called the power angle. The equation for power for a salient-pole machine in terms of its constants is:

$$P = \frac{E_a V_t \sin \delta}{x_d} + \frac{V_t^2 (x_d - x_q)}{2 x_d x_q} \sin 2 \delta \text{ (Power per Phase)}$$

When field excitation is held constant, maximum power for a salient pole machine is reached at some angle less than 90 degrees. It is interesting to note here that the second term of the equation shows some power is available even with zero excitation, i.e., when $E_a = 0$.

If calculations are to be made for transient conditions, the vector diagram is still applicable when the transient or subtransient reactances are substituted for the synchronous values.

When unbalanced loading is to be investigated, the simplest concept for a machine, a voltage behind a reactance, no longer applies. However, symmetrical component theory provides a means for extending this concept by resolving an unbalanced set of voltages into three balanced sets. Impedances can be determined for each of these

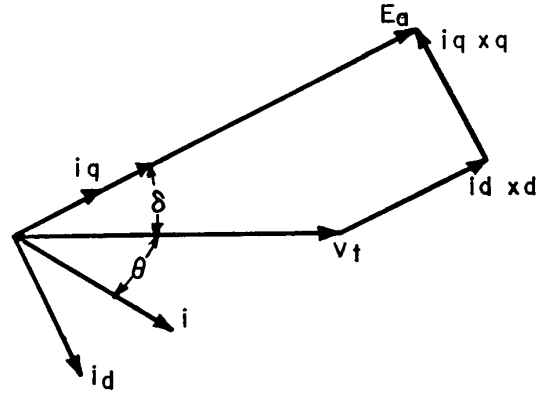


Figure I-3 Alternating-Current Voltage Vectors—Salient-Pole Machine with Load.

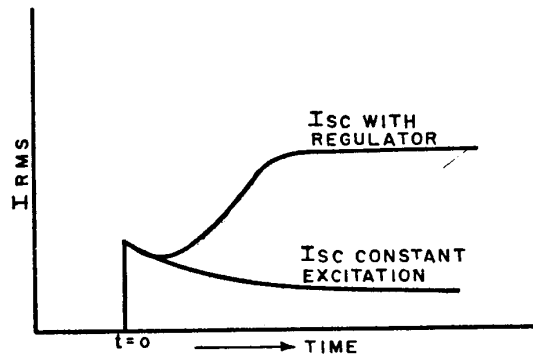


Figure I-4 Alternating-Current Generator Fault Currents with Constant and with Regulated Excitation.

balanced sets of voltages, each placed in its own simple network and combined to represent the unbalanced system.

The first set of balanced voltages are termed positive phase sequence. The rotation of these vectors is synchronous and in the same direction as normal. To measure X_1 , the positive phase sequence machine reactance the positive phase sequence voltages are divided by the positive phase sequence currents. If saliency is neglected, x_1 is equal to x_d . It has been found in system analysis that only a small error will result by neglecting saliency.

The second set of balanced voltages are termed negative phase sequence. When these voltages are impressed upon the stator windings in reverse rotation and at synchronous speed, the machine reactance encountered is termed X_2 , the negative sequence reactance. The exact value of this reactance differs with the type of fault, but an average value will suffice for most calculations.

The third set of balanced voltages are termed zero phase sequence. These voltages are in time phase with each other. One method of obtaining the value of this reactance is to impress a single-phase source across the three-phase windings in parallel. It is preferable to apply voltage with the three phase windings in series and the field shorted. This rotor may be blocked or at synchronous speed. $Z_0 = E/3I$.

The procedure in using symmetrical component analysis for unbalanced circuits is:

1. Write the phase current and voltage equations at the point of unbalance.
2. Convert these equations to their symmetrical components.
3. Interconnect the equivalent symmetrical component networks at the point of unbalance to satisfy the component equations which have been derived.

As an example, the symmetrical component equivalent circuit for connection of a single line-to-ground fault through fault impedance, Z_f , at the terminals of a ma-

$$I_a = \frac{3E}{Z_1 + Z_2 + Z_0 + 3Z_f}$$

chine, results in the equation I_a is the fault current and E is the machine open-circuit voltage prior to the fault. See Section 133 for a more complete discussion of the use of Symmetrical Components.

During transient conditions, if transient saliency is neglected, the transient reactances can be substituted for the positive-sequence network in place of the synchronous quantities.

Other constants which are necessary for analysis are the various time constants of the alternator. These constants can be inserted into equations to describe transient action. Time constants which are available for alternating-current machines are:

- (1) T'_{do} —Main field open-circuit transient time constant.
- (2) T'_d —Short-circuit transient time constant.
- (3) T''_d —Short-circuit subtransient time constant.

The quadrature axis quantities and T'_a the short-circuit time constant of the armature are also used in calculations.

An example will serve to illustrate the use of the various reactances and time constants just described. Assume a machine at no load which has a three-phase short circuit applied to its terminals and assume there is no regulator action, that is, the excitation remains fixed. The expression for the alternating current following the short circuit will be the sum of the currents obtained for the subtransient, transient and steady-state periods.

$$I_{ac} = (i''_d - i'_d)e^{-\frac{t}{T''_d}} + (i'_d - i_d)e^{-\frac{t}{T'_d + i_d}}$$

For this particular case, a solid three-phase short circuit from no load, with constant excitation $i_q = 0$, and since $V_t = E_a$ at no load:

$$i''_d = \frac{V \text{ rated}}{x''_d}$$

$$i'_d = \frac{V \text{ rated}}{x'_d}$$

and $i_d = \frac{V \text{ rated}}{x_d}$

In addition to the alternating-current component of fault current there will be a unidirectional, so-called direct-current, component present depending on the instantaneous value of the current before the instant of shorting. This component will decay according to the time constant of the armature T'_a . The total instantaneous value of short-circuit current will then be the sum of the alternating-current and direct-current components.

Figure I-4 on the lower curve shows the form of this current assuming the direct-current component is zero.

Regulator action can be added to the picture by writing the equation for the exciter response. If we assume an infinitely fast regulator, the response curve for excitation following a short circuit will be represented by the equation shown.

$$e_a = (e_x - e_o) (1 - (-t/T'_{do}) + e_o)$$

where e_a is the instantaneous internal generated voltage
 e_x is the ceiling excitation generated voltage
 e_o is the generated voltage for no load
and T'_{do} is the transient time constant of the field.

If this equation is solved simultaneously with the equation for constant excitation, the current for the actual system short circuit will be obtained. However for this case:

$$i''_d = \frac{e_o}{x''_d}$$

$$i'_d = (e_x - e_o) \frac{-t}{(1 - e^{-t/T'_{do}})} + e_o$$

$$i_d = \frac{e_x}{x_d}$$

The short-circuit current will then have the form given in the upper curve of Figure I-4, neglecting the direct-current offset.

Application of load may be considered a special case of short circuit by adding the external impedance to the machine reactances.

In general the subtransient period on an aircraft alternating-current generator is so short that it can be neglected. It should be repeated that this discussion has been incomplete and should serve only as a general outline on the subject.

MACHINE RATINGS

The capability of a machine or group of machines to carry load in a system depends upon two types of limits, stability and thermal. Stability limits may be subdivided into three categories: Steady-state power, transient power and hunting.

The first type is steady-state stability which considers system operation with very slow, smooth changes in system quantities. It is usually measured by a power limit denoting the maximum power a machine can deliver in synchronism to a system comprised of other machines and loads.

An isolated machine with voltage regulator is capable of generating balanced real power up to a limit determined by ceiling excitation, effective internal impedances and load power factor. A "rule of thumb" measure of this limit is that maximum real power output in per unit for unity power factor load is equal, roughly, to three-phase short-circuit current in per unit at ceiling excitation.

If a machine carrying a given load is paralleled with another machine carrying the same load and the machines are in step with equal regulator settings, there will be no interchange of current between them. Hence, each acts as though it were an isolated machine and the power limit of each is the same as for an isolated machine. This is changed little by the small amounts of circulating reactive current encountered in normal system operation. Thus, since the steady-state problem of maintaining synchronism does not exist in the parallel system when load division is effective, we conclude that a steady-state stability limit in the usual sense does not exist.

The second type is transient stability which may be described as the ability of a system to recover equilibrium following a shock. One criterion is often expressed as a power limit also: this limit is the maximum steady-state power which a machine may supply to a system of other machines and loads without loss of equilibrium due to a shock of specified characteristics.

This limit is determined by such factors as the type, size, and duration of the shock, transient characteristics of the machine, regulator speed and damping, drive response, real and reactive load division sensitivity, and power factor of the load. In practical aircraft systems, this factor is not important under normal operation. With extreme inequality in load division, it may limit before steady-state limits are reached.

The third type is hunting stability which may be said to be the ability of the system to operate without self-induced periodic deviations of system quantities from desired values.

There is, of course, a hunting stability problem in isolated systems and this is carried over into a parallel system and is one possible mode of instability. There is an additional mode introduced by the parallel connection. We may recall that parallel generators operate as though a flexible shaft connected their rotors. It is easy to picture the instability where one rotor oscillates with respect to

the other by twisting this flexible shaft. This equivalent shaft has a variable spring constant and with some machines, it has negative damping at some frequencies.

Military Specification MIL-G-6099 has established minimum standards for thermal limits to which most presently-available alternating-current machines are designed. For detailed requirements this specification should be consulted, but in general it provides for three classes of thermal ratings for machines and regulators. Class A is equivalent to the old MIL-G-6099 machine, and its basic rating is at 40°C inlet air. Class B rating is at 80°C inlet air, and Class C is at 120°C inlet air, with limitations on the mass flow of air, and the pressure drop across the machine at all ratings. See the specification for detailed ratings.

When alternating-current machines are designed for lowest weight, the thermal limit of the machine appears to shift from the stator to the rotor as altitude is increased above 20,000 feet. Any particular design then, will not follow a straight-line representation from sea level over the altitude range but will have a break in it at approximately 20,000 feet. Improvements in altitude performance can be had by better cooling paths in the rotor construction, while improvements in sea-level performance would result from the use of more copper in the stator or better cooling paths around the stator. Since the specifications establish only the nameplate ratings, it is obvious that charts of performance must be used to determine the ratings of the machine at other temperatures, pressure drops and altitudes.

There are several special problems involving alternating-current machines which must be considered. The following is a discussion of four of these, short-circuit characteristics, overvoltages, underspeed characteristics, and fault power requirements.

SHORT-CIRCUIT CHARACTERISTICS

The protection of alternating-current systems for aircraft from short circuits is accomplished primarily by the use of limiters, circuit breakers and fuses, similar to direct-current system practices. Since these devices respond to overcurrent only, the entire history of the short-circuit current must be accounted for when selecting the ratings of the protective devices. A root-mean-square current, for the time from the instant of shorting until steady state, can be found by integrating oscillographic test data. This current is used to obtain the clearing time for any limiter or circuit breaker.

A fast rate of buildup to steady-state short-circuit current is important in that the faults on the system can be cleared more quickly with less detriment to system operation and to the entire aircraft. A certain 40-kVA constant-speed machine will build up in approximately 0.07 second. Single-phase fault currents for the same machine average 4.5 to 5 per unit and therefore, the protective devices used should have ratings of sufficient capacity to interrupt this current.

With the advent of solid-state semiconductor circuit protective devices, the short-circuit current capacity requirements of the machine or source can be reduced to only

that required to satisfy overload current requirements. Solid-state circuit protective devices for 28-volt direct-current systems have been developed which limit short-circuit or overload currents to within the range of 1.3 to 1.5 per unit with eventual trip-out. Solid-state alternating-current devices have been developed with trip characteristics similar to those of the thermal circuit breaker but with trip-out within one half-cycle for short-circuit currents. It is desirable to limit the short-circuit current capacity of the source, particularly for alternating-current devices, in order to reduce the required I^2t rating of the semiconductor power switching element. A reduced requirement for source short-circuit current can result in a significant weight savings in the source. Furthermore, overall system electrical, mechanical and thermal stresses can be reduced.

OVERVOLTAGES

Overvoltages which occur most often are caused by one of the following conditions:

- (1) Removal of a heavy load or clearing of a short circuit causing a transient overvoltage.
- (2) A single-phase fault causing a steady-state overvoltage on the unfaulted phases.
- (3) Malfunction of the excitation system causing the exciter to go to ceiling.
- (4) An open phase on an isolated generator.

The magnitude of transient overvoltages due to the removal of short circuits is approximately 1.7 per unit for a certain 40-kVA constant-speed machine.

The steady-state voltages on the unfaulted phases during a single-phase fault will be somewhat lower than transient overvoltages and for the 40-kVA constant-speed machine are approximately 1.5 per unit. Since the machines are built to have low unbalanced voltages for unbalanced loads, this condition has been minimized.

Overvoltages on isolated generators due to excitation system malfunctions are limited only by saturation and available field current. However in a parallel system, due to the action of the normal generators on the system, the bus overvoltage will be generally lower.

Overvoltages on isolated generators due to an open phase result from the method of sensing in the regulator that will attempt to hold the average voltage of the two remaining phases equal to the normal three-phase average. A common method of regulator sensing is to use the average of the three phases for normal operation with high phase takeover for overvoltage protection.

UNDERFREQUENCY OPERATION

The third special problem to be considered is operation of alternating-current generators for sustained periods of time at speeds lower than rated which results in excess field heating for the following reasons. If the field switch is left closed, the regulator will attempt to maintain constant terminal voltage due to the decrease in generated

voltage with speed. This requires an increasing amount of excitation power with decreasing speed until terminal voltage begins to fall off. This results in two conditions. First, the regulator, if a static type, will be called upon to exceed its rating in supplying field current. And second, the alternator field can be overheated if the operation occurs on the ground with no blast air cooling. The possibility of this type of operation causing trouble was pointed out before MIL-G-6099 was completed but it was decided by the services not to include underspeed requirements in the specifications but to insure that the generators were applied correctly, thus not adding unnecessary weight to the electric system.

FAULT POWER REQUIREMENTS

The power consumed by an alternating-current machine and the system when a fault occurs, varies according to the type of fault, the machine constants and the fault resistance. It does not depend on the ability of the drive to produce that power or the rating of the protective devices used to clear the faults but only on the machine and circuit constants. However, if we consider the total energy over a period of time to be delivered to the system by the drive, the particular application may not require that the steady-state power demand be delivered, since the rotational energy from the drive and alternator is available.

If a three-phase fault with zero resistance is placed on the terminals, the theoretical power required is zero. However, even in this case the actual power required would depend upon the machine i^2R losses, the field i^2R_f losses, and the friction and windage losses. When fault resistance and line losses are added the power required becomes appreciable.

If an unbalanced fault is placed on the machine, two additional power requirements are present. Additional field windings such as ammortisseur bars result in i^2R losses thus increasing the machine losses. The second effect of an unbalanced fault is the power required by loads on the machine which were present before the fault occurred. With a static-type load and since the voltage is increased on the unfaulted phases, this power requirement will increase even further. On typical systems which have been analyzed, single-phase or line-to-line faults can result in requirements of 2 to 2.5 per unit power.

CONCLUSION

In conclusion, the application of alternating-current machines requires a working knowledge of the performance characteristics of the generator-regulator combination. Special emphasis should be placed on machine ratings, short-circuit, overvoltage, underspeed and fault power characteristics. Aid in understanding these characteristics is received by a study of synchronous machine analysis, but the detailed investigations performed by the cooperative effort of the machine and regulator designers relieve the system designer of much of this work by providing characteristics in an immediately usable form.

INTRODUCTION

This section is intended to present a brief description of some of the factors entering into distribution system design together with the basic geometries from which most systems are derived. For more detailed design procedures and considerations, the reader is referred to Section 900, Bibliography.

DEFINITIONS

Distribution System. This term, as used herein, is that part of the complete system between the generator line contactors and the load buses. It is comprised of two general areas, *viz.*

- (1) The source-bus system which provides the junction points between generator feeders, source-bus interconnections, and the transmission system.
- (2) The transmission system which is that part of the system between source buses and load buses.

Emergency Loads in commercial transports usually mean those necessary for continued flight and landing without passenger injury. In military flight vehicles, a similar definition is often used but in missiles, where the criterion is that the mission be accomplished, the definition may be broadened to include all loads necessary to reliable functioning of the missile.

Generator Feeders are the lines between the machine terminals and the generator line contactor. They are not, by definition, a part of the distribution system but enough points of similarity exist between feeder design and transmission system design to warrant discussion of feeders herein.

FUNCTION

The distribution system is used to transfer available source power to the load buses: in a multiple-source system, the distribution system is often designed to make more than one source available to the important load buses.

GENERAL CONSIDERATIONS

Thermal Capacity. Each feeder must be capable of carrying the full output of the machine. Wire is rated for current and ambient temperatures in such a fashion that an extremely-long insulation life is obtained. In most systems, a machine is carrying full load for a comparatively small proportion of the total operating life of the flight vehicle. For these reasons, some designers assign a rating to feeder wires in excess of the book value to obtain a lighter system with a probable insulation life still in excess of expected vehicle life. However, as a minimum requirement, the wire size must be sufficient to carry any load or overload up to the limit of machine capability without damage. It is of interest to note that most alternating-current machines will carry double load considerably longer than the five-second rating.

Voltage Drop. In low-voltage systems of large capacity (such as existing direct-current systems) this is usually the factor that determines wire size. In higher-voltage systems (such as existing three-phase 120/208-volt, alternating-current systems), thermal capacity is more usually the factor that determines wire size except in systems where very long lines are used (of the order of 100 feet or more) or where induction motors with high accelerating rates are required. However, the advent of high-temperature insulations shows promise of making wire sizes small enough eventually to make voltage drop the limiting factor even on 120/208-volt systems. With bundle conductors in three-phase systems, the voltage drop is primarily resistive. If the phase conductors are separated from each other, line reactance is increased and voltage drop is increased.

With single-phase loading, voltage drop in a given line may be considerably greater than the drop obtained with balanced load producing the same phase current and, for wire sizes larger than AN-10 or AL-8, is predominantly reactive. Since the zero-sequence reactance for a given wire size is dependent primarily on spacing of the line from the skin, voltage unbalance at the load bus with unbalanced loading is reduced by running distribution lines as close to the skin as possible. Representative line sequence impedances are shown in Table II-1.

Fault Currents. With bundled conductors, positive and negative-sequence impedances are small. Hence, three-phase fault currents are affected little and line-to-line fault currents are not greatly affected by distribution system and generator feeder lines of moderate lengths. However, line-to-ground fault currents and line-to-line-to-ground fault currents are very greatly affected by line lengths in stiff systems, particularly with large spacing to the skin. For this reason, it is possible to reduce these fault currents by increasing distribution and feeder-line spacing from structure or increase them by decreasing spacing. In practice, installation problems often make it difficult to obtain a very large range of control of fault currents by this means. It should be noted that decreasing fault currents by this method results in increased voltage unbalance at the load bus with unbalanced loading.

Multiple Paralleled Lines. In some instances, multiple paralleled lines have been used to improve distribution system reliability against faults. These are protected separately and are separated in the aircraft so that a fault on one line does not involve the other paralleled lines. In three-phase alternating-current systems, multiple lines per phase are often obtained by running three or more three-phase bundles for each set of three-phase lines. It is of interest to note that little is gained as far as faults are concerned by using two lines per phase instead of one. This is shown in Figure II-1.

In Figure II-1, the protection at the source-bus end of line 1 has already cleared and the fault current is now being supplied through line 2. It is apparent that coordination is not obtained in that the limiters in the good line see the same fault current as the limiter in the faulted line and load and are more likely to clear than the limiter

Table II-1 Aircraft Cable Characteristics

Wire or Cable Size		Maximum* Direct-Current Resistance ohms/1000 ft. 20°C	400-Hz Positive** (and Negative) Sequence Impedance ohms/1000 ft.	400-Hz Zero** Sequence Impedance ohms/1000 ft.	Nominal Weight* of Finished Wire lbs/1000 ft.	Continuous-Duty Current Amperes	
Aluminum	Copper					Single Wire in Free Air	Wires and Cables in Conduit Bundles
	AN-22	16.45			6.3		5
	AN-20	10.25	10.25 + j 0.304	10.44 + j 2.20	8.4	11	7.5
	AN-18	6.44	6.44 + j 0.289	6.33 + j 1.93	11.6	16	10
	AN-16	4.76	4.76 + j 0.278	4.95 + j 1.88	14.3	22	13
	AN-14	2.99	2.99 + j 0.264	3.18 + j 1.80	21.0	32	17
	AN-12	1.88	1.88 + j 0.247	2.07 + j 1.72	32.0	41	23
	AN-10	1.10	1.10 + j 0.228	1.29 + j 1.64	47.5	55	33
	AN-8	0.700	0.700 + j 0.226	0.792 + j 1.53	76.5	73	46
	AN-6	0.436	0.440 + j 0.221	0.632 + j 1.42	115	101	60
	AN-4	0.274	0.282 + j 0.212	0.474 + j 1.33	176	135	80
	AN-2	0.179	0.188 + j 0.206	0.380 + j 1.24	278	181	100
	AN-1	0.146			322	211	125
	AN-0	0.114	0.127 + j 0.204	0.319 + j 1.15	415	245	150
	AN-00	0.090			525	283	175
	AN-000	0.072			657	328	200
	AN-0000	0.057			820	380	225
	AL-8	1.093	1.093 + j 0.226	1.28 + j 1.53	32	60	36
	AL-6	0.641	0.648 + j 0.221	0.840 + j 1.42	55	83	50
	AL-4	0.427	0.439 + j 0.212	0.631 + j 1.33	74	108	66
	AL-2	0.268	0.282 + j 0.206	0.474 + j 1.24	107	152	82
	AL-1	0.214			133	174	105
	AL-0	0.169	0.188 + j 0.204	0.370 + j 1.15	167	202	123
	AL-00	0.133			203	235	145
	AL-000	0.109			242	266	162
	AL-0000	0.085			296	303	190

* Data from: MIL-W-5086B, Military Specification, "Wire, Electric, Hook-up and Interconnecting, Polyvinyl Chloride-Insulated, Copper or Copper Alloy Conductor," 18 June, 1968; MIL-W-5088E, "Wiring, Aircraft, Selection and Installation of," 28 March, 1972; MIL-W-7072B, "Wire, Electric, 600-Volt, Aluminum Aircraft, General Specification for (Asg)," 4 September, 1962.

** Data from: "Impedance Data for 400-Cycle Aircraft Distribution Systems," D. W. Exner, G. H. Singer, Jr., AIEE Technical Paper 52-322, October, 1952. Data for copper taken directly from this paper; data for aluminum extrapolated by the authors from this paper. Extrapolation method was spot-checked with data in "Experimental Determination of 400 Cycle Impedance of Wire in Aircraft Power Distribution Circuits," J. D. Andrew, AIEE Transactions Paper No. 54-374, June 14, 1954. Positive-sequence calculations checked within 5 percent and zero-sequence within 17 percent of the data for the two aluminum conductors in this paper.

Note: Impedance data are based upon tight, equilateral bundle. Positive-sequence data are nearly independent of skin distance; ** zero-sequence data are based upon two-inch skin distance.

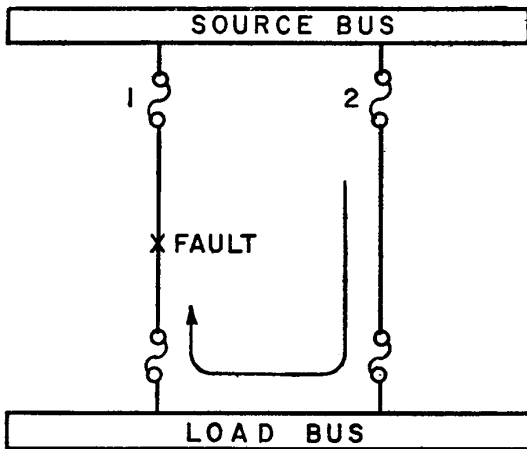


Figure II-1 Fuse Coordination with Fault on Dual Parallel Feeders.

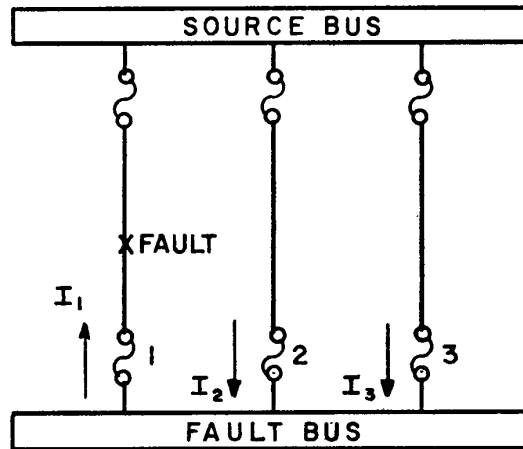


Figure II-2 Fuse Coordination with Fault on One of Three Parallel Feeders.

in the faulted line. An exception exists if any of the loads are capable of supplying current into the fault. For example:

- (1) A battery connected to a load bus in a direct-current system will provide enough fault current to obtain selectivity.
- (2) In three-phase alternating-current systems, wye-delta connected transformers and three-phase wye-connected induction motors are capable of acting as sizable sources for fault current into unbalanced faults. These three-phase loads are characterized by a large ratio of positive to negative and/or zero-sequence impedance. Other loads, for the most part, provide comparatively little additional feed into unbalanced faults.

With three or more lines as shown in Figure II-2 after source-bus limiter of line 1 has cleared it is seen that

$$I_1 = I_2 + I_3$$

whence, if lines 2 and 3 have nearly the same impedances, currents in lines 2 and 3 will be about half the total fault current in line 1 and selective clearing is obtained.

It should be noted that sufficient line length is required to insure reasonably good division of current in spite of variations between protective devices due to both temperature characteristics and manufacturing tolerances. With limiters, approximately ten feet of line is required to assure good current division. In addition, both positive and zero-sequence impedances of one line should be nearly equal to those of the other lines. If these conditions are met, coordination is obtained and the load bus is not lost. However, inspection must detect the blown limiters and the line must be replaced or this section of the system may be lost on any subsequent fault.

A fault involving only one phase between source bus and load bus, leaves one phase open at the load bus (with only one line per phase in the distribution system) and the three-phase loads connected to the load bus are left with one phase open. Thus, even though the fault is cleared, the loads may still be subject to overheating due to unbalanced currents. The use of multiple lines per phase affords protection against this consequence of distribution system faults, in addition to providing coordinated fault protection. However, if load protection is desired, the most direct approach is to provide protection at the load itself for those loads damageable by an open phase since an open load line could also cause an open phase at the load. These factors point to the need for three-phase protective devices for three-phase systems.

The above advantages are achieved at a cost in weight and complexity. The loss of one line per phase requires that the remaining lines in the phase be able to carry the load current. To minimize wire weight, many designers allow the remaining lines to be loaded to 125 percent of their rating. Even so, wire weight will be increased in many cases in addition to the increases in weight due to additional protective elements and their hardware.

Maintenance. In a large three-phase alternating-current system, the number of protective devices in the distribution system may become very large especially where multiple paralleled lines are used in a multiple source-bus system. This poses a serious maintenance problem in that protection may have operated and cleared a fault without loss of any loads and no indication of the fault has been given. Thus, it becomes necessary to inspect as many as one hundred or more limiters scattered over the aircraft before every flight. The situation is aggravated by the fact that many faults clear in such a manner that vaporization of the fuse element does not occur and, therefore, no very noticeable visual indication of operation is obtained.

GENERATOR FEEDERS

Nearly all systems use feeder and voltage regulator connections as shown in Figure II-3.

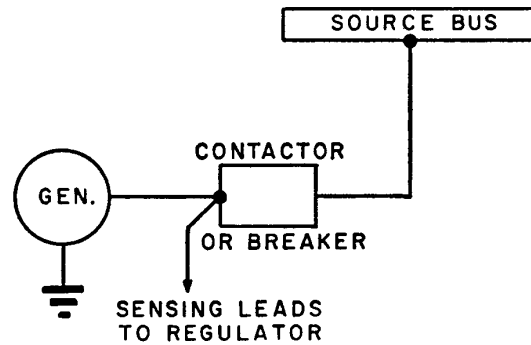


Figure II-3 Connection of Voltage Regulator Sensing Leads.

It is evident that feeder voltage drop does not affect source bus regulation appreciably as long as the regulator is within its operating range. However, the generator-regulator combination must be capable of supplying this drop along with the voltage appearing at the bus. Therefore, the generator must be rated at higher voltage than source-bus voltage and must be heavier by roughly the ratio between generator and source-bus voltage under loaded conditions. Generators are designed to take care of some line drop, i.e., alternating-current generators are usually designed to supply rated current at 120 volts into a system utilizing 115 volts at the source bus.

However, generator overload ratings are defined by MIL-G-21075 (and applicable Air Force drawings) at 115 volts + 3.5 percent for both the two-minute and five-second ratings. Thus, if feeder drop is such that generator voltage is 120 volts at full-load current with a bus voltage of 115 volts, a qualified machine need deliver only 103.5 volts to the bus for 150 percent load current and 101 volts for 200 percent load current. In nearly all cases, requiring 111 volts at the bus with feeder impedance sufficient to give 5 volts drop at rated load will require sizeable additions to the weight of the generation equipment over the weight of equipment that just meets the specifications.

In constant-speed systems designed to MIL-G-6099, the situation is eased somewhat by the fact that machines are

rated at 380 Hz on full load and are usually operated at 400 Hz.

In a 400-Hz system, therefore, machine voltage may be 125 volts with a bus voltage of 115 volts and the machine would be within its full-load rating but double load bus voltage could drop to 91 volts and still meet the minimum specification requirements. It is possible then to achieve a considerable wire weight saving in some instances at the expense only of overload capacity available at the bus. Since full-load requirements can be met in MIL-G-6099A at average speed, this possibility does not exist for systems designed to the "A" version.

Feeder protection (as noted in Section 332) in alternating-current systems is usually of the differential type and is usually incorporated in the generator protective system. Differential protection provides high-speed tripping of the generator excitation and of the line contactor. However, the flux stored in the machine must decay and this takes time. Thus, a sizable current may flow into the fault for from 30 to 1000 milliseconds after tripping has occurred. In addition, residual excitation coming from the exciter may provide a continuing source of fault current of surprisingly large size, in some cases, on a steady-state basis. For this reason, differential protection, no matter how sensitive, cannot be relied upon to prevent explosions where feeders run through areas containing explosive mixtures. Tests have shown that explosions do take place with differential protection operating normally. This protection does appear to offer advantages in preventing fires in nonvolatile materials by reducing the energy fed into the fault and is especially useful in obtaining system coordination since it does not operate at all on through faults.

Since feeders very often run through areas with potentially explosive atmospheres and highly combustible fumes, the designer must, in these cases, use the greatest care in mechanically protecting against faults in these critical areas.

Feeders in direct-current systems have been protected in most cases by reverse current relays and breakers. Differential protection utilizing shunts or transformers (designed to operate on the transient portion of fault current build-up) have been developed for this use.

SOURCE-BUS ARRANGEMENTS

Single Source-Bus. One or more generators may be connected to a single source-bus. Since a fault on this bus causes loss of all primary generation, reliance must be placed on mechanical protection against faults. This arrangement offers the advantage of being a simple system which can be given good mechanical protection.

Multiple Source-Buses. Protection of a paralleled bus system is a difficult problem. The following factors must be considered:

- (1) It must be possible to isolate a faulted bus from normal buses without loss of generation other than that connected to the faulted bus. It is highly desirable to isolate a faulted bus from its connected generation.
- (2) A source-bus must not be isolated from all generation by faults in the transmission or load system.

- (3) To utilize the parallel connection fully, it is desirable that tie lines be capable of transferring to a bus which has lost its generation the full-load and overload ratings of the lost generation.
- (4) In a three-phase alternating-current system complete loss of one phase in the bus interconnections should cause the affected bus to be isolated from the rest of the bus system.

SYNCHRONIZING BUS

The synchronizing bus is shown as a small block in Figure II-4 to illustrate the practice of making this simply a

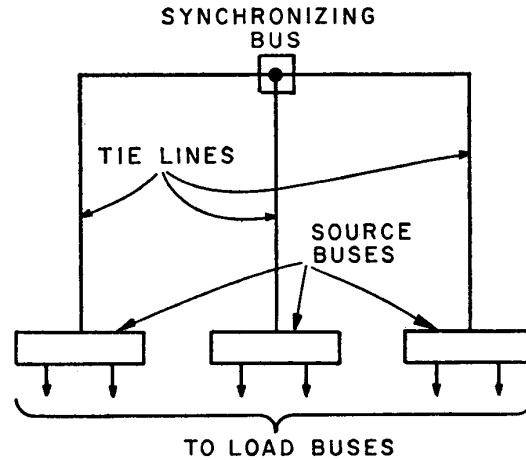


Figure II-4 Multi-Bus Arrangement with Synchronizing Bus.

tie point rather than a bus structure. This system has been used only on three-phase alternating-current systems up to this time. For this reason the following discussion pertains only to such a system.

Four general ideas of protection have been applied to this system:

- (1) Overcurrent protection with multiple, paralleled tie lines.

Advantages:

- (a) Any one tie line can be faulted and cleared quickly.
- (b) With three or more machines, selective isolation of a faulted source bus is obtained.

Disadvantages:

- (a) If power transfer requirements are fully met, clearing times for a three-phase fault at the tie bus are very long if clearing can be obtained at all.
- (b) An unbalanced fault on the tie bus results in the system being tied together by only one or two phases.
- (c) An unbalanced fault on a source bus results in the loads on that bus being supplied by only one or two phases.

- (d) With generation reduced to two source-buses, it may not be possible to isolate a faulted source-bus due to the factors of (a).
 - (e) Due to large sizes of overcurrent devices, a source-bus or tie-bus fault must be of low impedance if clearing is to be obtained.
 - (f) If an undervoltage device is incorporated in generator protection, a fault not heavy enough to clear the large overcurrent devices within a reasonable time can cause loss of all generation.
- (2) Overcurrent sensing which actuates three-phase breakers in the tie lines.

Advantages:

- (a) An unbalanced fault results in clearing all three phases.
- (b) With three or more machines, selective clearing of a faulted source bus is obtained.
- (c) Available devices will give protection against three-phase faults on the tie bus and still give a large proportion of the desired load transfer.

Disadvantages:

- (a) A fault current in the neighborhood of 150 percent of one machine rating can flow without actuating the protection.
 - (b) If an undervoltage device is incorporated in generator protection, a fault not heavy enough to clear the large overcurrent devices in a reasonable time can cause loss of all generation.
- (3) Unbalanced and undervoltage protection on the tie bus. The protection has a time delay sufficient to override all solid load and transmission system faults and actuates three-phase breakers in the tie lines.

Advantages:

- (a) Coordination with generator undervoltage protection can be obtained with relative ease such that no electric system fault can cause tripping of all generation.
- (b) In most cases, reasonably short clearing times for all bus-system faults can be obtained.
- (c) No unbalanced interconnections result from clearing an unbalanced fault.
- (d) The protection can be made to operate on fairly small fault currents without causing a false loss of generation due to large unbalanced loads.

Disadvantages:

- (a) Any fault in the source-bus system causes the system to be split.
 - (b) If high fault-current sensitivity is used, the system can be split by a large unbalanced load condition.
- (4) Differential protection with the unbalanced and undervoltage protection of (3). This is a proposed scheme which shows merit. The differential zone of generator protection is enlarged to include each source-bus and tie breaker by passing all load-bus leads and the bus-tie lead of each phase through the

hole of a single current transformer which operates in conjunction with another current transformer in the neutral lead of each phase of the machine. The differential protection can open either or both breakers.

Advantages:

- (a) This scheme has all the advantages of (3) plus the major advantage of giving very fast tripping for all faults except those associated directly with the synchronizing bus.
- (b) No coordination problem exists for source-bus faults or tie-breaker faults which can be cleared by opening the tie breaker.
- (c) Complete selective isolation of a faulted source-bus is very quickly obtained without splitting the entire system.

Disadvantages:

- (a) A feeder fault causes the tie breaker to trip unnecessarily. It may be necessary to incorporate a reclosing sequence in generator protection to avoid long interruptions to power to the associated source bus or to sequence breaker operation by tripping the machine breaker first and using this tripping action to arm the tripping circuit of the tie breaker.
- (b) Load-bus lines must be limited to the number that can pass through the current transformer hole together with the tie line.
- (c) In some installations, a wire weight penalty may be required to permit routing of load lines through the current transformers.
- (d) A tie-breaker fault may exist such that opening the breaker does not clear the fault and the system must be split.

SPLIT BUS

The split-bus system shown in Figure II-5 is used in both alternating-current and direct-current systems.

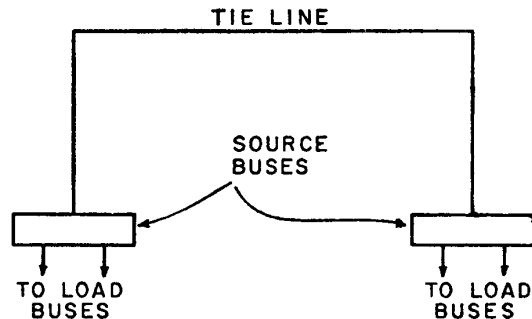


Figure II-5 Split-Bus System.

If protection is used at both ends of the tie lines, this is a special case of the synchronizing-bus system described before. The tie line itself constitutes the synchronizing bus and the comments in the preceding sections apply.

In many cases, a single set of protective devices has been used in the bus tie. This has taken the form of a limiter in most direct-current systems and, in some alternating-current systems, a single tie breaker operated by sequence currents has been used.

Use of limiters for protection gives the usual disadvantage of very long clearing times or even failure to clear if maximum power transfer capabilities are to be used.

The use of a single three-phase breaker actuated by sequence currents results in the following:

Advantages:

- (1) Only one breaker is required.
- (2) A faulted source-bus is isolated easily.

Disadvantages:

One major disadvantage lies in the fact that a faulted tie breaker can cause loss of all generation.

RING BUS

Advantage:

Since each source-bus has two feeds, the probability of loss of paralleling ties is reduced, as shown in Figure II-6.

Disadvantage:

Selective isolation of a faulted bus can be obtained only with differential protection around each bus.

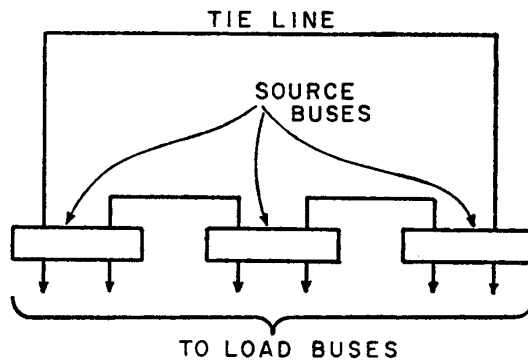


Figure II-6 Ring-Bus System.

TRANSMISSION SYSTEMS AND THEIR FEATURES

Since distribution system layout is highly dependent on source-bus arrangement, transmission systems are shown for both single source-buses and multiple source-buses. These systems represent only the basic principles involved; they may be greatly modified by physical locations of source-buses and loads. For example, in many installations, loads near the source-bus are connected directly to the source-bus and loads farther away use a load bus. Hence, the source-bus may be used as a source-bus for part of the loads and a load bus for another part.

Single Source-Bus.

In many direct-current systems and in single-generator alternating-current systems only one primary source-bus is used. In these instances, provisions are made to switch emergency loads to an emergency source such as a battery, ram-air turbine-generator, or other such independent source. Such a system is shown in Figure II-7.

The transfer device may be automatic or on a manned vehicle it may be simply a switch available to the crew. If an automatic device is used, it must be capable of transferring the emergency loads any time the primary source does not supply voltage and/or frequency within the operating range of the emergency loads.

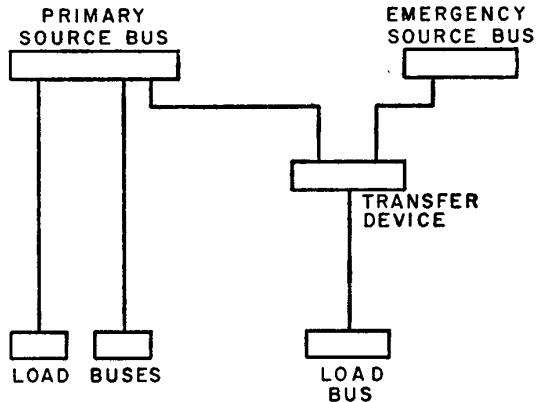


Figure II-7 Single Source-Bus System with Multiple Load Buses.

Advantages:

- a. In the small installation, this system is simple and light.
- b. Emergency loads are supplied even though the primary source is lost.

Disadvantages:

- a. Loss of the primary source means loss of supply to most of the loads.
- b. A fault or open on the load side of the transfer device means complete loss of one or more emergency loads even though both primary and emergency sources are still capable of supplying power.

An emergency load, in many cases, is a function which is duplicated at least in part by other functions. An example is the inclusion of both turn-and-bank indicators and artificial horizons in flight instruments or duplicate instruments in pilot and copilot positions. The disadvantage of *b.* may be eased by using two emergency load buses with duplicating functions being split between them in such a fashion as to permit emergency operation of the aircraft if either emergency load bus is lost. Such a system is shown in Figure II-8.

Multiple Source-Bus Systems

There are three basic transmission systems possible with multiple source-buses. These are shown in the following diagrams.

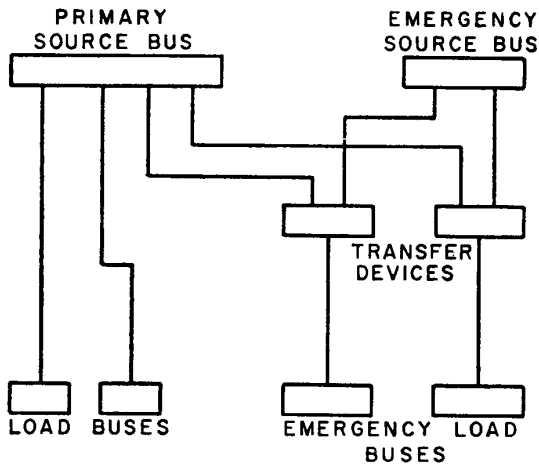


Figure II-8 Single Source-Bus with Multiple Emergency Buses.

INTERCONNECTED TRANSMISSION SYSTEM

The interconnected transmission system shown in Figure II-9 is used only with a parallel source-bus arrangement. Further, it cannot be used effectively with less than three source-buses since a fault on one source-bus in this case could result in complete loss of the distribution system unless loads capable of supplying sufficient fault current to insure selectivity in clearing are connected to each load bus, or reverse-current breakers are used in the transmission system.

Advantages:

- (1) Load buses can be supplied from more than one source bus.

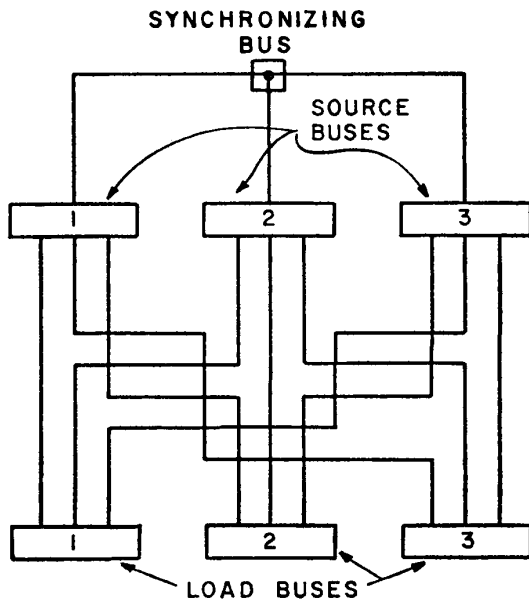


Figure II-9 Interconnected Transmission System.

- (2) With three or more source-buses, selectivity in clearing is obtained if each load bus is connected to three or more source-buses.

Disadvantages:

- (1) It is not possible to isolate a source-bus without clearing transmission system limiters. Thus, generator protection must be completely selective for all generator and control malfunctions and must be able to uncouple the paralleling ties in the bus system to isolate a faulted source-bus selectively.
- (2) If generation is reduced, fault current may be insufficient to clear a faulted source-bus.
- (3) Weight, higher probability of faults.

LOAD TRANSFER SYSTEM

This system as shown in Figure II-10 may be used with either paralleled or nonparalleled source-buses since the distribution does not provide parallel connections on the source-buses at any time.

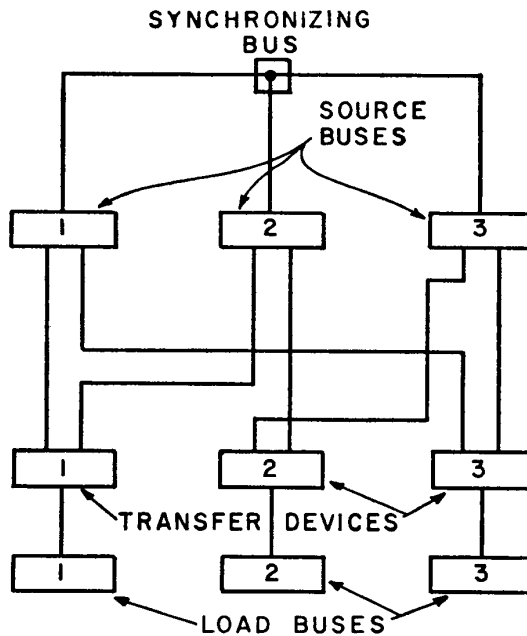


Figure II-10 Load Transfer System.

Advantages:

- (1) Any source-bus can be lost without loss of supply to any load bus.
- (2) Generator and bus protection is simplified in that sequentially selective protection may be used.
- (3) With three or more source-buses there is a higher probability of faults.
- (4) A three or more source-bus system has greater weight.

Disadvantages :

- (1) Transfer devices are needed. These represent added complexity and weight. If automatic, they must operate with a sufficient time delay to prevent chattering on a fault on the load side of the device.
- (2) The connection between load bus and transfer device is effectively a load-bus extension. A fault here causes loss of the load bus.

SINGLE-FEED DISTRIBUTION SYSTEM

In single-feed distribution systems each load bus is connected to just one source-bus as shown in Figure II-11.

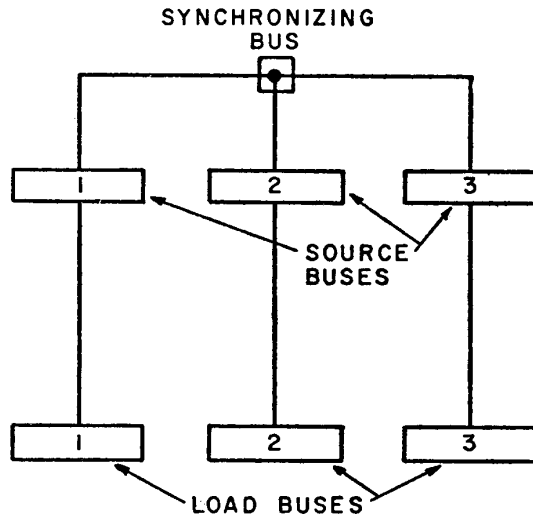


Figure II-11 Single-Feed Transmission System.

Advantages :

- (1) It is, by a considerable margin, the lightest and simplest.
- (2) It may be used on either paralleled or non-paralleled systems of any number of source-buses.
- (3) There are no selectivity problems other than those attendant to multiple paralleled lines (if such is used).
- (4) No additional selectivity requirements are imposed upon generator and bus protection.

Disadvantages :

There is one major disadvantage in that a fault on a source-bus results in complete loss of all loads connected to the source-bus.

Protection of Transmission Systems

Protection of the distribution system must be coordinated with generation protective functions, source-bus arrangement and protection, and with load line protection. Essentially, the protective functions of the entire system must be considered as a whole.

Transmission system protective devices are usually limiters, fuses, or circuit breakers. Where coordination re-

quirements are difficult such as with multiple, parallel lines in the distribution system, limiters are more generally used since they are considerably more precise in their characteristics than circuit breakers or fuses. Transmission system lines use protection at both ends where a load bus has more than one wire connected to one or more source-buses.

PROTECTIVE COORDINATION

Coordination is a complex problem: the entire system from prime mover to load must be considered as a whole. In many cases, it is even necessary to consider the characteristics of a mechanical or hydraulic load driven by an actuator or motor. A case becoming more common is that of a primary alternating-current system in which transformer-rectifier units are used as sources in a secondary direct-current system which may be nearly equal in complexity to the alternating-current system. This presents the designer with the coordination problem diagrammed in Figure II-12.

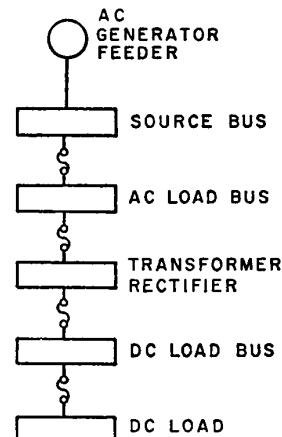


Figure II-12 Complex Coordination Problem.

It is seen that four series protection devices must be coordinated—two are alternating-current devices operating at 115 volts and the other two are direct-current devices operating at 28 volts. To further complicate matters, both the alternating-current and direct-current systems may be operated as parallel systems. Fortunately, the direct-current system cannot feed backwards into the alternating-current system.

There is an orderly process by which a coordinated system is usually built up. The primary function of the electric system is to supply the loads. Hence, coordination is usually started at the load and proceeds through the transmission system to the source-bus system and generator feeders.

Load and Load-Line Protection

Load lines are selected on the basis of the requirements of the load. Voltage drop, thermal rating, or minimum permissible size of the wire can be the determining factor. Practice has been to protect the wire against damage by using circuit breakers or fuses at the load bus. Inas-

much as wire protection will not give overload protection for the load itself in most cases, overload protection has been incorporated into the load assembly in a few instances. When the smoke and fire hazard of overheated loads is considered, it may be desirable to use overload protection at the load-bus end of the lines for many of the loads where protective device characteristics agree well enough with load thermal characteristics. In most instances, the best that can be done for overload protection is to use the smallest protector that will not produce false trips under the most adverse conditions of environment and protector tolerances.

This should by no means include emergency loads unless highly reliable duplication of these functions is available and, when function duplication is not available, a "non-trip-free" circuit breaker is often used to allow maximum load utilization even at the expense of the possibility of burning out the load itself.

Coordination Between Load and Transmission Line Protection

The criterion of coordination here is that, under the highest load condition at the load bus, no overload or fault on any one load line should cause the transmission-line protection to clear before the affected load-line protection clears.

PROTECTIVE DEVICE COORDINATION

As previously noted, limiters are often used in transmission system lines whereas load lines most often use "slow-blow" fuses and thermal or magnetic circuit breakers. As seen in Figure II-13, the characteristics of a limiter and a circuit breaker differ greatly. At 0.1 second, about 21 times rated current is needed to clear the circuit breaker and only nine times rated current will blow the limiter. Thus, if the circuit breaker rating is as much as

three-sevenths of the rating of the transmission system limiter through which the load bus is supplied, a fault on the load side of the circuit breaker that draws more than 21 times its rating will clear the limiter first causing the entire load bus to be lost on a fault on a load line.

To obtain coordination in these instances, it has sometimes been the practice to use a limiter in series with the circuit breaker in the load line. The limiter is selected to coordinate in the high-current regions with transmission system protection and the circuit breaker gives low-current wire protection. It is usually possible to improve wire protection this way.

Fault currents behind load circuit breakers are usually much smaller than those involved in source-bus system faults due to line impedances between these points. Hence, in many cases, circuit breakers as large as one-fourth to one-third of the limiter rating may be used safely without use of the additional limiter in the load line.

COORDINATION ON UNBALANCED FAULTS IN ALTERNATING-CURRENT SYSTEMS

As noted in GENERAL CONSIDERATIONS, loads such as wye-connected induction motors and wye-delta or three-legged, wye-wye transformers characterized by large ratios of positive to negative and/or zero-sequence impedances are capable of contributing fault currents well in excess of their rated currents to unbalanced faults anywhere in the system. Thus, where these faults require long clearing times (such as in the source-bus system) it is possible to operate load line protection and lose a load even though both the load line and the load are operable.

This can be avoided with transformer loads by designing them with delta-connected primaries or by operating with the neutral of the transformer wye ungrounded. The same procedures will ease the problem with induction motors

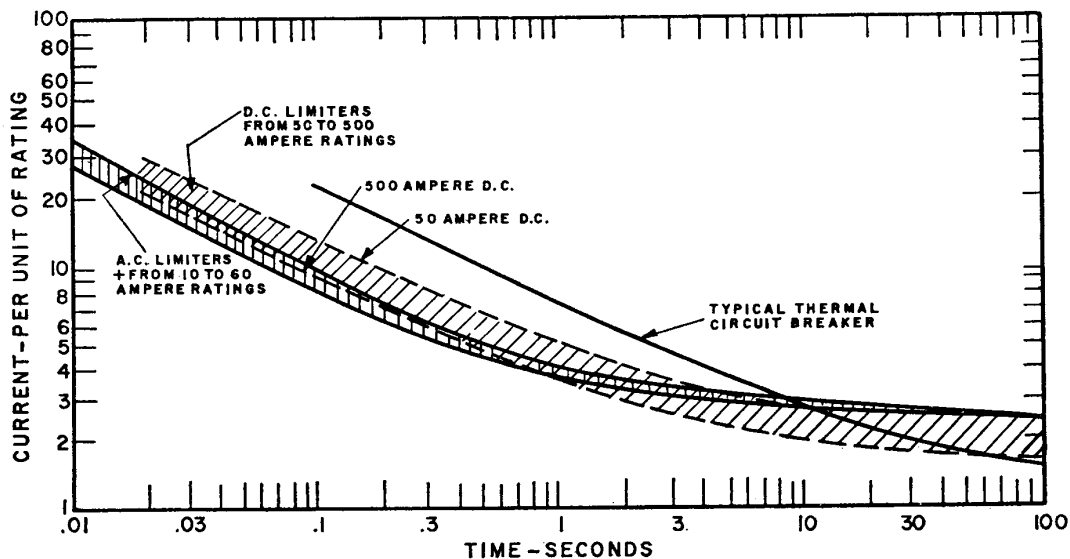


Figure II-13 Typical Aircraft Circuit Breaker and Current Limiter Characteristics.

but the low negative-sequence impedance of these motors may still cause trouble in a few instances.

Coordination Between Source-Bus System and Transmission System

The criterion here is that no source-bus or its generation can be lost as a result of any one fault in the transmission system or on a load line.

If thermal devices are used and there is a reasonable diversification of the lines tied to each source-bus, power transfer requirements usually dictate protection which gives comfortable margins over transmission system protection.

With fixed time delay devices such as a circuit breaker operated by an unbalanced and/or undervoltage device, the time delay may be set long enough to ensure coordination with the transmission system on solid faults. These devices do not coordinate well on faults which persist for long periods without clearing other protection.

With differential protection, no actuation is obtained for through faults and no coordination problem exists.

Coordination Between Generator Feeder Protection and the Source-Bus System

Generator feeder protection should be such that only a fault on the feeder itself will operate the protection. Thermal elements cannot be coordinated with other thermal elements in the bus interconnection system. Also, they inhibit the ability of the generator to produce at its full capability under all conditions. They have been used in conjunction with multiple, paralleled lines on the premise that a fault can exist on only one line. Thus, the size of the protector can be made large enough so that, with all lines intact, coordination can be obtained and still the machine has enough capacity to clear a fault on any one line.

Differential protection is not actuated by through faults and no coordination problem exists.

DISCUSSION

- (1) A great deal has been said about fault protection herein. This is not intended to infer that a well-coordinated and protected system should not be very carefully designed mechanically. Any fault that occurs is potentially a fire or damage source even though protection clears the fault. The preventive measures of careful mechanical design, installation, and maintenance are the best assurance of a trouble-free distribution system. Protection has come to be accepted as a necessary back-up to take care of defects in these three categories as well as to minimize damage resulting from combat in military aircraft.
- (2) The choice of distribution system type is dependent upon a multiplicity of factors. Among these factors are:
 - (a) Number of source buses.
 - (b) Reliability of the source buses.
 - (c) Duplication of emergency load functions available to be divided among the load buses.

- (d) Weight, space, and complexity penalties involved in making more than one source-bus available to the important load buses.
- (e) Degree and type of selectivity available in generator and bus protection equipment.

Most existing direct-current systems and some small alternating-current systems use the single source-bus arrangement shown in Figure II-7 with some means of transferring emergency loads to emergency sources. The main bus is carefully protected to provide a very high degree of reliability against faults.

Some direct-current systems have used the scheme of Figure II-9 together with batteries connected to load buses to provide selectivity. Most large alternating-current systems have used the load-transfer scheme of Figure II-10 but development of completely selective generator protection for many malfunctions, coupled with the duplication of emergency loads possible on large aircraft, make the very simple and light scheme of Figure II-11 much more attractive than it has been in the past. It appears that it is being considered very seriously for future large aircraft.

- (3) In coordinating protection, the entire protective system must be carefully considered. This includes:
 - (a) Generator and feeder protection.
 - (b) Source-bus protection.
 - (c) Distribution-system protection.
 - (d) Load-line protection.
 - (e) Secondary-system protection.
- (4) The performance of the generating system under fault conditions may be greatly affected by distribution and feeder-line lengths and resistances in direct-current systems. In three-phase alternating-current systems, conductor spacing from the skin is an added factor in unbalanced ground fault cases.
- (5) Voltage unbalance in alternating-current systems at the load bus with unbalanced phase loading is affected adversely by the distribution system and generator feeders if conductor spacing from the skin is large.
- (6) Three-phase loads with large ratios of positive to negative and/or zero-sequence impedances are capable of feeding fault current in excess of their normal load currents into unbalanced faults in the distribution system posing a coordination problem that, at present, is not completely solved. The use of delta-connected or ungrounded wye-connected transformer primaries will solve the problem for transformers. The same procedures will ease the problem on induction motors.
- (7) A great deal of work has been done on fault protection. Many designers consider open circuits more likely than faults. Since this can result in overheating and losing certain types of loads unnecessarily on three-phase alternating-current systems, due to unbalanced operation, it seems that additional work is

warranted in improving system ability to withstand these conditions.

- (8) Thermal and magnetic protective devices in alternating-current systems have been limited in usefulness because they are essentially single-phase devices and can create a condition by clearing that is nearly as bad as the fault that caused them to clear. A complete line of three-phase devices is needed. Very recently, a few types have gone into production—more are needed. Solid-state semiconductor protective devices can be made to function as three-phase devices by interlocking the control logic.
- (9) Comparatively little attention has been given to overload protection for the loads. There seems to be little advantage in keeping a wire from smoking if the load connected to it can overheat and fill the cabin with smoke without operating the protection. It seems that further work is warranted in developing overload protection that is matched to the non-emergency loads located in the fuselage or in areas where a possible fire hazard may exist.

133 Symmetrical Components

Introduction

Ever since the introduction of alternating-current systems in aircraft, there have appeared analyses of system action on the basis of Symmetrical Components. This method of analysis with its "positive," "negative," and "zero" sequences has proved a most flexible and useful tool in the hands of the utilities engineers, and it is only natural that it should be used in analysis of aircraft alternating-current systems. Unfortunately, however, the terms associated with the method have a mysterious sound, and almost by general consent are seldom used. This is very regrettable, for the term "unbalanced voltage relay" is a very poor name indeed, since there are three different types of unbalanced voltages in a four-wire, three-phase alternating-current system: line-to-line unbalance, line-to-neutral unbalance, and a combination of the two. The action of the relay, then, can only be accurately described by naming the type of unbalance to which it is sensitive. This is very readily done by using symmetrical component nomenclature, further, this method provides a means for accurately stating the relay sensitivity.

The basic elements of Symmetrical Components are very simple indeed, it is only when detailed calculations are being carried out that they become cumbersome. However, it is seldom that such computations need be made by the average engineer, and a small amount of time spent in understanding the subject will more than pay in increased understanding of the subject. This section will be devoted to a short explanation of Symmetrical Components, with a few numerical explanations of their use. For a more complete treatment, consult Section 900, Refs. [1]–[4].

Basic Assumptions.

No proof will be given here, but the basic theorem of Symmetrical Components is that any system of unbalanced vectors may be completely described as the sum of systems of balanced vectors, the number of such systems being the number of degrees of freedom the system possesses. This is the equivalent of saying that to solve the equations connecting a system of unknowns, there must be as many separate equations as there are unknowns. In the case of three-phase systems, it means that for the three-wire system, the sum of two sets of symmetrical vectors will represent any unbalance, while for a four-wire system the sum of three sets of symmetrical vectors will represent any unbalance. These sets of vectors are called positive, negative, and zero, the reasons for this will become clear as we go on.

Now let us assume that we have a system of unbalanced voltages, and it is a three-phase, three-wire system. What was said in the last paragraph means this: we can find two sets of symmetrical vectors (i.e., $E_a = E_b = E_c$ numerically in each set, and the vectors are 120 degrees apart in each set) such that when added they are equal to the unbalanced voltages. Here, we are saying nothing regarding the relative values (numerical) of the two sets, nor are we saying anything regarding the relative phase angle between E_a phase of one vector set and E_a phase of the other.

What we are saying is

$$\begin{aligned} E_{AB} &= E_{AB1} + E_{AB2} \\ E_{BC} &= E_{BC1} + E_{BC2} \\ E_{CA} &= E_{CA1} + E_{CA2} \end{aligned} \quad (1)$$

The sets of vectors are distinguished one from the other by the subscripts 1 and 2. These particular subscripts are used because they tie in very conveniently with the nomenclature to be used later.

If our set of unbalanced vectors had been current instead of voltage, then we could equally well have had the equations

$$\begin{aligned} I_a &= I_{a1} + I_{a2} \\ I_b &= I_{b1} + I_{b2} \\ I_c &= I_{c1} + I_{c2} \end{aligned} \quad (2)$$

Similarly, for a three-phase, four-wire system, the voltage and current equations become

$$\begin{aligned} E_{an} &= E_{a1} + E_{a2} + E_{a0} \\ E_{bn} &= E_{b1} + E_{b2} + E_{b0} \\ E_{cn} &= E_{c1} + E_{c2} + E_{c0} \end{aligned} \quad (3)$$

$$\begin{aligned} I_a &= I_{a1} + I_{a2} + I_{a0} \\ I_b &= I_{b1} + I_{b2} + I_{b0} \\ I_c &= I_{c1} + I_{c2} + I_{c0} \end{aligned} \quad (4)$$

The difference in the two voltage equations is due to the fact that in the three-wire system there are no line-to-neutral voltages, as in the four-wire case.

A very attractive feature of this system is that in any sequence if the sequence voltages and currents are known, the sequence impedance can be found. What we are saying is simply that each sequence behaves according to Ohms law.

$$I_{a1} = \frac{E_{a1}}{Z_1} \quad I_{a2} = \frac{E_{a2}}{Z_2} \quad I_{a0} = \frac{E_{a0}}{Z_0} \quad (5)$$

This is diagrammed in Fig. III-1 for clarity.

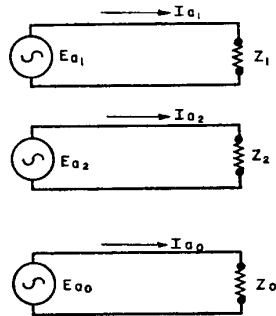


Figure III-1 Positive, Negative and Zero-Sequence Circuit Diagrams.

Let us end this portion of this section by recapitulating.

1. Any set of unbalanced vectors, voltage or current, can be represented by sets of balanced vectors, two sets for a three-phase, three-wire system, three for a three-phase, four-wire system.
2. These balanced vectors can be treated exactly like any balanced system, each having its own balanced voltages, currents and impedances.
3. The balanced vectors can be combined at any time to find the unbalanced conditions existing at any part of the circuit.

The Three-Phase, Three-Wire System.

Let us assume first that we have a three-wire system, with a balanced 100 percent power factor load applied. The diagram will be as shown in Figure III-2(a), the voltage and current relations are as shown in Figures III-2(b) and (c).

Now, phase rotation is E_{AB} , E_{BC} , E_{CA} , or I_a , I_b , I_c . This can only be accomplished by having both the voltage and current vectors rotating counterclockwise, or in a *positive* direction. Thus, vectors rotating counterclockwise, and with the sequence E_{AB} , E_{BC} , E_{CA} or I_a , I_b , I_c (also E_{an} , E_{bn} , E_{cn}) are known as *positive-sequence* vectors, and it is these vectors that are known as *positive-sequence* vectors. In other words, the balanced quantities we have been accustomed to deal with are *positive-sequence quantities*. In symmetrical component work, they are written with the subscript one, as follows, E_{a1} , E_{AB1} , I_{a1} , etc.

Next, assume a set of vectors with *negative* phase sequence, that is it rotates in a counterclockwise direction but with the phase sequence E_{AB} , E_{CA} , E_{BC} . Also, assume

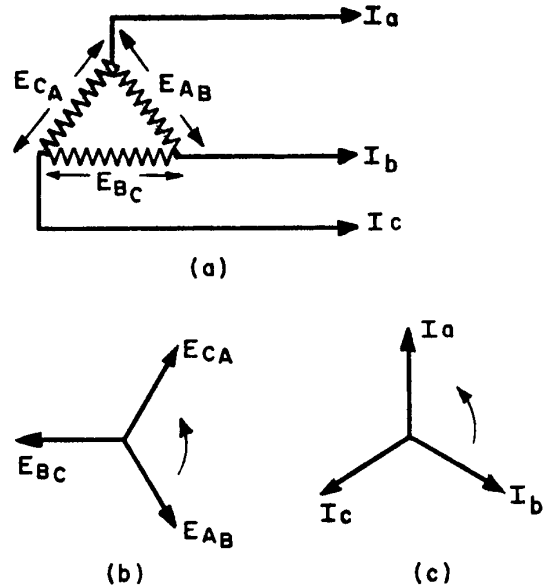


Figure III-2 Three-Phase, Three-Wire System Voltage and Current Vectors.

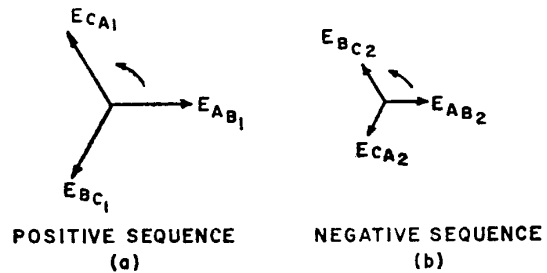


Figure III-3 Positive and Negative-Sequence Voltage Vectors and Their Resultant.

a set of positive-sequence vectors of twice the absolute magnitude of the negative sequence set with E_{AB1} and E_{AB2} with the same phase angle. In Figures IIIA and IIIB these two sets of vectors are drawn to scale, in Figure IIIC the addition operation is performed.

$$\begin{aligned}
&\text{Since } E_{AB1} = 1.0 / \underline{0^\circ} = 1.000 + j 0.000 \\
&\quad E_{BC1} = 1.0 / \underline{-120^\circ} = -0.500 - j 0.866 \\
&\quad E_{CA1} = 1.0 / \underline{120^\circ} = -0.500 + j 0.866 \\
\text{and } &\quad E_{AB2} = 0.5 / \underline{0^\circ} = 0.500 + j 0.000 \\
&\quad E_{CA2} = 0.5 / \underline{-120^\circ} = -0.250 - j 0.433 \\
&\quad E_{BC2} = 0.5 / \underline{120^\circ} = -0.250 + j 0.433 \\
E_{AB} &= E_{AB1} + E_{AB2} \\
&= 1.000 + j 0.000 + 0.500 + j 0.000 \\
&= 1.500 / \underline{0^\circ} \\
E_{BC} &= E_{BC1} + E_{BC2} \\
&= -0.500 - j 0.866 - 0.250 + j 0.433 \\
&= -0.750 - j 0.433 \\
&= 0.866 / \underline{-150^\circ} \\
E_{CA} &= E_{CA1} + E_{CA2} \\
&= -0.500 + j 0.866 - 0.250 - j 0.433 \\
&= -0.750 + j 0.433 \\
&= 0.866 / \underline{150^\circ}
\end{aligned}$$

Another situation of interest in the three-wire system is where I_{a1} and I_{a2} are equal in magnitude, but are 180 degrees out of phase. Writing out both the positive and negative sequence components:

$$\begin{aligned}
I_{a1} &= 1.000 / \underline{0^\circ} = 1.000 + j 0.000 \\
I_{b1} &= 1.000 / \underline{-120^\circ} = -0.500 - j 0.866 \\
I_{c1} &= 1.000 / \underline{120^\circ} = -0.500 + j 0.866 \\
I_{a2} &= 1.000 / \underline{180^\circ} = -1.000 + j 0.000 \\
I_{b2} &= 1.000 / \underline{-60^\circ} = 0.500 - j 0.866 \\
I_{c2} &= 1.000 / \underline{60^\circ} = 0.500 + j 0.866
\end{aligned}$$

Then

$$\begin{aligned}
I_a &= I_{a1} + I_{a2} \\
&= 1.000 + j 0.000 - 1.000 + j 0.000 \\
&= 0 \\
I_b &= I_{b1} + I_{b2} \\
&= -0.500 - j 0.866 + 0.500 - j 0.866 \\
&= 0.000 - j 1.732 \\
&= 1.732 / \underline{-90^\circ} \\
I_c &= I_{c1} + I_{c2} \\
&= -0.500 + j 0.866 + 0.500 + j 0.866 \\
&= 0.000 + j 1.732 \\
&= 1.732 / \underline{90^\circ}
\end{aligned}$$

It is evident that this is a case where a line-to-line load has been applied between phases B and C, and current flows in phases B and C only, the current in Phase B is 180 degrees out of phase with that in phase C. Actually, this is the most severe unbalance that can occur on a three-wire system, the general case is for E_{a2} to be only a few percent of E_{a1} .

In summary of this Section, the following should be noted:

1. Positive-sequence voltages, currents and impedances are the voltages, currents and impedances with which we have been familiar in calculating balanced circuits.
2. Negative sequence is simply reversed rotation. (Physically, in a machine containing iron, this is not so. This will be discussed later.) The negative-sequence impedance of static, linear devices, such as wire, is the

same as the positive-sequence impedance.

The Three-Phase, Four-Wire System.

This system is basically the same as the three-wire, but with an additional degree of freedom. That is, on the three-wire system, it was not possible to have an unbalanced voltage or current to neutral, because there was no neutral. The four-wire system of course has a neutral, so both voltage and current unbalances to neutral may occur.

That is, neutral current may flow, and the vector sum of the line-to-neutral voltages may not be zero, and an unbalanced voltage to neutral may occur. In order to analyze this condition, it is necessary to add another sequence, we now have positive, negative and zero sequences. Zero-sequence voltages and currents always involve the neutral, positive and negative-sequence voltages and currents do not.

The zero-sequence vectors differ somewhat from the positive and negative-sequence vectors. This is understandable, since positive and negative-sequence voltage and currents are three phase, while a voltage or current to neutral is single phase. Thus, the zero-sequence components of a current, say, are all equal and in phase (not equal and 120 degrees out of phase, as are the positive and negative sequences). Thus $I_{c0} = I_{b0} = I_{a0}$ and $E_{a0} = E_{b0} = E_{c0}$. Thus, $I_{\text{neutral}} = 3I_{a0} = 3I_{b0} = 3I_{c0}$. Furthermore there is no "rotation" as such, there is no phase sequence, since $I_{a0} = I_{b0} = I_{c0}$ in all respects.

Let us now assume the existence of three sets of current vectors, positive, negative and zero, and with $E_{a1} = 1.0/0^\circ$, $E_{a2} = 1.0/0^\circ$, $E_{a0} = 1.0/0^\circ$. This will provide us with an illustration of the most extreme case of unbalance possible, a single-phase current flowing in phase A only.

First

$$\begin{aligned}
I_{a1} &= 1.0 / \underline{0^\circ} = 1.000 + j 0.000 \\
I_{b1} &= 1.0 / \underline{-120^\circ} = -0.500 - j 0.866 \\
I_{c1} &= 1.0 / \underline{+120^\circ} = -0.500 + j 0.866 \\
I_{a2} &= 1.0 / \underline{0^\circ} = 1.000 + j 0.000 \\
I_{b2} &= 1.0 / \underline{120^\circ} = -0.500 + j 0.866 \\
I_{c2} &= 1.0 / \underline{-120^\circ} = -0.500 - j 0.866 \\
I_{a0} &= 1.0 / \underline{0^\circ} = 1.000 + j 0.000 \\
I_{b0} &= 1.0 / \underline{0^\circ} = 1.000 + j 0.000 \\
I_{c0} &= 1.0 / \underline{0^\circ} = 1.000 + j 0.000
\end{aligned}$$

Referring to Formula (4)

$$\begin{aligned}
I_a &= I_{a0} + I_{a1} + I_{a2} \\
&= (1.000 + j0.000) + (1.000 + j0.000) \\
&\quad + (1.000 + j0.000) \\
&= 3.000 + j0.000 \\
&= 3.000 / \underline{0^\circ} \\
I_b &= I_{b0} + I_{b1} + I_{b2} \\
&= (1.000 + j0.000) + (-0.500 - j0.866) \\
&\quad + (-0.500 + j0.866) \\
&= 0 \\
I_c &= I_{c0} + I_{c1} + I_{c2} \\
&= (1.000 + j0.000) + (-0.500 - j0.866) \\
&\quad + (-0.500 + j 0.866) \\
&= 0
\end{aligned}$$

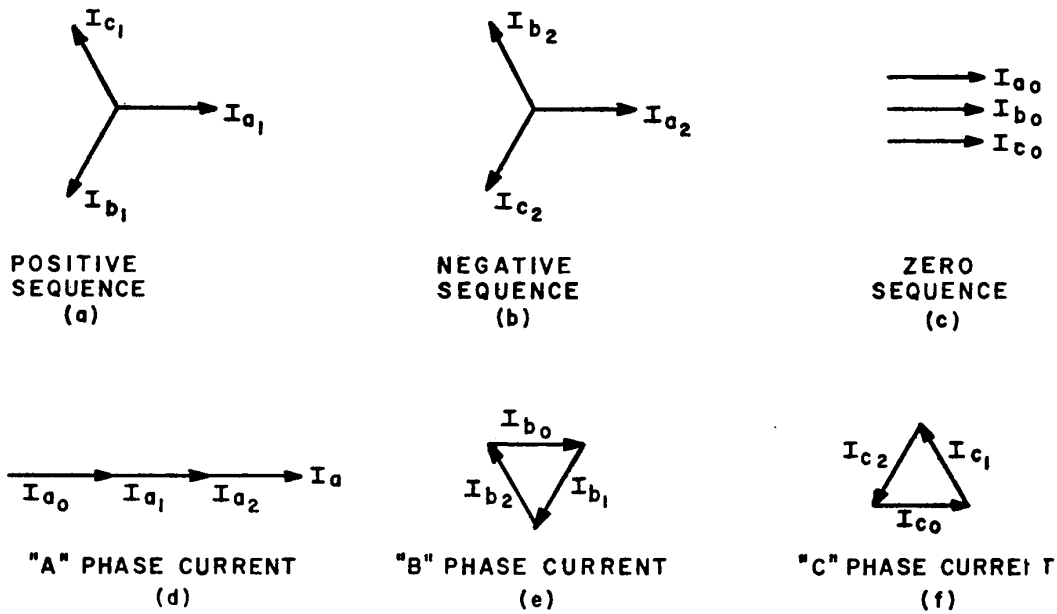


Figure III-4 Addition of Positive, Negative and Zero-Sequence Current Vectors and Their Resultant.

These operations are diagrammed in Figure III-4. The graphic solution is of course the same as the algebraic. It is thus evident that by means of the three components, positive, negative and zero, any degree of unbalance may be represented. The single-phase case is the worst, since the entire current is in one phase, the usual condition is for negative and zero-sequence components to be very small indeed. As a matter of fact, the normal unbalance allowed in aircraft systems is four percent, with a maximum phase shift of 5 degrees. This calculates out to be that the sum of the negative and zero-sequence voltages present is approximately four percent of the positive-sequence voltage.

The statement above regarding the amount of negative and zero-sequence voltages present in a system is the basis for a number of protection schemes. For, the presence of more than four or five percent, total, of negative and zero-sequence voltage or current in a system is proof of the existence of a heavy unbalanced load, either single or two-phase, or of a fault. If the maximum single or two-phase loads are known, a negative, zero, or negative plus zero-sequence relay set above this point will be an infallible indication of the existence of a fault. What is done about it, of course, depends upon the protection system design.

To summarize

1. Zero-sequence components are associated exclusively with line-to-neutral phenomena.
2. The zero-sequence vector does not rotate, since $I_{a0} = I_{b0} = I_{c0}$, $E_{a0} = E_{b0} = E_{c0}$.
3. No zero-sequence component is present in line-to-line voltages, or line currents not involving neutral.

Symmetrical Component Conventions.

In order to facilitate the use of symmetrical components, several conventions are employed. These will be illustrated below. We will consider first line currents containing a zero-sequence component. First, equation (4) will be repeated for convenience.

$$\begin{aligned} I_a &= I_{a0} + I_{a1} + I_{a2} \\ I_b &= I_{b0} + I_{b1} + I_{b2} \\ I_c &= I_{c0} + I_{c1} + I_{c2} \end{aligned} \quad (4)$$

Now, $I_{a0} = I_{b0} = I_{c0}$, so that I_{a0} may be used in all cases. Further I_{a1} , I_{b1} , I_{c1} are equal numerically, but are 120 degrees apart. The same is true of I_{a2} , I_{b2} and I_{c2} . Thus, if we rotate the vector I_{a1} by 120 degrees counter-clockwise, it will be equal to I_{c1} , if we rotate I_{a1} clockwise 120 degrees, it will be equal to I_{b1} . If we use the operators $a = 1.0 \angle 120^\circ$ (the unit vector, rotated counter-clockwise 120 degrees) and $a^2 = 1.0 \angle -120^\circ$ (the unit vector, rotated clockwise 120 degrees), we can write:

$$\begin{aligned} I_{b1} &= a^2 I_{a1} \\ I_{c1} &= a I_{a1} \end{aligned} \quad (5)$$

Similarly, for negative-sequence components

$$\begin{aligned} I_{b2} &= a I_{a2} \\ I_{c2} &= a^2 I_{a2} \end{aligned} \quad (6)$$

If these values are substituted in (4) we now have

$$\begin{aligned} I_a &= I_{a0} + I_{a1} + I_{a2} \\ I_b &= I_{a0} + a^2 I_{a1} + a I_{a2} \\ I_c &= I_{a0} + a I_{a1} + a^2 I_{a2} \end{aligned} \quad (7)$$

Since (7) is true, we never have to bother about writing any of the components except I_{a1} . The same is true in all cases.

The corrected formulas for line-to-line voltage, and line-to-neutral voltages are given here for convenience.

$$\begin{aligned} E_{AB} &= E_{AB1} + E_{AB2} \\ E_{BC} &= a^2 E_{AB1} + a E_{AB2} \\ E_{CA} &= a E_{AB1} + a^2 E_{AB2} \end{aligned} \quad (8)$$

$$\begin{aligned} E_{an} &= E_{a0} + E_{a1} + E_{a2} \\ E_{bn} &= E_{a0} + a^2 E_{a1} + a E_{a2} \\ E_{cn} &= E_{a0} + a E_{a1} + a^2 E_{a2} \end{aligned} \quad (9)$$

If formulas (7), (8) and (9) are solved for the sequence components, we have

$$\begin{aligned} I_{a0} &= \frac{1}{3} (I_a + I_b + I_c) \\ I_{a1} &= \frac{1}{3} (I_a + a I_b + a^2 I_c) \\ I_{a2} &= \frac{1}{3} (I_a + a^2 I_b + a I_c) \end{aligned} \quad (10)$$

$$E_{AB1} = \frac{1}{3} (E_{AB} + a E_{BC} + a^2 E_{CA}) \quad (11)$$

$$E_{AB2} = \frac{1}{3} (E_{AB} + a^2 E_{BC} + a E_{CA})$$

$$E_{a0} = \frac{1}{3} (E_{an} + E_{bn} + E_{cn})$$

$$E_{a1} = \frac{1}{3} (E_{an} + a E_{bn} + a^2 E_{cn}) \quad (12)$$

$$E_{a2} = \frac{1}{3} (E_{an} + a^2 E_{bn} + a E_{cn})$$

Formulas (10), (11) and (12) require that we know not only the absolute value of the voltage or current, but also the phase angle. The terms I_a , I_b , I_c , E_{AB} , E_{BC} , E_{CA} , E_{an} , E_{bn} and E_{cn} are therefore complex expressions, consisting of both a real and an imaginary part.

In cases where line-to-line voltages only are available, it is necessary to convert them to equivalent line-to-neutral values before the line currents can be found. This can be done by applying the well known delta-star conversion, but to save time the conversions will be given

$$E_{a1} = \frac{E_{AB1}}{1.73} \angle -90^\circ \quad (13)$$

$$E_{a2} = \frac{E_{AB2}}{1.73} \angle 90^\circ$$

$$E_{AB1} = 1.73 E_{a1} \angle 90^\circ$$

$$E_{AB2} = 1.73 E_{a2} \angle -90^\circ$$

(14)

This completes the necessary conventions and conversion factors for use of symmetrical components.

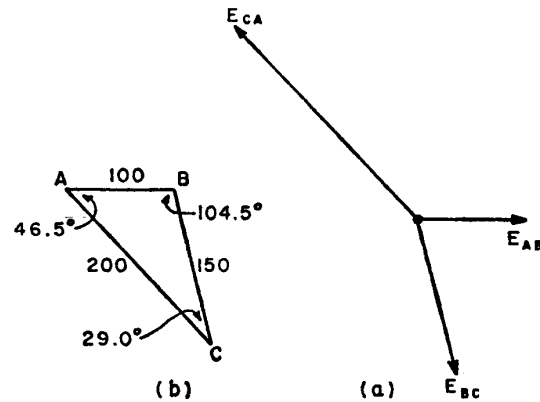
EXAMPLES IN THE USE OF SYMMETRICAL COMPONENTS

Three-Wire System.

Let us assume a case where the absolute values of the line-to-line voltages at a certain point are known, the sequence impedances past this point are known, we wish to find the line currents.

$$\begin{aligned} \text{Let } E_{AB} &= 100 \text{ volts} \\ E_{BC} &= 150 \text{ volts} \\ E_{CA} &= 200 \text{ volts} \\ Z_1 &= (1.000 + j 5.000) \\ &= 5.099 \angle 78.7^\circ \text{ ohm} \\ Z_2 &= (0.500 + j 1.000) \\ &= 1.116 \angle 63.4^\circ \text{ ohm} \end{aligned}$$

In this case, we know nothing of the phase angles between the line-to-line voltages. However, as is shown in Figure III-5 line-to-line voltages form a closed triangle, and knowing the value of all three sides of the triangle, we can compute the internal angles. The resultant vectors of this system are shown also.



$$\cos \angle A = \frac{AB^2 + AC^2 - BC^2}{2 \times AB \times AC}$$

$$\cos \angle B = \frac{BC^2 + AB^2 - AC^2}{2 \times BC \times AB}$$

$$\cos \angle C = \frac{BC^2 + AC^2 - AB^2}{2 \times BC \times AC}$$

Figure III-5 Resolution of Line-to-Line Voltage Vectors and Triangle Closing.

To find E_{AB1} and E_{AB2} , use equation (11). First find aE_{BC} , a^2E_{BC} , aE_{CA} , a^2E_{CA}

$$\begin{aligned} aE_{BC} &= 150 \angle -75.5^\circ \times 1.0 \angle 120^\circ \\ &= 150 \angle 44.5^\circ \\ &= 106.8 + j 105.0 \end{aligned}$$

$$\begin{aligned} a^2E_{BC} &= 150 \angle -75.5^\circ \times 1.0 \angle -120^\circ \\ &= 150 \angle 164.5^\circ \\ &= -144.5 + j 40.2 \end{aligned}$$

$$\begin{aligned} aE_{CA} &= 200 \angle 133.5^\circ \times 1.0 \angle 120^\circ \\ &= 200 \angle -106.5^\circ \\ &= 56.8 - j 191.8 \end{aligned}$$

$$\begin{aligned} a^2E_{CA} &= 200 \angle 133.5^\circ \times 1.0 \angle -120^\circ \\ &= 200 \angle 13.5^\circ \\ &= 194.5 + j 46.7 \end{aligned}$$

$$\begin{aligned} E_{AB1} &= \frac{1}{3} (100 + j 0.00) + (106.8 + j 105.0) \\ &\quad + (194.5 + j 46.7) \\ &= 133.8 + j 50.8 \\ &= 143.2 \angle 69.2^\circ \end{aligned}$$

$$\begin{aligned} E_{AB2} &= \frac{1}{3} (100 + j 0.00) + (-144.5 + j 40.2) \\ &\quad + (-56.8 - j 191.8) \\ &= -33.8 - j 50.2 \\ &= 60.3 \angle -124^\circ \end{aligned}$$

These must now be converted to line-to-neutral values. Applying formula (13)

$$\begin{aligned} E_{a1} &= \frac{E_{AB1}}{1.732} \angle -90^\circ \\ &= \frac{143.2}{1.732} \angle 69.2^\circ \times 1.0 \angle -90^\circ \\ &= 82.7 \angle -20.8^\circ \end{aligned}$$

$$\begin{aligned} E_{a2} &= \frac{E_{AB2}}{1.732} \angle -90^\circ \\ &= \frac{60.3}{1.732} \angle -124^\circ \times 1.0 \angle 90^\circ \\ &= 30.8 \angle -34.0^\circ \end{aligned}$$

$$\begin{aligned} I_{a1} &= \frac{E_{a1}}{Z_1} \\ &= \frac{82.7 \angle -20.8^\circ}{5.099 \angle 78.7^\circ} \\ &= 16.22 \angle -99.5^\circ \end{aligned}$$

$$\begin{aligned} I_{a2} &= \frac{E_{a2}}{Z_2} \\ &= \frac{60.3 \angle -20.8^\circ}{1.116 \angle 63.4^\circ} \\ &= 54.05 \angle -84.2^\circ \end{aligned}$$

In order to find I_a , I_b and I_c , we must know the complex values of I_{a1} , aI_{a1} , a^2I_{a1} , I_{a2} , aI_{a2} , a^2I_{a2} .

$$\begin{aligned} I_{a1} &= 16.22 \angle -99.5^\circ \\ &= -2.68 + j 16.00 \end{aligned}$$

$$\begin{aligned} aI_{a1} &= 16.22 \angle -99.5^\circ \times 1.0 \angle 120^\circ \\ &= 16.22 \angle 20.5^\circ \\ &= 15.16 + j 5.68 \end{aligned}$$

$$\begin{aligned} a^2I_{a1} &= 16.22 \angle -99.5^\circ \times 1.0 \angle -120^\circ \\ &= 16.22 \angle 140.5^\circ \\ &= 12.52 + j 10.32 \end{aligned}$$

$$\begin{aligned} I_{a2} &= 54.05 \angle -84.2^\circ \\ &= 5.46 - j 53.77 \end{aligned}$$

$$\begin{aligned} aI_{a2} &= 54.05 \angle -84.2^\circ \times 1.0 \angle 120^\circ \\ &= 54.05 \angle 35.8^\circ \\ &= 43.84 + j 31.62 \end{aligned}$$

$$\begin{aligned} a^2I_{a2} &= 54.05 \angle -84.2^\circ \times 1.0 \angle -120^\circ \\ &= 54.05 \angle 155.8^\circ \\ &= 49.30 + j 22.16 \end{aligned}$$

$$\begin{aligned} I_a &= (-2.68 + j 16.00) + (5.46 - j 53.77) \\ &= 2.78 - j 37.77 \\ &= 37.87 \angle -85.8^\circ \end{aligned}$$

$$\begin{aligned} I_b &= (-12.52 + j 10.32) + (43.84 + j 31.62) \\ &= 31.30 + j 41.94 \\ &= 52.35 \angle 53.3^\circ \end{aligned}$$

$$\begin{aligned} I_c &= (15.19 + j 5.68) + (49.30 + j 22.16) \\ &= -34.11 + j 27.84 \\ &= 44.03 \angle 140.8^\circ \end{aligned}$$

It may be seen that there is no special difficulty in making the computations, except that they are tedious. The line-to-line voltage and the line-current vectors are plotted together in Figure III-6. It should be observed that I_b leads I_c , so that effectively the phase rotation is $A-C-B$. This is undoubtedly due to the large negative-sequence current flowing. This is not a condition likely to be met in practice, the example is only illustrative.

THE FOUR-WIRE SYSTEM.

First, we will analyze the general situation of a single-phase load connected to a generator through a transmission line, as shown in Figure III-7.

The voltages around the circuit are:

$$\begin{aligned} E_{INT} &= I_{a1} Z_{G1} + I_{a2} Z_{G2} + I_{a0} Z_{G0} + I_{a1} Z_{L1} \\ &\quad + I_{a2} Z_{L2} + I_{a0} Z_{L0} + I_a Z_f \\ &= I_{a1} (Z_{G1} + Z_{L1}) + I_{a2} (Z_{G2} + Z_{L2}) \\ &\quad + I_{a0} (Z_{G0} + Z_{L0}) + I_a Z_f \end{aligned}$$

That is, the internal generated voltage of the generator is equal to the voltage across the load plus the voltage drops in the generator and line impedances.

Now,

$$I_b = 0, I_c = 0.$$

Substituted into equation (10) this will give

$$\begin{aligned} I_{a0} &= \frac{1}{3} I_a \\ I_{a1} &= \frac{1}{3} I_a \\ I_{a2} &= \frac{1}{3} I_a \text{ and } I_{a0} = I_{a1} = I_{a2} \\ \text{and } I_{a0} + I_{a1} + I_{a2} &= I_a = 3I_{a0} \end{aligned}$$

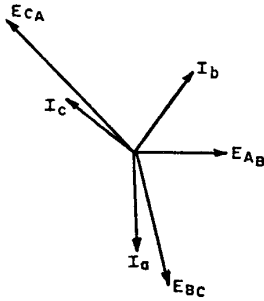


Figure III-6 Line-to-Line Voltage and Line-Current Vectors.

$$\begin{aligned} \text{Let } Z_{G1} + Z_{L1} &= Z_1 \\ Z_{G2} + Z_{L2} &= Z_2 \\ Z_{G0} + Z_{L0} &= Z_0 \end{aligned}$$

Then

$$E_{INT} = \frac{I_a}{3} (Z_0 + Z_1 + Z_2) + I_a Z_f \quad (15)$$

$$= \frac{I_a}{3} (Z_0 + Z_1 + Z_2 + 3Z_f) \quad (16)$$

$$\text{Thus } I_a = \frac{3E_{INT}}{Z_0 + Z_1 + Z_2 + 3Z_f}$$

Now, if the following impedances are given

$$\begin{aligned} Z_{G0} &= 0.025 + j0.050 \\ Z_{G1} &= 0.025 + j1.500 \\ Z_{G2} &= 0.050 + j0.150 \\ Z_{L0} &= 0.021 + j0.177 \\ Z_{L1} &= 0.016 + j0.020 \\ Z_{L2} &= 0.016 + j0.020 \\ Z_f &= 1.000 + j0.000 \\ &= 1.000 / 0^\circ \end{aligned}$$

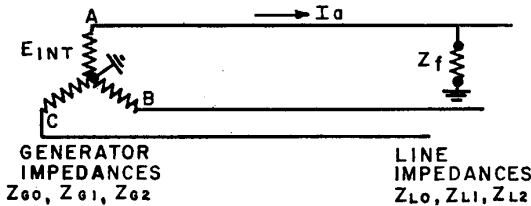


Figure III-7 Single-Phase Load Connected to End of Transmission Line.

Then, if the current at the load is 115 amperes, what is the internal generated voltage E_{INT} , and what are the phase voltages at the generator? Say that the voltage

E_{AN} at the load is $115 \angle 0^\circ$ volts, I_a is 115 amperes and Z_f is $1.0 \angle 0^\circ$.

Then:

$$\begin{aligned} Z_{AN} &= 115 \times 1.0 \angle 0^\circ \\ &= 115 \angle 0^\circ. \end{aligned}$$

From the formula (15)

$$\begin{aligned} E_{INT} &= \frac{115 \angle 0^\circ}{3} (0.025 + j0.050 + j0.021 \\ &\quad + j0.177) + (0.025 + j1.500 + 0.016 \\ &\quad + j0.020) + 0.050 + j0.150 + 0.016 \\ &\quad + j0.020) + 115 \angle 0^\circ \times 1.0 \angle 0^\circ \\ &= 38.3 \angle 0^\circ (0.153 + j1.917) + 115 \angle 0^\circ \\ &= 38.3 \angle 0^\circ \times 1.920 \angle 85.6^\circ + 115 \angle 0^\circ \\ &= 73.6 \angle 85.6^\circ + 115 \angle 0^\circ \\ &= 5.86 + j73.40 + 115 + j0.00 \\ &= 120.86 + j73.40 \\ &= 141.40 \angle 31.3^\circ \end{aligned}$$

Since only positive sequence voltage is generated in the machine, E_{INT} is essentially the positive-sequence voltage generated. No other voltages are generated as such, but are generated by positive-sequence currents flowing in unbalanced loads.

The voltage at the generator terminals will of course be the internal generated voltage less the internal drop. The internal impedances are of course Z_{G0} , Z_{G1} , and Z_{G2} , and the sequence currents are I_{a0} , I_{a1} , I_{a2} . Also $I_{a0} = I_{a1} = I_{a2} = I_a/3 = 38.3 \angle 0^\circ$.

The sequence voltages at the generator terminals are

$$\begin{aligned} E_{a1} &= E_{INT} - I_{a1} Z_{G1} \\ E_{a2} &= -I_{a2} Z_{G2} \\ E_{a0} &= -I_{a0} Z_{G0} \end{aligned} \quad (17)$$

This equation comes about since E_{INT} is the generated positive-sequence voltage, and the positive-sequence voltage at the generator terminals is E_{INT} less the positive-sequence voltage drop. Since no negative or zero-sequence voltages are generated in the generator, the negative and zero-sequence voltages at the generator terminals are equal to the negative and zero-sequence voltage drops in the generator, respectively.

Substitute values

$$\begin{aligned} E_{a1} &= 141.40 \angle 31.3^\circ - 38.3 \angle 0^\circ (0.025 + j1.500) \\ &= 120.86 + j73.40 - 0.96 - j57.4 \\ &= 119.90 + j16.00 \\ &= 120.96 \angle 7.6^\circ \\ E_{a2} &= -38.3 \angle 0^\circ (0.050 + j0.150) \\ &= -1.92 - j5.74 \\ &= 6.06 \angle -108.5^\circ \\ E_{a0} &= -38.3 \angle 0^\circ (0.025 + j0.050) \\ &= -0.96 - j1.92 \\ &= 2.15 \angle -116.6^\circ \end{aligned}$$

In order to find E_{an} , E_{bn} , and E_{cn} , we must have aE_{a1} , a^2E_{a1} , aE_{a2} , a^2E_{a2} .

$$\begin{aligned} aE_{a1} &= 120.96 \angle 7.6^\circ \times 1.0 \angle 120^\circ \\ &= 120.96 \angle 127.6^\circ \\ &= -95.71 + j73.97 \end{aligned}$$

$$\begin{aligned} a^2E_{a1} &= 120.96 \angle 7.6^\circ \times 1.0 \angle -120^\circ \\ &= 120.96 \angle -112.4^\circ \\ &= -46.10 - j111.84 \end{aligned}$$

$$\begin{aligned} aE_{a2} &= 6.06 \angle -108.5^\circ \times 1.0 \angle 120^\circ \\ &= 6.06 \angle 11.5^\circ \\ &= 5.93 + j1.21 \end{aligned}$$

$$\begin{aligned} a^2E_{a2} &= 6.06 \angle -108.5^\circ \times 1.0 \angle -120^\circ \\ &= 6.06 \angle 131.5^\circ \\ &= -4.02 + j4.53 \end{aligned}$$

$$\begin{aligned} E_{an} &= (-0.96 + 119.90 - 1.92) + j(-1.92 + 16.00 \\ &\quad - 5.74) \\ &= 117.02 + j8.34 \\ &= 117.32 \angle 4.1^\circ \text{ volts} \end{aligned}$$

$$\begin{aligned} E_{bn} &= (-0.96 - 46.10 + 5.93) + j(-1.92 - 111.84 \\ &\quad + 1.21) \\ &= -41.13 - j112.55 \\ &= 119.83 \angle -110.1^\circ \text{ volts} \end{aligned}$$

$$\begin{aligned} E_{cn} &= (-0.96 - 45.71 - 4.02) + j(-1.92 + 73.97 \\ &\quad + 4.53) \\ &= -100.69 + j76.58 \\ &= 126.49 \angle 127.3^\circ \text{ volts} \end{aligned}$$

Since no current flows in phases B and C , the voltages at the load terminals are virtually that at the generator. The voltage drop on A phase is found to be 2.32 volts, while there is a 4.83 volt rise on phase B and a 11.49 volt rise on phase C . The average voltage is 121.21 volts, and the deviation from average is 5.03 percent. It would have been considerably more had the load been at 75 percent power factor. With the example given, this should not be too difficult to figure out.

Physical Significance of the Sequence Components

The question now arises as to the physical meaning of the sequence components, do they really exist, or is this merely a convenient method of analysis? The answer, of course, is that sequence volts, amperes and ohms have as much a basis in reality as just plain volts, amperes and ohms. Any such standard is only an agreed-upon system of reference and measurement. The physical definition of an ohm as being the resistance of a certain material at certain physical conditions is no more nor less arbitrary than saying that a set of unbalanced impedances can be resolved into three sets of symmetrical impedances. In other words, negative or zero-sequence resistances are as "real" as the resistance we measure with an ordinary ohmmeter, they are simply another way of describing resistance, and are as real under our new set of definitions as conventional ohms resistance is under our usual mode of thinking.

However, since it is our custom to assign names to our defined conditions and then to consider them as real, it is

certainly not out of line to expect that physical significance can be given to the elements of Symmetrical Components. This is a rather difficult problem, for it is not easy to point to one particular part of a generator, for example, and say that this is the location of some particular impedance. The same difficulty exists in more conventional matters, where would you say that the "voltage" of a generator was, in the armature or in the field windings, or possibly in the magnetic flux? Nevertheless, the sequence components can be given physical significance to some extent, and this will be done here.

1. Sequence Voltages and Currents.

It is a convention of Symmetrical Components that only one voltage is generated by a rotating alternating-current generator and it is a positive-sequence voltage numerically equal to the internal generated voltage of the generator. A positive-sequence voltage applied to unbalanced load impedance gives rise to negative and zero-sequence currents. These currents flowing in the circuit negative and zero-sequence impedances, produce negative and zero-sequence voltage drops across them.

2. Sequence Impedances.

If we think of positive sequence quantities as being those which produce counterclockwise rotation, and negative-sequence quantities as being those which produce clockwise rotation, it would seem that if we applied first a positive-sequence voltage and then a negative-sequence voltage to an impedance, and measured the current flow under the two conditions, we would have accurately determined the two impedances. This is entirely correct as long as the impedance under consideration is linear, that is, it contains no iron. The positive and negative-sequence impedances of wiring for example, are equal, and since positive-sequence impedance is the ordinary impedance with which we are familiar, we have a convenient definition of both terms.

Zero-sequence impedance of wiring is something different. Essentially, it is the impedance of a wire over ground, with ground return of current, and varies with spacing from structure. Tables giving both positive and zero-sequence impedances of wire are available in current literature.

In the case of non-linear circuits such as those containing iron, as a generator or motor, the situation is different. Positive-sequence impedance is obtained in the usual manner, a positive sequence set of voltages is impressed on the machine, the current measured, and the impedance calculated from this.

Negative-sequence reactance in a machine is very difficult to define, except to say that it is very nearly one-half the sum of the direct and quadrature-axis subtransient reactances. These parameters are inherent in the rotating machine, and will not be defined here, other than to say that they are double frequency quantities. The negative-sequence reactance varies continuously between the two reactances, the value commonly used is the average. In general, negative-sequence reactance is located in the rotor and damper bar structure, heavy damper bars in both direct and quadrature axes reduce the reactances in these axes from an exciting reactance to a leakage reactance.

Heavy damper bars also reduce the negative-sequence resistance, and it is thus generally considered that the negative-sequence resistance is "located" here, although this is not strictly accurate.

Zero-sequence impedance is a single-phase quantity, and the nature of it is best suggested by noting that if the armature conductors were infinitely distributed, so that the generated voltage were sinusoidal, the zero-sequence reactance would be essentially zero. In other words, a machine with low zero-sequence impedance will have correspondingly low harmonic content, and in the ideal case, where the reactance was zero, there would be no generated harmonics.

CIRCUIT ANALYSIS

This Section will present very briefly some analyses of various types of unbalanced circuits, with no further explanation than the circuit presentation, since the derivation of the circuits is quite lengthy, and properly belongs in a text book. If the circuit parameters are known, these values may be substituted for the symbols and the circuit solved. From a knowledge of the sequence voltages and currents, the actual conditions may be found by means of the formulas previously presented.

1. Three-Phase Symmetrical Fault

Since there is no coupling between sequence networks, there is no current flow in either the negative or zero-sequence networks. The positive-sequence network only is involved, as is shown in Figure III-8.

2. Line-to-Line Fault, No Load on the Generator

Z_f is the fault impedance. In calculations, it is of course used as one element. Note that $I_{a1} = -I_{a2}$. Z_o is not included in the network. See Figure III-9.

3. Line-to-Line Fault, Preload on the Generator

In Figure III-10, Z_L is the symmetrical load impedance. It is across each sequence element, including the zero

sequence. This latter is not coupled to the other sequence networks so no current flows in it. Also, $I_{a1} = -I_{a2}$ since I_{a2} includes several branch currents, including that through the load impedances.

4. Line-to-Neutral Fault, No Preload on the Generator
Note that in Figure III-11 the total fault impedance is three times the applied impedance. Also note that this diagram shows definitely that in a single-phase load, or fault, that the positive, negative and zero-sequence currents are equal and of like phase.

5. Line-to-Neutral Fault, Generator Preload

Again, the total fault impedance is three times the applied impedance. Note in Figure III-12 that the positive, negative and zero-sequence currents are not equal in this instance.

Numerical Analysis

To complete this Section, we will consider the case where a single generator is connected to a load bus through a line consisting of three AN 2 wires, closely bundled, 100 feet long, and 6 inches from structure. At the bus, a symmetrical load of three ohms at 75 percent power factor is connected. At this bus, then, a fault of 0.2 ohm occurs, line-to-line, between phases B and C. The regulator is the type which regulates the voltage so that the highest-phase voltage is 115 volts at the bus.

The generator sequence impedances are:

$$Z_{G0} = 0.075 + j0.055 = 0.0928 \angle 36.3^\circ \text{ ohm}$$

$$Z_{G1} = 0.075 + j1.565 = 1.565 \angle 87.3^\circ \text{ ohms}$$

$$Z_{G2} = 0.125 + j0.112 = 0.1675 \angle 41.9^\circ \text{ ohm}$$

From the tables of wire impedances, the sequence impedances for 100 feet of AN 2, 6 inches from structure, are:

$$Z_{L0} = 0.0209 + j0.1774 = 0.180 \angle 83.3^\circ \text{ ohm}$$

$$Z_{L1} = 0.0158 + j0.0195 = 0.0251 \angle 51.0^\circ \text{ ohm}$$

$$Z_{L2} = 0.0158 + j0.0195 = 0.0251 \angle 51.0^\circ \text{ ohm}$$

The circuit may now be shown physically as shown in Figure III-13.

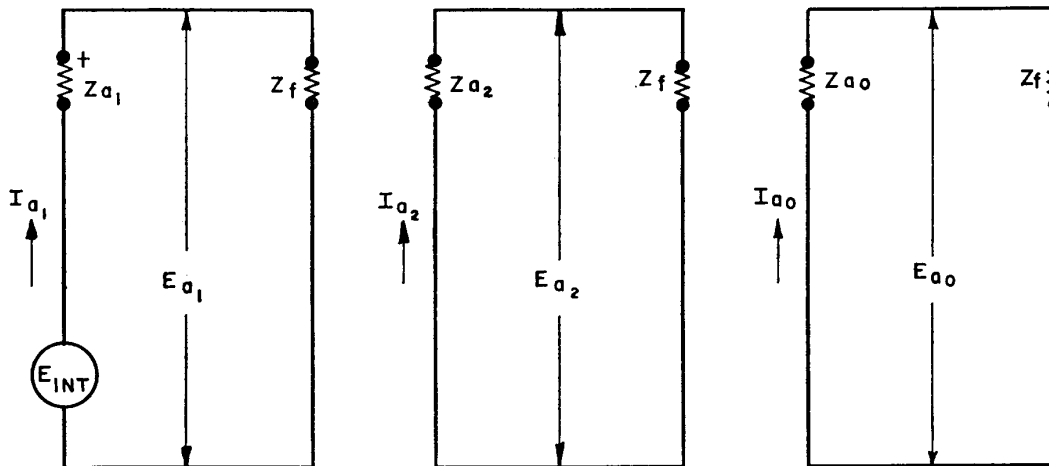


Figure III-8 Sequence Impedance Connections for Three-Phase Symmetrical Fault.

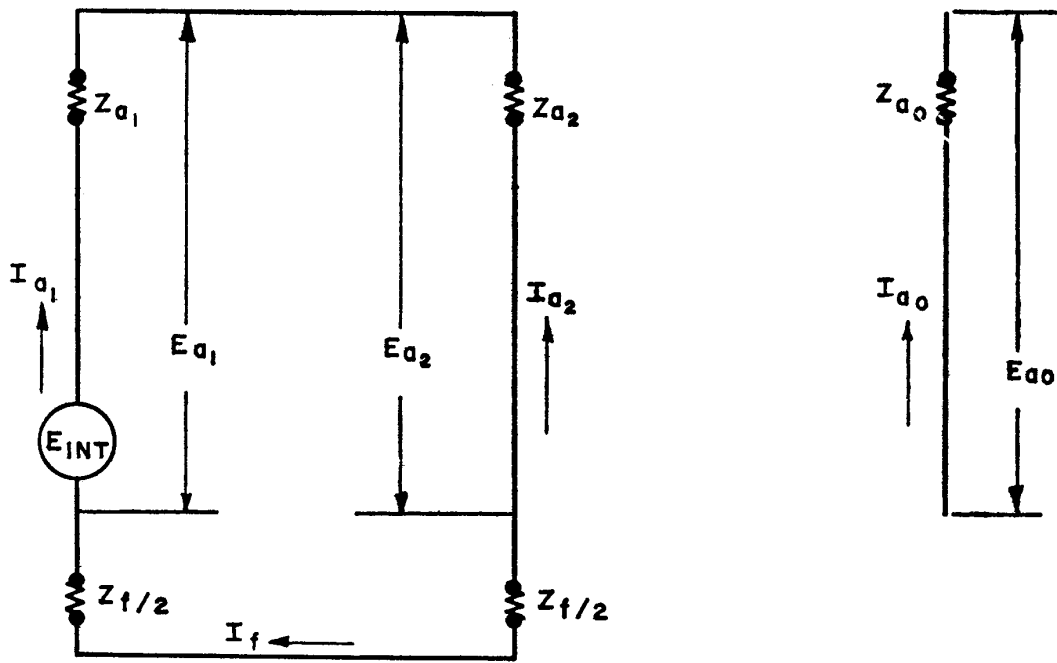


Figure III-9 Sequence Impedance Connections for Line-to-Line Fault, No Generator Load.

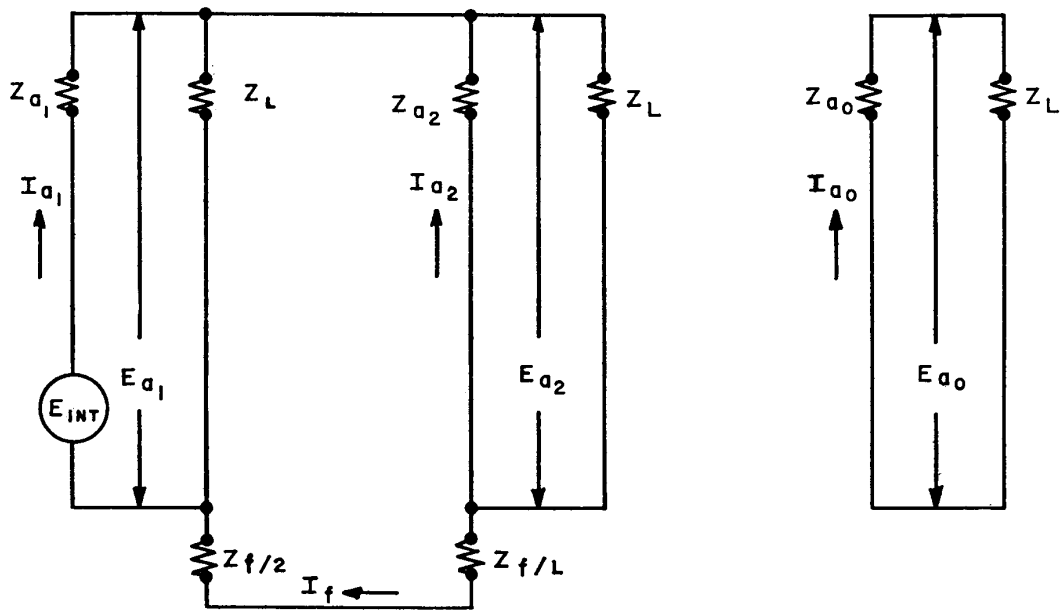


Figure III-10 Sequence Impedance Connections for Line-to-Line Fault, Generator Preload.

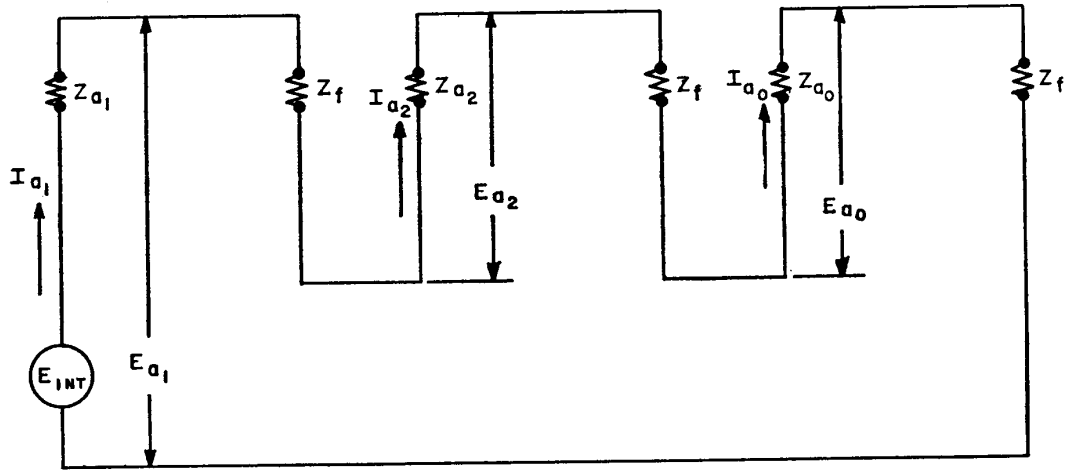


Figure III-11 Sequence Impedance Connections for Line-to-Neutral Fault, No Generator Load.

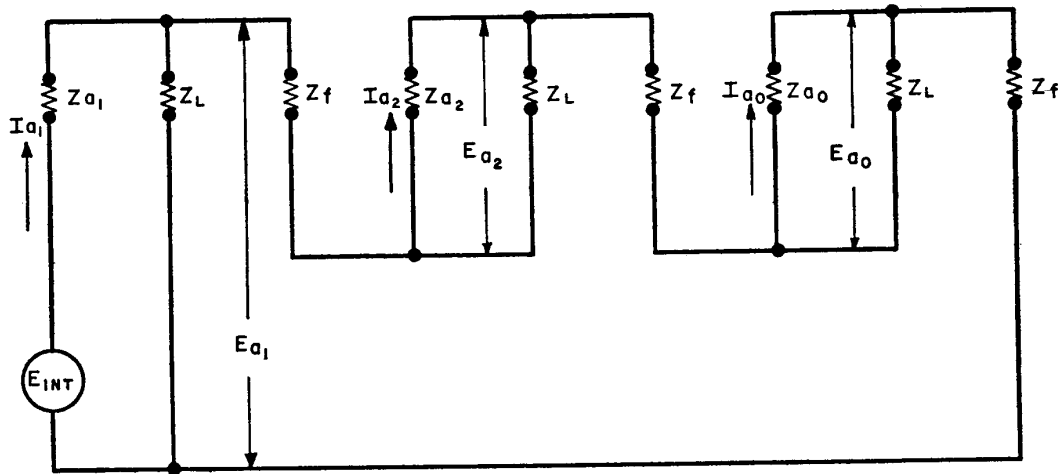


Figure III-12 Sequence Impedance Connections for Line-to-Neutral Fault, Generator Preload.

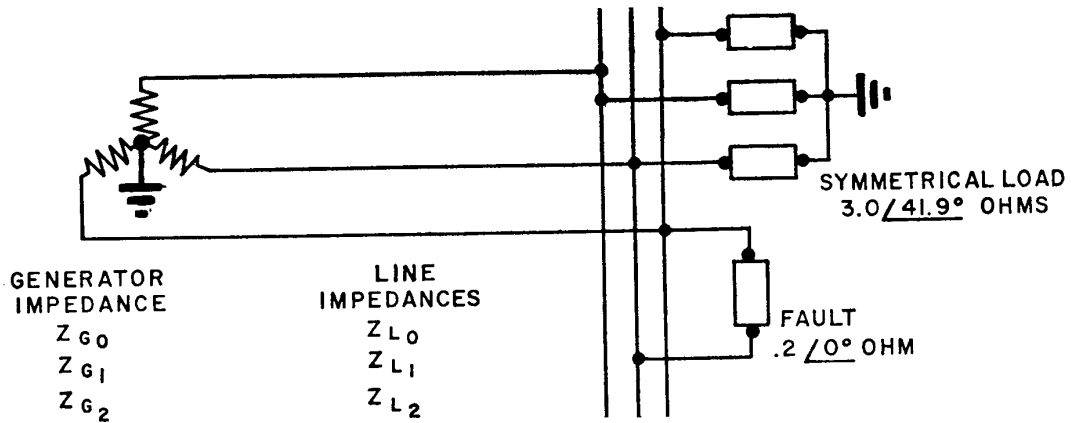


Figure III-13 Schematic Diagram, Generator Connected to Symmetrical Load and Line-to-Line Fault Through Transmission Line.

If these values are put in the schematic shown under "3. Line-to-Line Fault, Preload on the Generator," it becomes as shown in Figure III-14.

When the series positive-sequence impedances are combined and also the series negative-sequence impedances, the schematic is shown in Figure III-15(a).

If Figure III-15(a) is broken down in stages, the last two elements to the right become:

$$\begin{aligned} & \frac{0.193 \angle 43.1^\circ \times 3.0 \angle 41.4^\circ}{0.193 \angle 43.1^\circ + 3.0 \angle 41.4^\circ} \\ &= \frac{0.193 \angle 43.1^\circ \times 3.0 \angle 41.4^\circ}{0.141 + j0.132 + 2.250 + j1.984} \\ &= \frac{0.578 \angle 84.5^\circ}{2.391 + j2.116} \\ &= \frac{0.578 \angle 84.5^\circ}{3.192 \angle 41.5^\circ} \\ &= 0.181 \angle 43.0^\circ \\ &= 0.133 + j0.124 \end{aligned}$$

as is shown in Figure III-15(b).

Then combining the two series impedances, see Figure III-15(c).

$$\begin{aligned} & 0.200 + j0.000 + 0.133 + j0.124 \\ &= 0.333 + j0.124 \\ &= 0.355 \angle 20.3^\circ \end{aligned}$$

Combine the two parallel elements as in Figure III-15(d).

$$\begin{aligned} & \frac{0.355 \angle 20.3^\circ \times 3.0 \angle 41.4^\circ}{0.355 \angle 20.3^\circ + 3.0 \angle 41.4^\circ} \\ &= \frac{0.355 \angle 20.3^\circ \times 3.0 \angle 41.4^\circ}{0.33 + j0.124 + 2.250 + j1.984} \\ &= \frac{1.064 \angle 61.7^\circ}{2.583 + j2.108} \\ &= \frac{1.064 \angle 61.7^\circ}{3.333 \angle 39.2^\circ} \\ &= 0.319 \angle 22.5^\circ \\ &= 0.295 + j0.122 \end{aligned}$$

Combine the two series impedances and the circuit is finally Figure III-15(e).

$$\begin{aligned} & 0.091 + j1.585 + 0.295 + j0.122 \\ &= 0.386 + j1.707 \\ &= 1.750 \angle 77.3^\circ \end{aligned}$$

To find the current flow, assume E_{int} to be some arbitrary value. Then, solve the circuit, and calculate the voltage at the bus from the sequence voltages. Since the regulator acts to keep the highest phase voltage at 115 volts, a multiplication factor can now be found; then bring all sequence voltages and currents up by this factor. Assume first that $E_{int} = 100$ volts.

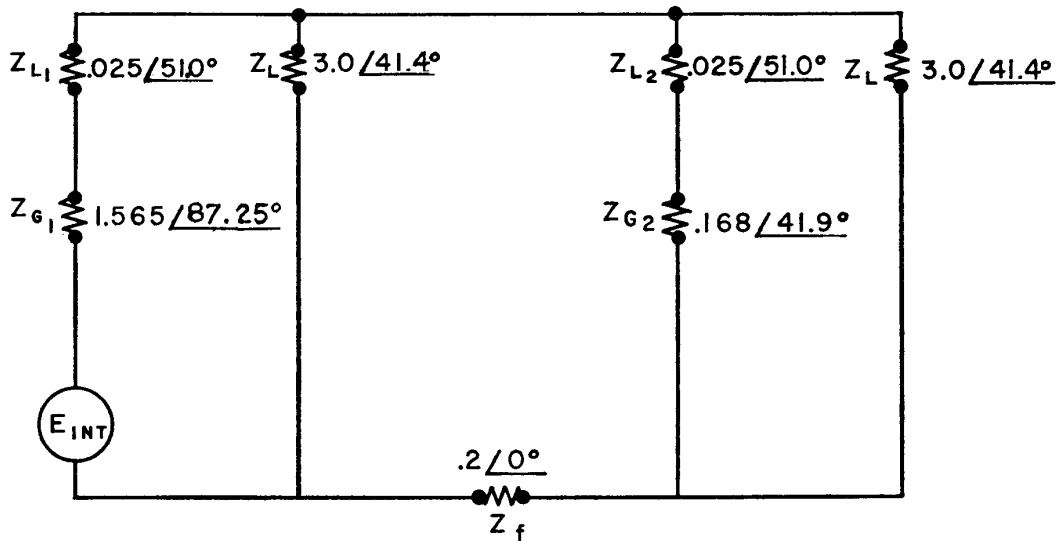


Figure III-14 Symmetrical Component Schematic of Generator Connected to Symmetrical Load and Line-to-Line Fault Through Transmission Line.

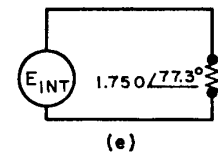
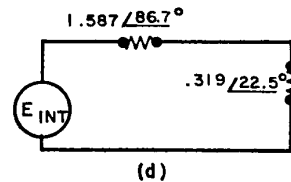
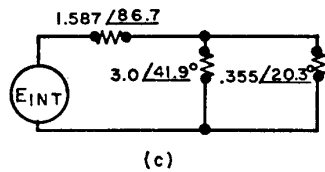
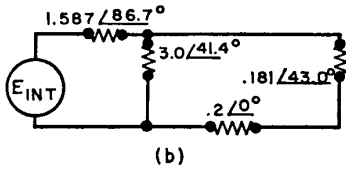
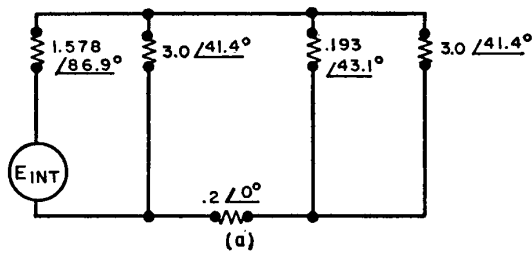


Figure III-15 Resolution of Symmetrical Component Schematic Diagram.

$$\begin{aligned}
 I_{a1} &= \frac{100 \angle 0^\circ}{1.750 \angle 77.3^\circ} \\
 &= 57.159 \angle -77.3^\circ \\
 &= 12.60 - j55.760 \\
 E_{a1} &= 57.159 \angle -77.3^\circ \times 0.319 \angle 22.5^\circ \\
 &= 18.251 \angle -54.8^\circ \\
 &= 10.520 - j14.914 \\
 I_x &= 18.251 \angle -54.8^\circ \div 0.355 \angle 20.3^\circ \\
 &= 51.454 \angle -75.1^\circ \\
 E_{a2} &= 51.454 \angle -75.1^\circ \times 0.181 \angle 43.0^\circ \\
 &= 9.324 \angle -32.1^\circ \\
 &= 7.898 - j4.955
 \end{aligned}$$

$$\begin{aligned}
 I_{a2} &= -9.324 \angle -32.1^\circ \div 0.193 \angle 43.1^\circ \\
 &= -48.358 \angle -75.2^\circ \\
 &= 48.358 \angle 104.8^\circ \\
 &= -12.353 + j46.754
 \end{aligned}$$

Then to calculate the line-to-neutral voltages

$$\begin{aligned}
 aE_{a1} &= 18.251 \angle 65.2^\circ \\
 &= 7.65 + j16.568 \\
 a^2E_{a1} &= 18.251 \angle -174.8^\circ \\
 &= -18.176 - j1.654 \\
 aE_{a2} &= 9.324 \angle 87.90^\circ \\
 &= 0.342 + j9.317 \\
 a^2E_{a2} &= 9.324 \angle -152.1^\circ \\
 &= -8.240 - j4.363 \\
 E_{an} &= (10.520 + 7.898) + j(-14.914 - 4.955) \\
 &= 18.418 - j19.868 \\
 &= 27.978 \angle 47.2^\circ \\
 E_{bn} &= (-18.176 + 0.342) + j(-1.654 + 9.317) \\
 &= 17.834 + j7.655 \\
 &= 19.418 \angle 155.7^\circ \\
 E_{cn} &= (7.166 - 8.240) + j(16.568 - 4.363) \\
 &= -0.585 + j12.205 \\
 &= 12.220 \angle 92.8^\circ
 \end{aligned}$$

The multiplication factor then is

$$K = \frac{115}{27.078} = 4.247$$

Now, all voltages and currents are raised by this factor, to find the actual values

$$\begin{aligned}
 E_{a1} &= 77.511 \angle -54.8^\circ = 44.679 - j63.337 \\
 E_{a2} &= 39.597 \angle -32.1^\circ = 33.543 - j21.042 \\
 I_{a1} &= 242.752 \angle -77.3^\circ = 44.875 - j236.812 \\
 I_{a2} &= 205.377 \angle 104.8^\circ = -52.463 + j198.562 \\
 I_e &= 218.524 \angle -75.0^\circ \\
 E_{an} &= 115.000 \angle -47.2^\circ = 78.222 - j84.379 \\
 E_{bn} &= 82.466 \angle 155.7^\circ = -75.741 + j32.545 \\
 E_{cn} &= 51.896 \angle 92.8^\circ = -2.482 + j51.834 \\
 aI_1 &= 242.752 \angle 42.7^\circ = 178.401 + j164.625 \\
 a^2I_1 &= 242.752 \angle 162.7^\circ = -231.770 + j72.187 \\
 aI_2 &= 205.377 \angle 135.2^\circ = -145.729 + j144.715 \\
 a^2I_2 &= 205.377 \angle 15.2^\circ = 198.193 + j53.848 \\
 I_a &= (44.857 - 52.463) + j(-236.812 + 198.562) \\
 &= -7.606 - j38.250 \\
 &= 38.992 \angle -101.2^\circ \\
 I_b &= (-231.770 - 145.729) + j(72.187 + 144.715) \\
 &= -377.499 + j216.902 \\
 &= 435.459 \angle 150.1^\circ
 \end{aligned}$$

$$\begin{aligned}
 I_c &= (178.401 + 198.193) + j(164.625 + 53.848) \\
 &= 376.594 + j218.473 \\
 &= 435.293 / 30.1^\circ
 \end{aligned}$$

The fault current will be found by dividing the phase-to-phase voltage by the fault impedance.

$$\begin{aligned}
 I_{fault} &= \frac{E_{BC}}{Z_f} \\
 &= \frac{(-75.741 + 2.482) + j(32.545 - 51.834)}{0.2} \\
 &= \frac{-73.258 - j19.289}{0.2} \\
 &= \frac{75.772 / -165.2^\circ}{0.2} \\
 &= 378.361 / -165.2^\circ
 \end{aligned}$$

The voltage at the generator may be found by obtaining the sequence voltage drops in the generator leads, combining to find the line voltage drop, and adding it to the bus voltage.

$$\begin{aligned}
 E_{1(drop)} &= 242.752 / -77.3^\circ \times 0.025 / 51.0^\circ \\
 &= 6.093 / -26.3^\circ \\
 &= 5.462 - j2.700
 \end{aligned}$$

$$\begin{aligned}
 E_{2(drop)} &= -205.377 / -104.8^\circ \times 0.025 / 51.0^\circ \\
 &= -5.155 / 155.8^\circ \\
 &= 4.7 - j2.14
 \end{aligned}$$

$$\begin{aligned}
 aE_1 &= 6.093 / -26.3^\circ \times 1.0 / 120^\circ \\
 &= 6.093 / 93.7^\circ \\
 &= -0.393 + j6.080
 \end{aligned}$$

$$\begin{aligned}
 a^2E_1 &= 6.093 / -26.3^\circ \times 1.0 / -120^\circ \\
 &= 6.093 / -146.3^\circ \\
 &= -5.069 - j3.381
 \end{aligned}$$

$$\begin{aligned}
 aE_2 &= 5.155 / -24.2^\circ \times 1.0 / 120^\circ \\
 &= 5.155 / 95.8^\circ \\
 &= -0.51 + j5.1
 \end{aligned}$$

$$\begin{aligned}
 a^2E_2 &= 5.155 / -24.2^\circ \times 1.0 / -120^\circ \\
 &= 5.155 / -144.2^\circ \\
 &= -4.18 - j3.02
 \end{aligned}$$

$$\begin{aligned}
 E_{A(drop)} &= (5.462 + 4.7) + j(-2.700 - 2.11) \\
 &= 10.16 - j4.81 \\
 &= 11.2 / -25.4^\circ
 \end{aligned}$$

$$\begin{aligned}
 E_{B(drop)} &= (-5.069 - 0.51) + j(-3.381 + 5.1) \\
 &= -5.58 + j1.72 \\
 &= 5.84 / 162.9^\circ
 \end{aligned}$$

$$\begin{aligned}
 E_{C(drop)} &= (-0.393 - 4.18) + j(6.080 - 3.02) \\
 &= -4.57 + j2.06 \\
 &= 5.5 / 146.2^\circ
 \end{aligned}$$

$$\begin{aligned}
 E_{A(GEN)} &= (78.222 + 10.16) + j(-84.379 - 4.81) \\
 &= 88.38 - j89.19 \\
 &= 125.5 / -45.2^\circ
 \end{aligned}$$

$$\begin{aligned}
 E_{B(GEN)} &= (-75.741 - 5.58) + j(32.545 + 1.72) \\
 &= -81.32 + j34.265 \\
 &= 88.2 / 157.1^\circ
 \end{aligned}$$

$$\begin{aligned}
 E_{C(GEN)} &= (-2.48 - 4.57) + j(51.834 + 3.06) \\
 &= -7.05 + j54.9 \\
 &= 55.4 / 97.3^\circ
 \end{aligned}$$

Addition of the voltage drop to the bus voltage works out fairly well for phases A and C, but is incorrect for phase B. This is because the voltage drop is out of phase with the bus voltage, and they add directly only when they are in phase.

From this example, we also obtain some additional information, we may determine directly the watts loss in each impedance element. That is, knowing the current flowing in each circuit element, and the resistive component of the impedance, the watts loss in the element may be found by

the familiar I^2R rule, or $\frac{E^2}{R}$ where the voltage across

the impedance element is known, and remembering that the loss thus found is one-third, since each sequence is symmetrical and has three elements. To summarize the conditions in the circuit just solved, the following table is presented:

Impedance	Current Through	Voltage Across
Z_{G1}	242.75	
Z_{L1}	242.75	
Z_{G2}	205.38	
Z_{L2}	205.38	
First Load Resistor		77.51
Second Load Resistor		39.60
Fault	378.36	
Total Losses		
Generator		
Positive-Sequence Impedance	$3(242.75^2 \times 0.075)$	
	= 13,200 watts	
Negative-Sequence Impedance	$3(205.38^2 \times 0.175)^*$	
	= 21,850 watts	
Total Generator Losses	= 35,050 watts	

*Note:—

The value of 0.125 ohm negative-sequence resistance is not used here for computing negative-sequence losses, due to the effect of negative-sequence braking torque. That is, in any rotary machine where negative-sequence voltages are present, there is a torque created in the opposite direction to normal rotation. Pages 271-272, Volume II, of Circuit Analysis of AC Power Systems, by Edith Clarke show that the proper value is equal to $(2R_2 - R_1)$. Since R_1 is 0.075 ohm, and R_2 is 0.125 ohm, 0.175 ohm is the proper value to use.

Table II-1—Principal Subdivisions of Aircraft Electric Systems

Generation	Distribution	Utilization
1. Primary Generators	1. Bus Arrangements and Interconnections	1. Electrical Equipment and Devices
2. External Power	2. Bus Switching and Protection	2. Load Power Control Circuits
3. Emergency Generators	3. Remote Bus Feeder Switching and Protection	3. Load Power Circuit Protection
4. Auxiliary Generators	4. Power Transformation, Conversion and Conditioning	4. Utilization Equipment Circuit Protection
5. Drives and Transmissions		
6. Energy Source Interface		
7. Generator Control and Protection		
8. Generator Feeders		
9. Feeder Protection and Switching		

erator and a frequency converter to change the variable frequency power to constant frequency. These systems are designated as variable speed constant frequency (VSCF) systems. In the VSCF system the frequency converter is considered part of the generation system.

Other items included in this subdivision are as follows:

- a. Main Generator Control and Protection.
 1. Voltage regulator
 2. Load division circuits (for parallel operation)
 3. Switching circuits for operating the generator contactor and generator
 4. Generator protection
 5. Feeder protection up to the main bus (sometimes includes main bus protection).
- b. Frequency Converter for VSCF Systems.
 1. Frequency control
 2. Individual phase voltage regulation
 3. Real and reactive load division
 4. Paralleling circuits
 5. Synchronizing circuits.
- c. Auxiliary Power Unit Generator Control and Protection.
 1. Voltage regulator
 2. Frequency control
 3. Switching circuits for operating the generator contactor and generator
 4. Generator protection
 5. Circuit protection up to the main bus.
- d. External Power Channels.
 1. External power monitoring to protect the main bus against abnormal power and reverse phase rotation
 2. Switching circuits (for operating the external power contactor)
 3. Monitor self-protection against extremes of voltage or frequency.

220 DISTRIBUTION

The distribution subdivision of the electric system performs the functions of:

1. Interconnecting generators, interconnecting generators with external power and interconnecting generators and external power with load buses
2. Transmission of generated and external power from source to load buses
3. Transformation, conversion and bulk conditioning of power for utilization equipment.

The distribution subdivision normally consists of an arrangement of source and load buses interconnected through bus switching devices, protective devices and transmission cables. Most aircraft will have primary, secondary and emergency power distribution systems. The primary distribution system is a bus arrangement formed to distribute generated and external power. Secondary distribution systems are bus arrangements used to distribute the power from transformers, converters and bulk conditioners. As the name implies, the emergency distribution system is a bus arrangement used to distribute the power from emergency generators and batteries. Most often the emergency distribution system is interconnected to the primary and secondary distribution systems in such a fashion that emergency loads are supplied from these systems during normal electric system operation, but are transferred to the emergency generator or battery upon loss of the primary generators or the primary and secondary distribution systems. Also included under the distribution subdivision are the cables used to interconnect buses, bus and cable protection, bus switching contactors and the transformers, converters and bulk conditioners.

230 UTILIZATION

The utilization subdivision of the electric system includes all of the many electrically operated devices on the aircraft, as well as the power and control circuit from the

g. **FREQUENCY**—The selection of frequency depends to a large extent upon the type of utilization equipment used in the aircraft. In general, selection should be made for minimum weight of the entire electric system which will provide satisfactory performance. It is desirable to operate motors at high speeds, up to the limits of good bearing performance, since this tends to minimize equipment weight even when reduction gears are required. The frequency should be high enough to permit motor speeds in the order of 8000 to 12,000 revolutions per minute and yet not so high as to require gearing for efficient motor design. Much of the direct-current motor-driven apparatus used on present day aircraft is designed for motor speeds of 8000 revolutions per minute. This has been found satisfactory for continuous operation of grease-packed ball bearings. For intermittent operation, grease-packed ball bearings in small sizes operate satisfactorily up to 12,000 revolutions per minute. It is desirable to utilize these same speeds insofar as possible to avoid unnecessary redesign of gear reduction mechanisms and to make use of maximum speed permitted by practical bearing design. It is advisable, therefore, to select a frequency which will provide these speeds.

The frequency should be selected so that speeds up to 24,000 revolutions per minute are not ruled out, because such speeds may be desirable for light-weight turbo-alternators which hold promise for the future. Such machines would probably be designed with oil pressure lubrication of the bearings, which is feasible. Again, certain gyroscopic instruments require motor speeds of this order.

For motors which are not geared, the frequency should be such that at least the majority can be designed with a number of poles (preferably four, six, or eight) which will result in the required speed with an efficient, light-weight design. The frequency should be high enough so that a sufficient number of speed steps are available in the desired motor speed range to permit flexibility in application, yet without requiring an excessive number of poles.

Iron-core transformers become lighter with increasing frequency, within practical limits, so that this becomes a consideration in frequency selection.

High frequency reduces the size of capacitors (in microfarads) necessary to accomplish power-factor correction, but increases dielectric losses at the same time.

Filter components for radio are smaller at high frequencies, although inductive pick-up effects may be increased.

Instruments such as synchro-ties and position indicators are smaller and lighter at high frequencies.

Tuning-fork control of frequency is more practical at 400 Hz and higher than at lower frequencies. This has been considered for some instrument requirements.

If too high a frequency is used, skin effect in conductors, and eddy current and penetration effects in iron cores, increase the weights of wiring and equipment. Except for frequencies well above 400 Hz, nevertheless, these ef-

fects are not significant for most wire sizes and equipment designed for use in aircraft. For example, in wire sizes AN-8 and smaller, the skin and proximity effects at 400 Hz increase weight and losses by less than 1 percent. This includes the majority of wires in most 115/200-volt systems now contemplated. For larger wire sizes, skin and proximity effects increase considerably. Thus, for AN-0 it is 11 percent and for AN-000 it is 30 percent at 400 Hz. These figures are based on minimum practical spacings with insulated aircraft cables.

320 EMERGENCY SYSTEMS

Anticipating possible failure of the primary electric system on the aircraft, measures should be taken to provide power to critical loads. An example of this necessity is the case where a double flameout occurs with a two-engine jet aircraft. In this case, an emergency electric power supply can provide power to restart the engines. Another example is an aircraft which has exhausted its fuel supply and is attempting a landing. In this case, the emergency power supply can provide power to operate the hydraulic pumps and allow the aircraft control surfaces to be operated.

In order to insure that the emergency source is always operative, it may be good practice to have it operate under all normal conditions as well as during the emergency conditions. Automatic or manual monitoring of loads is then mandatory when the primary electric source fails. The following is a list of possible emergency sources:

- a. **Battery**—Small amounts of power may be available by the use of a battery for a limited period of time. However, if this is relied upon, great care must be taken to keep the battery adequately charged. Switching to an emergency bus would bring the power to the correct loads.
- b. **Separate Engine-Generator Set**—These devices were used widely during World War II on bomber aircraft and are presently used on some large aircraft. This equipment is fairly heavy. Also, it is relatively inefficient and difficult to start at high altitudes but may be made in units with large capacities.
- c. **Ram-Air or Hot-Gas Turbine-Generator Units**—Air turbine units may use ram pressures to drive generators. These units are comparatively light and may be put into operation by a valve which diverts a portion of the air from a jet engine intake duct or they may be swung out into the air stream by manual means when needed. Auxiliary turbine power to supply mechanical and electric loads may be obtained conveniently from liquid fuels. Existence of critical aerodynamic conditions at the time of main system power failure may warrant use of such hot-gas turbine units.
- d. **Mono-propellant systems independent of altitude and of other generation systems.**
- e. **Engine-bleed-air turbine-generator set may be used as an emergency source if the primary system is not also driven by bleed air. This would be ineffective in case of loss of motive power.**

- f. A hydraulic motor-generator emergency source driven by a main-engine-driven pump would be effective except after loss of the engine, or it might be designed to have adequate output at the windmilling speed of a turbine engine. A transmission-driven source in a helicopter is adequate if driven during auto rotation.

The U. S. Air Force currently requires that, on aircraft having dual sets of primary flight instruments, each set be powered from separate sources. In some cases this requirement has been satisfied by separate supply from different sections of a sectionalized multi-generator main bus system. In other cases a small independent supply, such as an hydraulic motor-generator set, has been used for one set of instruments.

321 Primary System Emergency Procedure

At the present time it is felt that the needs of safety should be provided for wherever possible by adequate primary power system emergency procedures rather than the use of separate emergency systems. This takes advantage of the fact that the major components of the primary system are larger, more durable, and have undergone more extensive development and service proof testing. Also, modern circuit protection techniques have produced major advances in the reliability of the primary system. This philosophy is being applied primarily to multi-generator systems. Many of these systems, though designed to operate normally in parallel, are arranged to break apart manually or automatically into a group of separate systems in the case of major system trouble or during critical flight conditions. In the separated mode, critical or essential loads are provided for by various means. Extremely critical loads may be duplicated for their own reliability and connected to different main bus sections. Other essential loads may be switched to any of several main bus sections or directly to any of several generator outputs. Even more elaborate schemes are being specified in which switching configurations are automatically set up for any combination of failed generators in order to assure power to the essential loads and to disconnect the less important loads. The present trend toward breaking up the entire system into separate generator systems under emergency conditions is reflected in the FAA regulation for commercial aircraft which requires three separate power supplies during "category three" or instrument landings.

322 Auxiliary and Ground Power Systems

In some large transport aircraft, auxiliary generating systems are provided which are similar to those described under Section 320, Emergency Systems, but which are intended primarily or only for ground power use. In present aircraft design these generators are usually driven by a gas turbine auxiliary power unit (APU) which may also be used for starting the main engines. (See Section 541.) A separate battery is often provided for starting the APU. This avoids draining the main battery which may be required to serve as an emergency source during flight.

Electrical power for ground operation may also be provided by external ground power sources plugged into the

aircraft. An external power monitor must be provided in the aircraft to make certain that the voltage, frequency and phase rotation of the power are acceptable before admitting it to the aircraft.

330 GUIDE TO PROTECTION

331 Direct-Current System Protection

Protection of direct-current generator parallel systems involves in general two items: Removal of a generator when its voltage is abnormal, and short-circuit protection. The first item is accomplished by a "generator reverse-current cut-out." It consists of a line contactor and a polarized pilot relay mounted in one enclosure. This device senses the difference between generator and bus voltage and also senses the generator current. When the generated voltage exceeds bus voltage, the pilot relay closes and completes the circuit to the contactor. When the generated voltage drops below normal, reverse current opens the pilot relay, removing the generator from the bus. Service experience has indicated the necessity that the contactor of the cutout be designed with sufficient capacity to interrupt the maximum output voltage and current on a wide-speed-range generator under full field, as could occur in the case of regulator failure or accidental contact between the generator shunt field wire and the positive line wire.

Short-circuit protection is provided for in some measure by the reverse-current cutout. However, a circuit breaker with a reverse-current trip having sufficient time delay to override normal transients is sometimes used to provide: (a) higher interrupting capacity up to 12,000 amperes, (b) back up protection for a welded contactor or a pilot relay failure, (c) auxiliary contacts to deenergize the generator and prevent its continuing to feed the fault, and (4) interrupting capacity for overvoltage conditions, using a shunt trip coil actuated by an overvoltage relay. In some cases, differential-current protection is used to disconnect a faulted generator or generator feeder and deenergize the field without time delay to reduce the hazard of fire. Several successful types of differential-current protection for direct-current generator circuits are available, using series-coil current-balance relays, using a current-balance relay operated from special metering shunts in the line and ground leads, or using a current-balance relay operated from a metering shunt in the line lead and the potential across the generator series windings on the grounded side. Several of these types have been used widely. Development work has been done on methods which compare the transient voltages of mutual reactors in the line and ground leads. The latter type requires an auxiliary alternating-current source for maximum effectiveness.

A third type of protection is overvoltage protection. Full-field conditions can produce very high voltage on direct-current systems and, because of the potential damage to load equipment, it is customary to provide fast-acting overvoltage protection to de-energize and remove the faulty machine from the bus. The various methods employed sense either generator field voltage or bus voltage. The former is inherently selective because the field voltage

of the unfaulted machine is always below rated value. However, it does not protect for a partial failure at high speed, for the field voltage may still be below rated value and yet sufficient to produce an overvoltage at the terminals. Bus voltage sensing protects for all overvoltages above the protection setting but requires a more complex means of selecting the faulty machine. This method requires biasing of the overvoltage circuit or the use of a separate selector circuit acting on a directional unbalance in the regulator equalizer current.

332 Isolated Alternating-Current System Protection

The following is a list of various types of protection which are used for isolated alternating-current systems.

- a. Overvoltage protection
- b. Ground-fault protection
- c. Undervoltage protection
- d. Underspeed or underfrequency protection
- e. Phase-sequence protection
- f. Overfrequency protection.

The overvoltage circuit may sense the average of the three phase voltages, the highest of the three phase voltages, or some variation of these two sensing methods, applying the sensed voltage to a circuit with an inverse-time-voltage characteristic. Care is necessary in selection of the sensing method to avoid nuisance tripping of part or all of the generators during a line-to-ground fault. Under this condition, when using an average-sensing voltage regulator, one or both of the unfaulted phases will experience overvoltage. Depending on the magnitude of the fault current and the sequence impedances of the generators, this overvoltage may result in tripping a high-phase-sensing type of overvoltage relay before the other protection can clear the fault from the system. The only recourse then may be to locate and clear the fault manually before power can be restored to the system. Use of a high-phase-sensing voltage regulator in combination with a high-phase-sensing overvoltage relay solves this problem but results in a major reduction in line-to-ground fault current, with a resulting increase in fault clearing time. In reaching a decision on the type of sensing to be used, the following are some of the factors which need to be evaluated for the particular system being studied:

- a. The magnitude of single-phase overvoltage attained with various magnitudes and locations of line-to-ground faults
- b. The clearing times for these faults
- c. The protection coordination problems
- d. The effect of overvoltage versus time on sensitive load equipment
- e. The feasibility of applying individual high-phase overvoltage protection to sensitive loads.
- f. The protection coordination problems and longer system disturbance time which may result from use of a high-phase-sensing regulator.

The time-voltage tripping characteristic is defined by MIL-STD-704, as this specification gives the maximum voltage that the load equipment may be required to withstand—one of the design criteria being load protection. The generator and regulator must be designed so that normal transient conditions will not cause system voltage to rise beyond this curve and cause false tripping.

Short circuits at the generator terminals or in the cables up to the bus may cause hazard from fire and smoke or cause loss of electric power. Thus far, some type of differential-current fault protection has been considered desirable on most alternating-current generators and their feeders because it is inherently selective and thus can be made instantaneous. In an alternating-current system, the current in a phase lead is normally equal to the current in its neutral. If there is a fault, somewhere within the loop, there will be a current unbalance between the phase lead and the neutral lead. To detect a fault, the current unbalance in the loop is sensed by using current transformers (CT) operating a circuit to trip the generator control panel. There may be either six or three current transformers depending solely on the weight comparison of the additional three current transformers in the six-transformer system versus the added length of the neutral leads necessary to run them through the three current transformers in the three-transformer system. There is slight difference in the protection level between the systems of three or six transformers. Problems caused by lightning strikes have occurred due to difference in potential by using the airframe ground as the fourth common wire in the CT secondary on aircraft with long generator feeders. A 4-wire ungrounded secondary on the CT is recommended.

Use of the six-transformer protection system causes some reduction in reliability because of the possibility of breakage of the small wires used to complete the loop between transformers. An open circuit in the loop causes immediate and non-resettable tripping of that generator. This disadvantage should be weighed against the advantage of quick, selective fault clearing for the generator and its feeder. In a multi-generator paralleled system, the occasional loss of a generator from this cause may not be a serious objection.

Protection levels of approximately 20 to 40 amperes difference current can be obtained. The necessity for a protection level as high as this has not been thoroughly demonstrated on generator systems of 60 kVA and smaller. On larger systems, this magnitude increases by the ratio of generator capacity to 60. Example: 120 kVA is 40–80 amperes. This current can be decreased by using faster action devices. Consequently, other methods of fault protection may be used as discussed in the following paragraph.

Undervoltage protection offers several types of protection, among which are load protection and fault protection. For example, many loads can be damaged by undervoltage. In the case of fault protection, undervoltage sensing gives a measure of protection against solid bus faults. A three-phase solid fault on the main bus to ground will so depress the bus voltage as to cause the undervoltage protection to trip after a slight time delay. The delay is

necessary for overall system coordination so that a fault on the distribution system will trip distribution circuit breakers prior to tripping the alternator on undervoltage.

Underspeed and/or underfrequency trips on a controlled frequency system are utilized to provide for switching the generator on and off the bus and to coordinate with the undervoltage trip when shutting down the system. In addition, some loads must be protected against underfrequency. The coordination of an underspeed trip with the undervoltage circuit is necessary so that in shutting down the system, the underspeed switch takes the generator off the bus and does not permit the undervoltage circuit to operate.

Overfrequency protection in the control equipment is not as common as underfrequency protection because slight overfrequencies are not permanently harmful to most loads. However, overfrequencies can cause some degree of impaired function in some types of loads. Induction motors run faster, inductive loads operate at lower power factors, etc. External power monitors usually include overfrequency protection because of the wide variety of ground power equipment encountered, its uncertain maintenance status, and the possibility of misapplication. Aircraft systems with a constant speed drive or with an auxiliary gas turbine drive usually have overspeed protection built into the drive. In systems where the generator is directly driven from the main engine, the entire system is designed for a wider range of frequencies. These provisions usually make it unnecessary to include overfrequency protection in the control equipment of on-board systems.

Phase-sequence relays have been called for in some specifications. In general, phase-sequence protection is dependent on system maintenance requirements. Phase sequence should always be checked when changing a generator, however.

Anti-cycling protection is necessary to prevent damage caused by cycling of a system on a fault. Without this protection, when the generator switch is held in the reset position on a fault, the fault will cause the system to trip again and the reset switch will cause it to reclose. Therefore, a lockout relay or anti-cycling relay is used to electrically interlock the reset switch and permit only one reset on a fault when the reset switch is held closed. Electric power is required from an external source when electric anti-cycling is employed.

333 Parallel Alternating-Current System Protection

In order to attain the highest degree of utilization from a parallel alternating-current system, it is necessary to prevent a fault or a malfunction on one part of the system from destroying the power-producing abilities of the remainder of the system. Moreover, it is advantageous to remove the faulted portion with minimum power interruption to the loads and quickly enough to prevent further damage to the system.

In designing system protection, the first function of the generator protective panel is to distinguish between failures in the distribution or load system and those in the generator system. If the failure is in the generating system, removal of the faulty machine should take place as quickly as possible. If the distribution and load system is

adequately protected and coordinated, the panel should take no action for failures in this area except, possibly, when protective devices fail to operate properly.

Some of the malfunctions most likely to occur and the method of protection are as follows:

- a. Excitation protection
- b. Open-phase protection
- c. Bus-fault protection
- d. Generator short-circuit protection
- e. Unbalanced real power protection

One of the foremost problems has been protection against excitation failures. It has been determined that both overexcitation and underexcitation can result in the loss of an entire generating system. In the past, relays operating at the ceiling voltage of the exciter have been used for overexcitation protection. However, since this method gives incomplete protection, other methods have been developed to allow full protection for both overexcitation and underexcitation. Either of these malfunctions result in circulating reactive current flow between machines. However, a system which has an overexcited machine will have a higher than average bus voltage or, for a heavily-loaded system, at least normal bus voltage. This is contrasted with a system with a machine which is underexcited. In this case, the bus voltage will be lower than normal. For both types excitation failures, circuitry sensing unbalanced reactive current flow and bus voltage produce signals used to detect and initiate the isolation of the abnormal machine from the system. Differential sensing circuitry can be so designed that the magnitude and direction of the unbalanced reactive current flow can be determined.

An open circuit on a phase wire which includes a load division current transformer can cause loss of the entire system. Provided the system load does not approach the total machine capacity, an open on any other phase is not serious since the effects of the load division circuits are not present. For this reason, it is recommended that both the real load and reactive load division current transformers be located in the same phase.

One method of protection for an open phase when operating isolated is to detect an unbalance in the three-phase voltages. This signal may be used with a time delay to remove the generator from the line. In parallel operation, an open phase will result in a high neutral current. It has been suggested that this might be used as a sensing means to isolate the generator if a split bus system is used. (See Section 132.) Following isolation, the unbalanced voltage sensing would be used to remove the open phase generator or system from the bus. Nevertheless, a line-to-ground fault anywhere on the system also results in high neutral current. Thus the system would be split apart at the very time when high fault-clearing capacity is desired. For this reason this method is not recommended.

Open-phase protection as described above will also serve as a method of bus fault protection since the signals for these two malfunctions are similar. Here also, the protection depends upon a split bus configuration, but again

would result in isolating all generators when a line-to-ground fault occurs on the system. Another method would be to use total differential current to separate the generators followed by single-phase undervoltage relay sensing circuitry with a time delay to remove the faulted generator.

The probability of having a closely-balanced three-phase fault on a bus system is quite low as compared to the probability of a single-phase or line-to-line fault. Making use of this, most bus faults may be detected by sensing excessive negative-sequence voltage and using this to trip the bus tie contactors after a time delay sufficient to provide coordination with distribution system fault protection. This leaves the faulted bus section supplied by one generator. The exciter ceiling voltage relay, mentioned previously, is a relatively simple means of removing this generator from its faulted bus. This relay must have sufficient time delay to coordinate with the other system fault protection devices, such as distribution circuit breakers.

The differential fault protection as described under isolated alternating-current protection is applicable also to parallel operation.

In a parallel system, the protection against failures of the prime mover has to date been of three types—overspeed, underspeed, and reverse power. Reverse power is power transmitted into the drive from the system. The total action of the three types of protection is directed towards separation of the faulted drive and generator from the remainder of the system.

The most satisfactory reverse-power protection device used to date on alternating-current systems has been a mechanical over-running clutch, installed between the generator and its driving source. Attempts have been made to design reverse-power relays to perform an equivalent function by opening the generator contactor. These attempts have not been completely successful to date, possibly because of the difficulty of designing a relay to measure accurately the net direction of three-phase power under conditions of badly-unbalanced voltages and currents under some fault conditions.

One method of overspeed protection on a hydraulic drive is mechanical speed sensing. If an overspeed occurs, the drive is transferred into its maximum underdrive ratio. Assuming that synchronous speed of the alternator is reached at some medium value of drive ratio, action of the overspeed protection would result in drive speed slower than that required for synchronous operation. However, because of the overrunning clutch in the drive, the alternator motors in synchronism with the remainder of the system. Because of the possibility of sustained motoring, it is important that the clutch have proper lubrication under this condition of operation.

Mechanical overspeed protection is also supplied to turbine drives to shut off the pneumatic or fuel supply.

Underspeed protection has been used to remove the alternator from the bus rather than produce any reaction on the drive itself. An underspeed sensing device is used to supply the signal to the alternator control circuit resulting in the alternator being removed from the bus.

The action of both overspeed and underspeed devices rely on the over-running clutch in order to obtain selectivity between good and bad units.

In order to illustrate, let us assume an overspeed condition on a parallel, two-generator system. During the overspeed condition, the faulty drive and its alternator can raise the system frequency and will assume all the real load. The other alternator will be rotating faster than its drive, but is able to do so because of the over-running clutch. After the overspeed device has operated and the output speed of the faulted drive has been lowered below normal, the alternator on the faulted drive remains in synchronism with the system by means of the over-running clutch. The underspeed device on the faulted drive will then operate, resulting in its alternator being removed from the bus.

The above type of reverse-power protection operates only for failure of the drive and not for mechanical failure of the alternator itself. It is possible, with electric circuits somewhat similar to reactive sensing in excitation protection, to sense reverse real power. This would protect against alternator mechanical failures. However, the settings of the device must be such that operation is prevented when reverse power appears as the result of an overspeed condition on one of the other alternators and its drive. A mechanical failure of the generator will probably include a ground fault eventually so that differential protection will remove the generator from the bus. Also, underexcitation will trip the machine when it is no longer generating voltage. The most frequent cause of generator failure is a bearing failure. At the present time many generators are equipped with built-in bearing failure detectors. These are of various designs, some of which anticipate actual failures by several hours. The detector energizes a warning light which permits a manual disconnect of the drive, thus avoiding or minimizing damage to the generator.

In considering the type and amount of protection to be used, we must consider the type of bus system on the aircraft. It is obvious that bus-fault protection serves little useful service on a single source-bus system. However, if the bus is short and mechanically well protected, it is possible that such protection is not necessary. With a split-bus system, or a synchronizing bus, protection can be modified such that under some conditions, the machines can be separated and each will then supply successfully the system loads on its individual bus. (See Section 132.) All systems should be considered on their own merits to decide the type and amount of protection to be used. It should be emphasized that protection is available for the most likely malfunctions that can occur on parallel alternating-current systems. These are overexcitation, loss of excitation, faults on the generator system up to the bus, open phases, bus faults on split-bus systems and unbalanced real power.

340 PARALLEL VERSUS NON-PARALLEL OPERATION

341 Advantages of Parallel Operation

- a. Total electric load proportioned among active generators.

- b. Failure of a unit generator output in multiple-generator system results in no primary service interruption. Sufficient overload capacity in each generator allows adequate time for load monitoring. Additional safety is provided by continued service prior to monitoring.
- c. In some applications installed capacity allows larger starting demands and peak load demands for a given time-voltage disturbance.
- d. Inverse-time overcurrent fault protection will operate faster.
- e. Installed generator capacity is more effectively used, making possible a fewer number or smaller rating generators.
- f. Redistribution of load to remaining generators is automatic upon loss of a generator, thus simplifying operator supervision.
- g. Human element of selecting proper bus for various loads is avoided.
- h. Beat-frequency effects in sensitive equipment, such as autopilots and radar, are eliminated by synchronous operation of all alternating-current sources.
- i. Loss of complete system due to human error and a later fault have posed problems.
- j. The physical division of loads among the buses is not critical.
- k. The addition of growth loads is not as likely to cause extensive rearrangement of existing loads.
- l. Unbalanced phase loading is not as critical since the unbalance is usually a small percent of the paralleled system capacity.

342 Advantages of Non-Parallel Operation

342.1 Direct-Current Systems

- a. The need for automatic load division circuitry and mechanism between generators is unnecessary, thus reducing complexity.
- b. Disturbances in a section of the electric system affect only the section associated with one generator.
- c. Fault current of the system is reduced in magnitude, allowing use of smaller and lighter switching and protective equipment.
- d. Full individual generator capacity may be utilized since no load unbalance need be considered due to meter error or paralleling efficiencies.

342.2 Alternating-Current Systems

- a. The need for automatic real load division circuitry and mechanism between drives is unnecessary, reducing complexity.
- b. The need for automatic reactive load division circuitry and mechanism between generators is unnecessary, reducing complexity.
- c. Disturbance in a section of the electric system affects only the section associated with one generator.

- d. Fault current of the system is reduced in magnitude, allowing use of smaller and lighter switching and protective equipment.
- e. Full individual generator capacity may be utilized since no load unbalance, due to meter error or paralleling deficiencies, need be considered.
- f. Isolated systems can be designed to operate synchronized (but not paralleled) and in this mode of operation beat-frequencies that might affect sensitive equipment, such as autopilots and radar, are eliminated. VSCF systems can be designed to operate synchronized under transient conditions.
- g. The distribution system is significantly more simple, contributing to improved reliability.

350 GROUNDED VERSUS UNGROUNDED OPERATION (applicable only with metallic aircraft structure).

The trend in structural material for high-speed, high-performance aircraft is toward exotic metallic alloys and non-metallic structural composites which can have an electrical resistance too great to be used for an electrical return. The alternates, here, are to use an ungrounded system or provide a neutral return conductor or bus throughout the vehicle.

351 Direct-Current System

351.1 Advantages of Structurally Grounded Systems

- a. Weight savings achieved by the use of electric conductors for the positive polarity only, as the aircraft structure is used for the negative conductor.
- b. Single-pole switching is adequate for both main and control circuits.
- c. Static voltage build-up between conductors and metallic structure is eliminated.
- d. Installation is simplified by reducing the number of connections, wires and switch sizes.
- e. Maintenance is reduced by the reduction in the number of connections and wires. This allows the addition of circuitry by a single connection from the bus through the equipment to ground structure. It also allows simple checking of circuit integrity by testing voltages from circuit connections to ground.
- f. Safety is enhanced by allowing positive identity of the power bus and thus preventing crossed or reversed connections.
- g. In general, the resistance of a ground-return path through metallic structure will be much lower than that of any practical return wire. The effects of fault currents through the structure should be analyzed.

351.2 Advantages of Ungrounded Systems

- a. Accidental contact of line to structure would not create an electric fault, provided the system and all components remain above structure potential.

Table III-1—General Requirements for Aircraft Electrical Components, Equipment, and Systems

Electrical Performance	Mechanical and Physical	Environmental	Installation	System Effectiveness		Other
				Documentation	Documentation	
1. Electrical Ratings and Power Characteristics	1. Weight and Size	1. Temperature Range	1. Equipment Location and Installation	1. Reliability	1. Specifications	1. Standards and General Practices
2. Dielectric Strength	2. Packaging	2. Altitude Pressure Range	2. Wire Selection and Wiring	2. Maintainability	2. Drawings	2. Rules and Regulation (Industry and Government Agencies)
3. Self-Test	3. Shock	3. Humidity	3. Equipment and Wire Identification	3. Safety	3. Test Reports	
4. Test Points	4. Acceleration	4. Moisture	4. Heat Loads and Equipment Cooling	4. Man-System Interface	4. Operation and Maintenance Manuals	
5. Operating Cycle	5. Life (Rotational or Cycle)	5. Water Tightness	5. System and Equipment	5. Initial and Operating Cost	5. Guarantees	
6. Operating Time	6. Mounting Provisions	6. Thermal Shock	6. Component and Assembly Packaging	6. Logistics (System Support)		
	7. Life (at Elevated Ambient Temperature)	7. Life (at Elevated Ambient Temperature)		7. Standardization		
	8. Mounting Position	8. Sand and Dust		8. Change Flexibility		
	9. Lubrication	9. Fungus		9. Growth Capability		
	10. Materials	10. Flammability		10. EMI Control		
	11. Processes and Finishes	11. Explosive Atmosphere		11. Personnel Skills and Training		
	12. Connectors					
	13. Resistance to Solvents, Fuels and Oils					
	14. Sealing and Potting					
	15. Acoustical Noise Output and/or Susceptibility					
	16. Solderability					
	17. Resistance to Soldering Heat					

- b. Positive and negative conductors can be run close together and twisted, if necessary, to reduce electromagnetic interference.
- c. Electrolytic action between various materials in areas of high current concentration is reduced or eliminated.
- d. Better circuit connections are probably possible by making connections wire-to-wire in lieu of wire-to-structure, since structure finish or paint must be removed.
- e. Variations in sensitive circuits caused by differential voltage on the structure are eliminated.

(The special considerations necessary to avoid grounded system problems are limited, thereby indicating advantages outweigh disadvantages.)

352 Alternating-Current Systems, 115/200-Volt, Three-Phase

352.1 Advantages of Grounded System

- a. Eliminated cable as a neutral conductor, providing a weight saving.
- b. Permits the use of three-pole switching for three-phase and single-pole switching on single-phase 115-volt circuits.
- c. Motors can be designed for successful starting and running with one line open circuited, by grounding the motor neutral.
- d. Polyphase power is transmitted at 200 volts without exceeding 115 volts to ground.
- e. Allows simple sensing for ground faults on power feeder leads.
- f. Permits flexibility of providing power at 115 volts to ground at any point in the system "without additional wires."

352.2 Advantages of Ungrounded System

- a. A single connection to ground does not represent an electric fault.
- b. Inductive interference with other equipment decreased.
- c. Generator harmonic characteristics are improved with a three-wire system (neutral not used) because of cancellation of generated triple harmonic voltages.

360 ELECTRIC SYSTEM REQUIREMENTS

Aircraft and missile electrical components, equipment and systems have many requirements imposed upon them which are different from those of industrial and commercial installations and ground vehicles. As aircraft and systems become more sophisticated, the list of requirements becomes more lengthy. Table III-1 is a listing of the more general and more common requirements imposed on aircraft and missile electrical components, equip-

ment and systems. This list is intended as a guide in the design of new systems and the modification of existing systems. Any particular component or piece of equipment will not have all these requirements imposed upon it. On the other hand they will have many special requirements unique to a particular device which is not listed here. The listing is intended to provide a checklist for the most common requirements.

400—INSTALLATION PRACTICES

410 SYSTEM ARRANGEMENT ORGANIZATION

411 Utilization and Simplification

The design objectives should be directed toward the accommodation of components of a system into packages of such size as the space and weight limitations dictate. Here, components are made into assemblies to facilitate the work of servicing and removal from the aircraft, and therefore cannot be of such dimensions or weight as to thwart these design aims.

412 Integration of Source Centers

To provide centralized control of power supplies and to facilitate primary distribution, servicing and maintenance, all power sources, including auxiliaries should be controlled and coordinated from one center, where feasible. Compliance with this will result in a compact installation, which will permit easy system check-outs from one point in the aircraft.

413 Integration of Distribution Centers

As a corollary to Section 412, distribution centers may be set up to feed load centers; these distribution centers are subsidiary to the primary distribution center and are usually removed from it.

414 Organization of Control Systems and Panel Layout

Once the type of system is selected, the next step is to plan the control circuitry and to plan for simplicity in operation. Each generator or power source should be arranged for a minimum of manual switching and control operations. Where non-parallel operation is selected, it is desirable that not more than one manual operation be required to re-establish power to all but monitored loads when a generator failure has occurred. Full automatic operation is desirable, but simplicity and safety should be balanced against the necessary interruptions required by manual transfer.

In planning the panel arrangement for a system, the first objective is to prevent errors in the operation of the controls. To this end, indicator, lights, meters, and controls with concisely lettered names and instructions, should produce actions that are instinctively or intuitively correct. However, where full or semi-automatic operation is provided, considerable panel simplification may be accomplished by eliminating the manual controls for the

automatic portions of the control system on the panel. Where systems are necessarily complicated, use may be made of "facsimile" panels, showing in a true and diagrammatic way, the operation of the system components.

415 Accessibility

System layout should be based on the required accessibility of the components, that is, whether access is required in flight or on the ground. Fuses or other thermal or electromagnetic devices fitted in essential circuits, for instance, should be located where they are easily accessible by one or more members of the flight crew.

Other auxiliary devices and components should be so installed as to permit easy access by ground personnel for servicing purposes. Such remarks apply particularly to remotely-controlled switchgear, terminal blocks, limiters, etc.

420 IDENTIFICATION PRACTICES

421 Cable Identification

Proper identification of all electric cables and the use of the identification codes on wiring diagrams, does much to simplify installation and maintenance procedures. A cable identification number should indicate the general function and the gauge of the cable and should have a designation for each conductor and segment. For standardization, it is recommended that all cable identification numbers be assigned in accord with the classifications and procedures outlined in Military Specification MIL-W-5088.

In addition to the individual cable identification, cable groups at connectors should be marked to prevent incorrect attachment and to assist in maintenance. Wherever possible, the installation should be designed to make it physically impossible to assemble the wrong connector into a receptacle. Experience has shown that if incorrect assembly is possible it will be done. This objective may be accomplished by use of different connector shell sizes, different insert polarizations, or possibly by physical restraint of cable attachments.

A common cause of service difficulty is the accidental interchange of connections at the terminal boards of equipment during service replacement. Adverse conditions, such as inaccessibility, low visibility, illegible wire marking, and inclement weather, greatly increase the probability of error. Use of fanning strips to pre-position the wire terminals to match the positions of the equipment terminal studs will encourage correct connection.

422 Bus and Equipment Identification

The correlated use of identification numbers on equipment and terminals and the use of the same codes on the wiring diagrams will also serve to assist in installation and maintenance.

430 WIRING

433 Wire Connections and Terminations

433.1 Function

The function of connections and terminations is to permit assembly and disassembly of electric circuits

at desired points with minimum degradation of the normal circuit operation. Due to the possibility of failure, misconnection, etc., the number of connections and terminations should be minimized.

433.2 Individual Conductor Splices

Connection of wire ends is achieved by splicing. The use of splices facilitates wiring and interconnection of subassemblies during aircraft fabrication and maintenance.

433.21 Where disassembly is improbable, permanent splices may be used. These consist of conducting metal sleeves in which the two or more wires are mechanically crimped to form a continuous electric circuit.

433.22 Where ease of disassembly is mandatory, a quick-disconnect splice may be used. Quick-disconnect splices must not be used where adjacent wiring can be reverse connected or interconnected. The splices consist of conducting metal terminals attached to wires by a mechanical crimp and constructed to mate and mechanically interlock with each other to form a continuous electric circuit. Present quick-disconnect splices are susceptible to failure from flexing of the wire bundle, loose insulation and pulling wires through conduit as well as increasing the possibility of crossed connections when multiple wire disconnects are involved.

433.3 Connectors

These are used to permit connection and disconnection of single or multiple electric circuits to facilitate calibration, troubleshooting, removal, and replacement of parts and equipments. Connectors have various envelope and contact configurations and designs; however, pin and socket type connectors are susceptible to failure in a number of ways and must be used with caution. Connectors are usually bulky, heavy, and difficult to manipulate under certain conditions. The limitation on the number and size of pins in a connector is determined by the force required to mate and unmate the connectors.

433.31 "MS" connectors for aircraft use were originally as follows:

Class "A" are solid-shell connectors intended to meet the requirements for general applications; Class "B" are split-shell connectors intended to meet the requirements for general applications but are not adaptable to uses where potting is required; Class "C" are special-purpose connectors intended for use on walls or bulkheads of pressurized compartments and on cases of pressurized equipment; Class "E" are special-purpose connectors intended for use where heavy condensation and rapid changes in temperature or pressure, and where high vibratory conditions exist; Class "K" are special-purpose connectors intended for use where it is necessary to maintain electrical continuity for a limited time even though the connector is subjected to continuous flame. Classes "A", "B" and "C" have been inactivated for future design, and Class "E" has become the standard connector for general-purpose applications in addition to

the uses listed. Miniature connectors have been developed in a wide range of sizes, but no formal classification has been adopted, in spite of the fact that they are more widely used than the "MS" types. Also available are connectors of the general application type (referred to as pigtail connectors), in which wires have been attached to the connector contacts and molded in a resilient insert which is bonded to the insulation of the wires and to the interior surface of the shell. The latter connectors are moistureproof and may be assembled in wiring harnesses or may be connected into existing circuits by means of splices.

433.32 Individual contacts in a connector are of high-conductivity metal and may be in the form of round pins and sockets or flat-surfaced springs, usually engaging each other by a linear motion. Since the contact pressure required for low-resistance continuity is provided by spring members, precautions must be taken to preclude overstressing these spring members such as by the insertion of an oversize pin or test prod in a socket. This is accomplished in the case of socket contacts by means of entrance-hole restrictions and adequate spring design. Connectors for printed circuit applications sometimes employ the flat-spring contacts.

Individual wires are attached to the conducting member of the connectors by means of solder, mechanical crimp, wire wrap or taper terminations.

433.33 The insert material serves to separate and insulate the individual pins and sockets within the shell of a connector and must be non-hygroscopic and non-carbon tracking and non-shrinking to minimize leakage current and to prevent the insert from rotating within the shell.

433.34 To prevent moisture from entering the back of connectors which are subjected to the elements or are in critical circuits, the connectors are potted, after the wires are installed, with a plastic compound which adheres to the wires, inserts, and shells and forms an impervious moisture seal. Exclusion of moisture from the mating surfaces of a hard insert connector is accomplished by compression of an O-ring surrounding the contact pins or a resilient gasket suitably punched to admit the contact pins. Connectors with resilient inserts are so constructed to cause compression of the mating surfaces of the insert material to prevent the entrance of moisture. The O-ring method permits trapping of air and has resulted in condensation at low temperatures. Connectors with elastomeric, environmental seals are also available and are now commonly used. Pigtail connectors referred to in Section 433.31 are of moisture-proof construction and require no additional processing.

433.35 Wires attached to the connector contacts are usually bundled and encased in a resilient wrapping or grommet which is clamped at the rear of the shell. This reduces the possibility of wires breaking at the terminations as a result of vibration and longitudinal force applied to the cable bundle. Because of the

elongation characteristic of potting materials, it is desirable to use cable clamps with potted connectors to avoid transmitting longitudinal forces to the connections.

433.36 All mated connectors should be locked in some manner to prevent loosening as a result of vibration causing loss of contact and moisture leakage. This is particularly necessary in areas of high vibration and shock, and in other areas which are inaccessible in flight.

433.4 Strip Terminal Block

Used to permit connection and disconnection of single or multiple circuits much the same as connectors but in a more laborious manner, consists of an insulating strip supporting screw studs to which individual eyed terminals of connecting wires are attached. Electric connections on terminal strips should always be made by surface-to-surface contact of the conducting terminals, and the studs should never be required to carry current. The design should be such that plastics will not be in compression. Studs on the terminal strips should be separated by insulating risers to prevent electric contact of adjacent stud assemblies, and other places where assembly and disassembly is common and are provided with insulating covers which offer physical protection against personnel hazard and that of movable metallic articles. Terminal strips are more dependable than some connectors but provide more chance for errors in maintenance and require more installation time.

433.5 Wire Terminations

Wires in the electric system may be terminated by soldering or mechanical crimping into contacts, taper terminations or ring-type terminals for stud connections. Of the several configurations used, straight-eyed terminals are the most prevalent.

433.51 Mechanical crimp terminations are preferred over solder connections because of their simplicity, reliability and speed of installation. During installation of terminals, depth and shape of crimp is a very important factor in the mechanical crimping process. Tools must be used which require full closure of the crimping dies before the terminal lug can be removed to insure a low voltage drop and adequate strength as indicated by appropriate pull tests.

433.52 A portion of the insulation of the wire should be gripped in the insulation-gripping portion of the terminal lug barrel to provide added strength and resistance to breakage of the conductor by vibration, especially on wire sizes up to and including AN 10.

433.53 Bare terminal lugs offer exposed areas along the barrels, making them vulnerable to short circuits caused by loose metal, and to contact between adjacent barrels. For this reason the barrels are usually preinsulated with a plastic coating capable of maintaining its dielectric properties after the crimping operation, or the barrels are insulated by the application of an insulating tube or tape after the terminal lug is installed on the wire.

433.6 Current-Carrying Capacity.

The current-carrying capacity of each individual contact of the several types discussed must be compatible

with that of the wire to which it is attached. Because the contact area is difficult to control and measure, it is common practice to establish the current-carrying capacity of contacts by a millivolt drop measurement while carrying a current of the rating of the wire attached thereto. These type data are often available from the terminal manufacturer. Ideally, the millivolt drop of the contact should be no greater than an equivalent length of wire; however, practically, for weight and space reasons, a millivolt drop slightly in excess of that of an equivalent length of wire is more often obtained. Hermetically-sealed terminals must be of a relatively high-resistivity material to be suitable for the seal, and this also adds to the voltage drop. To minimize the millivolt drop, contacts of all types are usually tinned or plated with silver or gold. Terminal lugs for high-temperature applications are usually nickel plated or made of nickel alloy. Quick-disconnect splices, connectors and strip terminal blocks rely on contact area and pressure to perform their duty and serve reliably without overheating; thus, every precaution must be taken to provide adequate contact area and pressure.

433.7 Aluminum Terminal Lugs

The use of stranded aluminum wire and associated terminal lugs present problems more severe than those associated with copper because of the adverse conducting quality of aluminum oxide which forms rapidly on aluminum exposed to air, and because of the softness of the metal, and its inherent creepage characteristic when under pressure. To overcome the surface oxidation effect, aluminum terminals are suitably plated for the application.

Greater care must be exercised when installing aluminum terminal lugs on aluminum wires: by stripping insulation in a manner which does not damage the wire strands, by applying an air-prohibiting compound within the terminal barrel, by using the crimping tools and procedures recommended by the terminal lug manufacturer, and by providing means of securing and maintaining adequate tongue pressure without excessive cold flow of the aluminum. Providing adequate hardness of aluminum terminal lugs to alleviate the last condition while maintaining satisfactory conductivity has been difficult.

Satisfactory control of the creep problem has resulted from use of pressure washers of a diameter approximately equal to the width of the terminal tongue and with sufficient thickness to prevent "cupping" under the bolted stress. Standard MS washers are completely unsatisfactory for this purpose because of insufficient diameter and thickness. It is important that equipment terminals also provide a seat with adequate area. One solution to this problem has been to splice short lengths of copper cable to either end of a long run of aluminum cable. The copper cable is then terminated with a copper lug. Special techniques are required, however, to achieve a satisfactory splice between the aluminum and copper cables.

434 Wiring Installation Practices

434.1 General

Discussion of wiring installation practices in a guide such as this must of necessity be very general indeed,

inasmuch as every company or service making such installation must have their own design criteria and individual preferences for one method or another. However, in all wiring installations there are certain basic objectives, and it is the intent of this section of the guide to point out these, with only minor attention to detailed methods of accomplishing these objectives.

434.2 Intent

The intent of a wiring installation is of course, to supply electric power to some device, throughout the operational profiles of the aircraft for the first line life of the aircraft. The accomplishment of this intent must be subject to a number of limitations.

Weight

The wiring installation must be designed to minimize the weight. However, it is not necessary to reduce the weight below readily practicable minimums.

Replacement or Repair

Regardless of the installation, one-shot missile or passenger transport, this factor must be taken into account.

Accessibility

Wiring that is inaccessible for inspection may prove to be a hazard, due to the possibility of damage during installation, deterioration due to environmental factors, etc.

Simplicity

This is possibly the most important factor of all. The complex installation may prove to be impossible to maintain or service, because the service man cannot understand it. Further, complicated installations are difficult to install.

434.3 Installation Methods

In general, there are two methods of installation in use, open and conduited. Each of these installational methods will be considered individually.

434.31 Open wiring is by far the most popular method of installation, it has so many ready advantages that its disadvantages are often lost sight of. Often cited advantages are:

- a. Ease of installation.
- b. Ease of replacement and repair.
- c. Accessibility following naturally from ease of installation
- d. Wiring bundles may be jigged and a complete assembly installed as one operation.

However, there are a number of disadvantages also:

- a. Damage. Since the wiring is installed in the open, it is readily damaged as a matter of course by the very people who install it. Further, plugs, connectors, etc., which are attached to wire bundles prior to installation must be protected from damage.
- b. Extreme care must be taken in jigging the wire, to insure that it lays properly and is not snarled.
- c. Replacement and repair are not as easy as is imagined, as wire bundles are tied relatively frequently, and the bundle must be virtually disas-

sembled to permit the replacement or repair of a single wire.

- d. Despite the restrictions on bundle size, the very fact that there is no physical limitation on bundle size (as there is for installation in a conduit) makes it almost inevitable that wire bundles will grow to unmanageable size.
- e. Reputed ease of installation often leads to an excessive number of wire bundles in one area.
- f. Since wiring is so easy to install and change, the electrical groups receive inadequate consideration when structural changes are being made.

Virtually none of the above objections will be valid where adequate engineering control and inspection are exercised.

434.32 Conduited wiring enjoyed great popularity in the days when radio noise was an extreme problem and was not understood. The theory was to "bottle up the waves and keep them bottled." Recent work in this field has made it possible to conduit, or shield, only the wiring that contributes to EMI.

Advantages of conduited wiring are:

- a. It may be installed behind equipment, linings, etc., and still be readily replaced.
- b. It is not damaged by service personnel stepping on or using the bundle as a hand hold.
- c. When properly installed, additional wires may be added easily.

There are, of course, disadvantages:

- a. A conduited installation weighs more, and occupies more space than an open bundle.
- b. It is impossible to inspect the condition of the wiring without pulling it from the conduit. Thus, wiring damage due to environmental factors is never known until failure occurs.
- c. Installational personnel never seem to learn that they cannot drill drain holes in a conduit after the wire is installed.
- d. Conduit is frequently designed with close to the maximum number of wires in it, so if the wiring requirements grow, new conduit must be installed.
- e. Since conduit is most often installed in areas that are likely to be inaccessible, it is installed in sections, so the wiring bundle is difficult to prefabricate.
- f. Where plugs or connectors are installed on both ends of a conduited bundle, the plug or connector on one end must be installed after installation of the bundle.
- g. It is absolutely essential that the wiring bundle be well combed out prior to installation. It is frequently the custom of installation personnel to tie the bundles after combing. Unless ties are removed before the bundle is drawn into the conduit, this effectively prevents subsequent replacement of a single wire.

434.4 Wiring Installation Control Methods

After an installation is well engineered, some type of control is necessary to see that it continues to be in-

stalled as designed, and to control any changes that become necessary in the course of time. Various methods have been proposed and used; none of them are uniformly successful. The most important are treated below.

- a. *Drawings*—For correct functioning, this method would necessitate complete control by engineers, with detailed changes made for every circuit change. This is virtually impossible on most production lines, as the time required to make such changes, issue new drawings, etc., is such that the drawings never reflect the actual condition of the installation.
- b. *Photographs*—This method of control has been fairly successful, in that circuit changes have little effect on the installations shown on the photographs. Used in this manner, the photograph, properly labeled, may control installations with a fair degree of success.
- c. *Shop Liaison*—In this method, there may be very little formal control of the installation, but considerable informal control. This is excellent for small jobs and development projects. In large installations, it may be very unsatisfactory, as there is no formal control other than the rather elastic consciences of liaison personnel.

434.5 Special Precautions

There are a few general items in wiring installations which require special precautions and control.

- a. *Fluid Lines*—Due to the effects of certain aircraft fluids on wiring, or the hazard of fire in the case of a wiring fault, great care must be taken in the routing of cables in the vicinity of lines carrying such fluids. In no case should there be possibility of contact between these lines and cables. This, of course, includes oxygen lines.
- b. *Control Cables*—As in the above case, all wiring should be installed so that there is no possibility of contact between the wiring and the control cables at any time.
- c. *Magnetic Coupling*—Any direct-current wiring in the vicinity of the magnetic compass must be run as a twisted pair, never as a line with ground return, to prevent the formation of a magnetic field which will affect the compass.
- d. *Effect of Metallic Structure*
 - (1) Direct-Current Wiring. Proximity of metallic structure has no effect upon the electrical characteristics of direct-current wiring.
 - (2) Alternating-Current Wiring. Proximity to metallic structure:
 - (a) *Increases* the alternating-current resistance
 - (b) *Decreases* the alternating-current reactance. The two effects must be weighed against each other to obtain the optimum result.

- e. *Bend Radii*—The minimum bend radius should not be exceeded on any wire installation; however, it is more likely to lead to a failure when coaxial cable, aluminum wire, or thermocouple leads are involved.
- f. *Wire Bundle Support*: The choice of the device used to support the wire bundle should be based on the following criteria:
 - (1) No abrading surfaces exposed to the wiring during or after installation.
 - (2) Visually inspectable for positive support after installation.
 - (3) Contribute minimum volume and weight to the installation.
- g. *Drip Loops*—Low points or drip loops should be provided before the wiring reaches an unsealed (non-moisture-resistant) termination.
- h. *Aluminum Wire*—Aluminum wire should not be installed where maintenance demands such wire be disconnected and reconnected at frequent intervals.

435 Electrical Diagrams

435.1 Purpose

The purpose of an electrical diagram is to convey information concerning a circuit. The type of diagram to be provided is determined by the type of information which is to be conveyed.

435.2 Types of Electrical Diagrams

435.21 Systems Diagrams—A general system layout diagram may be either electrically or physically oriented or both; it is intended to show the relations between the main components. The diagram is used mainly in clarifying the major system paths, which are specified in detail on other diagrams. System diagrams may be provided as:

- a. A "block" diagram in which the main components are shown as identified blocks with interconnection lines showing functional relationships.
- b. A flow diagram (sometimes drawn in block form) which shows the sequence of events in a circuit.

Both of these diagrams are mainly planning diagrams, and seldom appear other than in designers' notebooks or in introductory explanatory literature.

435.22 Schematic Diagrams—A schematic diagram shows by means of graphic symbols the electrical connections and functions of a specific circuit arrangement. The schematic diagram facilitates tracing a circuit and its functions without regard to the actual physical size, shape, or location of the component devices or parts. Schematic diagrams should be prepared in accordance with ANSI Y14.15-1966 (R1973), *Electrical and Electronics Diagrams*, using graphic symbols from IEEE Std 315-1971, *Graphic Symbols for Electrical and Electronics Diagrams* (ANSI Y32.2-1970).

435.221 Logic Diagram—Circuit diagrams for equipment circuits using binary logic devices should use

graphic symbols in accordance with IEEE Std 91-1973, *Graphic Symbols for Logic Diagrams* (Two-State Devices), (ANSI Y32.14-1973).

435.23 Production-Type Connection (Wiring) Diagram—This diagram is made to facilitate production operations and shows components approximately in their proper physical relationship, component terminal location, marking, and wire bundle routing. It is also useful in installation and field servicing. Connection and wire data are often provided in tabular rather than diagrammatic form; the tabulation must be supplemented with physical layout information. Diagrams emphasizing interconnection between units (or black boxes) and showing minimum information on the unit internal connections are called interconnection diagrams. The connection or interconnection diagrams should be prepared in conformance with ANSI Y14.15-1973.

435.231 A complete connection or wiring diagram shows all the wiring and components of a particular installation. It is useful only for a relatively simple installation. In a more complex installation the information may be generally conveyed with a block diagram which serves to aid in the planning of the system wiring installation and circuit wiring diagrams. A circuit connection or wiring diagram confines itself to a single circuit, and unless the circuit is extremely complex, may be made as a relatively small, easily handled diagram. It shows each component of the circuit usually as a generalized outline with the terminals in their approximate physical position. Another type of diagram may show only the terminals of a piece of apparatus with their identification and the connecting wires properly identified going into an identified bundle or highway. Only in extremely simple cases are the wires shown individually run from one terminal to another.

440 INSULATION

450 INSTALLATION PROBLEMS

451 Phase Voltage Unbalance

To avoid objectionable voltage unbalance between phases it is necessary to have the loading of the three phases reasonably balanced in both magnitude and power factor. The effect of reactive power (var) unbalance may be greater than that of active power unbalance because of the predominance of reactance over resistance in the impedance of aircraft wiring.

The problem is made difficult by the fact that many of the individual loads are single-phase, and by the lack of complete control over the sequence in which the aircraft crew will switch them. Large electronic equipment loads, for instance, have often been designed for single-phase input when they could have been designed for three-phase input with a consequent saving of filter weight. Because of the emphasis on this point in MIL-STD-704, the problem should decrease as new equipments become available with better-balanced three-phase loading.

Unbalanced loading results either from unequal distribution of single-phase real and reactive load blocks among

the three phases, or from the connection of nominally three-phase load blocks in which the input current to all line terminals is not equal in magnitude and phase angle. This means that the mere provision of three-phase input terminals to a device is not sufficient. It is important that the equipment designer, within practical limits, also balance the input real and reactive power, respectively, among the three phases.

In distributing unbalanced loads between phases, consideration should be given to the probable operating schedule of these loads so as to minimize the chance occurrence of objectionable voltage unbalance caused by unforeseen switching combinations. Loads which are particularly sensitive to voltage deviations may require use of individual feeders from the main bus, or connection to the regulated phase of a system regulated by single-phase sensing. Transferring the unbalanced loads to another point in the system will help isolate them from the sensitive circuit but will not result in a major improvement. This is because of the fact that in a typical aircraft system, the principal portion of the unsymmetrical voltage drops occur across the positive, negative, and zero-sequence impedances of the generators. To effect a major reduction in these generator impedances would require an uneconomic increase in generator weight.

For a given unbalanced load, increasing the number of paralleled generators, i.e., increasing the system capacity, will effect a proportional decrease in voltage unbalance. This is one of the advantages of parallel operation of generators as compared with isolated operation. In the larger system there is also a greater probability that the random combination of individual unbalanced loads will result in a decreased unbalance on a per unit basis. With the sequence impedances of the generators and wiring known, the voltage unbalance caused by a given unbalanced load may be calculated by the methods given in the AIEE paper "Calculations on Voltage Unbalance for 3-Phase Synchronous Systems", by Wilson and Gardner. AIEE Transactions, Volume 73, Part II, Pages 426-37, 1954.

Induction or synchronous motors running on the system will reduce voltage unbalance. In effect, the impedances of the motor are in parallel with the sequence impedances of the rest of the system and therefore a lower total system impedance results. Also, coupling interaction between phases tends to reduce unbalance. Unless motor loads are unusually large in relation to generating capacity, their phase-balancing effect is not particularly significant. Static loads on the system also reduce the net system sequence impedances and therefore, if they themselves are balanced, help to reduce the voltage unbalance.

452 Power Factor Problems

On normal constant-frequency primary alternating-current systems, power-factor correction has not as yet been found to be worth the weight and volume of the capacitors which would be required. It is the present general practice to design the generators for rated operation at 0.75 power factor. Actual large systems in use today present a load power factor in the region of 0.8 to 0.85, but

may run as high as 0.9 because of unusual amounts of resistive loads. Nevertheless, when unusual system conditions are encountered the possibility of benefitting by power-factor improvement should be investigated, bearing in mind the potential hazard of failures which might reduce reliability. The need for power-factor improvement capacitors on variable-frequency generator systems is highly questionable because of the fact that maximum leading vars would be obtained in the upper range of system frequency, in which range an excess of field excitation is available. Another reason is the fact that this type of system supplies principally resistive loads and no induction motor loads. If a variable-frequency system has to supply load over an unusually long or high-reactance line, it is conceivable that a limited amount of shunt capacitive correction might assist in minimizing the change of load voltage with frequency.

The use of shunt capacitors may introduce some switching problems, causing excessive burning or even welding of contacts on closure. Also, possible personnel hazards which might result from the presence of a charged capacitor on a supposedly de-energized circuit should be investigated.

Usually other load equipment on the circuit will promptly discharge the capacitor when the circuit is switched, but possible abnormal conditions may make this undependable. Rotary inverters are generally rated 0.95 power factor lagging, which is usually adequate for the types of loads supplied. There have been cases where the capacity of fluorescent lamp ballasts resulted in an overall leading power factor load being applied to the inverter. This has resulted in voltage regulation problems because of the limited control range of the voltage regulator.

On constant-frequency primary systems supplying fluorescent cabin lighting as one of the loads, it is advisable to check the light-load condition to make certain that no regulation problem exists.

454 Electromagnetic Interference (EMI) Control

454.1 General

Electromagnetic compatibility (EMC) may be accomplished in several ways, the choice of methods depends upon the type of interference to be suppressed, the equipment causing the interference, and the equipment being interfered with. No general rule can be given, as the circumstances covering each case govern. As the state of the art advances it has been possible to design equipment so that coupling from an interference source does not occur, except in isolated cases. On the other hand, due to an increased understanding of EMI, it has been possible to design equipment which tends by design to suppress or avoid interference. MIL-STD-461 defines the EMI characteristics and requirements for military service equipment.

Where a piece of equipment is in use which is susceptible to EMI from any one of a number of causes, it may be necessary to accomplish local suppression, either on the source of interference or on the receiver. This may be done by filters or by shielding.

454.2 EMI Sources and the Nature of the Interference Field

An EMI source may be considered as one in which either—:

- a. Stored energy discharges into a circuit, and the resultant shock excitation sets up a radiation field. Coupling to a receiver, etc., may be radiation or coupling through some connecting wiring. This interference source commonly covers a very wide band of frequencies.
- b. A piece of equipment as a part of its normal mode of operation may generate a signal of some type which by incorrect design is allowed to couple into other apparatus. Such sources may operate at some discrete frequency and cause interference at this frequency, or as is the case in radar, pulses are generated at a "Pulse Repetition Rate" and cause interference by shock excitation.

The most usual case is the first, in this category are such items as motors, contact devices, or other apparatus in which step functions are generated, and such step functions shock excite circuits in which storage elements are present.

The second case is relatively common where communication transmitters operate in close proximity to receivers.

Since in the majority of cases the interference source operates by shock excitation, the frequency band covered and the strength of the emission depends both on the excitation apparatus and the shock excitation network.

If the entire spectrum of an interference source is analyzed, it will be found that the majority of the energy is concentrated at multiples of the shock excitation frequency and the natural frequency or frequencies of the excited network. From an analytical standpoint then, the interference source can be looked upon as a multifrequency generator with a complex internal impedance, varying between a series of resonant and anti-resonant points. Measurement of interference source voltages then is not necessarily indicative of the interference potential of the source, since a low voltage may be accompanied by high current in a resonant circuit, at anti-resonance the reverse is true. From the above, it is evident that an EMI source may be a network which is excited in any way, with shock excitation being the usual mode. Such networks may be of any character, such as the windings of a motor shock excited by commutation, or even a short section of shield which is imperfect, allowing pulse currents to flow outside the shielded area. In some cases, an induction field may be formed, in others coupling from the source may be from connecting wiring, or a combination of the two cases may occur.

- a. By the direct creation of a radiation field, which may couple to the receiver by either radiation or induction.

- b. By the coupling of a radiation field to wiring, which conducts the interference to the receiver.
- c. By direct conduction from the source to the receiver.

454.3 Adaptation of Shielding to Isolating Either the Interference Source or the Receiver.

Shielding may be either of two types, inductive or capacitive.

- a. Inductive shielding is as the name implies, shielding from an induction field. Where shielding is to prevent coupling to induction fields, e.g., fields created by current flow, the shielded item must be completely enclosed by the shield. Partial shielding, as by running the item to be shielded besides longerons, etc., will be ineffective. It must be understood here that such shielding is necessary only when the coupling is sufficient to transfer sufficient energy to a receiver circuit to deteriorate its performance.
- b. Capacitive coupling exists between any charged body and space. Shielding against such coupling, therefore, may simply take the form of the interposition of a grounded metallic body between the charged body and the item to be shielded. Complete enclosure is not needed. Thus, where this type of coupling is present, suppression may be accomplished by placing either the interfering source (or wiring, if this be the coupling element) or the receiver behind a simple shield. (In this case, the "receiver" may be the antenna lead in, or any other circuit element which may be susceptible.)

It is necessary, then, to analyze the method by which an interfering source is coupled to a receiver before shielding can be applied intelligently. Simple care to run open antenna leads away from wire bundles, or better still, in their own shielding enclosures, and to isolate shield braid wiring from power wiring, is good preventive engineering. But often all such devices are inadequate, and in this case nothing is superior to a good analysis on the basis of coupling theory.

Shield braid, except where it is tightly-woven tinned copper, double layer, is pervious to a strong field, and cannot be depended upon for shielding except in elementary cases.

Complete enclosure of the interfering source is often accomplished. Where the source is intense, a thick, low-resistance shield is necessary, as the depth of penetration may be great at the impulse frequencies or their first few harmonics. Copper is frequently used. It must be realized that when this is accomplished, the currents flowing on the interior of the shielded enclosure may be very large, and even a small opening may be enough to allow some current to flow outside the enclosure, creating a small radiation source. Also, it is essential to filter all leads emerging from the enclosure, such filtering may have to be superior to that which is applied to the item before the complete enclosure is effected.

454.4 Application of Filtering to Isolation of the Interfering Source of the Receiver.

It is obvious that either source or receiver filtering may be employed. Which is chosen is entirely an engineering choice.

When a filter is applied to wiring from an interference source, the filter impedance which the source sees must be lower than the internal impedance of the source. The filter acts as a short circuit on the source interference. Thus, since interference sources may be of very low impedance at their resonant frequencies, it is frequently necessary to make a filter of several sections to obtain the proper attenuation. Further, the current flowing from the source to the filter may be very high at the resonant frequencies.

Source filters thus must be located physically as close to the source as possible. Current flows from the source to the filter may be high enough to cause intense induction fields, coupling to other wiring and causing more receiver interference than without the filter. The wires between the source and the filter must be shielded to prevent coupling to other circuits.

Equipment filters, such as on the input wiring to receivers, etc., should present a high impedance looking into the filter from the interference source, and a low impedance looking into the filter from the equipment. Again, placement is extremely important. If at all possible the filter should be an integral part of the equipment.

454.5 Equipment Design for Inherent Suppression

There are several approaches to this problem. Either the equipment is designed so that the interference levels generated are very low, or else shielding and filtering are so applied that any generated level may be tolerated.

The details of shielding and suppression for reducing conducted or radiated interference already has been treated adequately, and will not be discussed further.

An interference source, as previously pointed out, generally operates on the principle of shock excitation of some type of tuned circuit. Thus, in order to control EMI by design, either the oscillatory circuit parameters may be controlled, or means employed to ensure that the excitation level is very low or non-existent.

If the oscillatory circuit parameters are so controlled that the circuit resistance equals or exceeds the value for critical damping, oscillations cannot occur regardless of the level of shock excitation. The trouble is that resistances capable of accomplishing this result may compromise operation, a case in point being a motor.

The shock excitation by commutation of the armature and field circuits could conceivably be controlled by making the resistance so high that oscillations are damped out, but the motor would no longer deliver torque. Generally, oscillatory circuit parameters

are controllable only when they consist of control cables, structural elements, etc., which function as an oscillatory circuit because they are shock excited.

Control of the magnitude of the shock impulse, while difficult, is frequently the most practical method of control. Successful application of this principle has been in the redesign of commutators, brushes and commutating fields in motors and generators, to improve commutation, thus eliminating or reducing the shock impulse. It is significant that the greatest amount of trouble has been experienced with small components. Since the design of major components for most efficient operation has resulted in a reduction of the magnitude of the shock impulse, no such considerations operate in the case of the small unit, low efficiency is expected, and commutation that would ruin a large machine in a short time is accepted in the small machine.

454.6 Audio-Frequency Interference

Audio-Frequency interference has come to the fore since the wide introduction of 400 Hz alternating-current systems to aircraft. Such interference has been present before this, since inverters have been installed, but was seldom any great problem, due to the low capacity of these machines and the small amount of wiring associated with them.

Audio-Frequency Interference is generally coupled to low-level circuits, such as microphone inputs, synchro circuits, etc., although it may occur to any circuit whenever the interference signal and the coupling factor are high enough, producing shock excitation at a low frequency.

- a. The present 400 Hz system is 200/115 volt Y, and under certain conditions, such as on large single-phase loads or on faults, a heavy field between a wire and structure may occur. Coupling between this field and other wiring may be present.
- b. The field referred to above is of limited area, being strong only in the region between the conductor carrying the interference and structure, so the position of the coupled circuit in relation to the conductor is important. The field may thus be restricted by routing all alternating-current power conductors as close to structure as possible, and of course, routing them away from circuits which might be affected.
- c. The length of the coupling path is also very effective in producing Audio-Frequency Interference. A light field, coupled for a long distance, will have as much effect as a heavy field for a short distance.

Common impedance coupling is a term which may be used to describe all the methods noted above. That is, the two coupled circuits have a common impedance element, current flowing in one circuit thus inducing a voltage into the other circuit. This coupling impedance is most likely to be a ground-current return path at 400 Hz. Thus, the first efforts in controlling Audio-Frequency Interference is careful routing of all low-level circuits away from power and distribution circuits, or shielding of such low-level circuits.

Even in this latter case, heavy ground currents may penetrate light shielding, correct routing and shielding may both be necessary.

455 Safety To Operating Personnel

The voltage which will cause dangerous or fatal shock varies from voltages of the order of 40 volts to several thousand volts, according to the conditions of contact. ANSI C1-1971, National Electrical Code, for ground installations defines everything above 50 volts as hazardous, although it permits a maximum of 150 volts to ground for circuits where contact with inexperienced personnel is possible.

Because most aircraft today have large exposed grounded metal surfaces which provide convenient hand-holds for work in confined spaces, contact with 115-volt circuits must be considered hazardous. This is especially true when surfaces are wet with condensation, or when personnel are perspiring freely in a hot location.

Table IV-1 has been derived for let-go currents and voltages under wet conditions. (See also Section 900, Ref. [5].)

Table IV-1—Let-Go Voltage with Wet Contacts

Pathway	Threshold Voltage (0.5 percentile)		Reasonably Safe Voltage (99.5 percentile)	
	Direct Current	400 Hz Alternating Current	Direct Current	400 Hz Alternating Current
	Hand-to-hand	128	45	103
Hand-to-feet	62	22	51	12.5

Regardless of the circuit voltage, the current available in present-day systems can result in serious burns from direct arcs or metal spatter from carelessly-handled tools, or attempts to replace a fuse or limiter under load. Flash damage to eyes may also result.

Good safety practices are:

1. Covering exposed equipment and junction terminals.
2. Main and load buses be enclosed in insulating and/or isolating shields.
3. Bus shields marked to show that energized power circuits are within, and possibly provided with signal lights to indicate when bus is energized.
4. Signs posted to caution against working on energized circuits.
5. Means provided for safe handling of fuses which have to be replaced in flight.
6. Control circuitry should be so designed that once a bus has been de-energized manually, it will not re-energize automatically, even if a complete loss of power has intervened. Re-energizing should require another manual operation.

500-EQUIPMENT CHARACTERISTICS

510 FLIGHT VEHICLE GENERATORS

Flight vehicle generators are designed and built to obtain the greatest possible output for their weight. The economies of operation justify almost any expense to reduce weight. This minimum weight is obtained by careful design and development, to the end that the maximum capabilities of all parts, electric, magnetic, insulating and mechanical, are realized. Forced ventilation or other special cooling means permit compact designs. Required life is far less than in industrial equipment, sometimes being as low as 1000 hours. This allows operation of the generator insulation at a higher temperature level, giving high output with relatively small size and light weight, consistent with the reliability requirements of the installation.

New developments have continued to decrease aircraft generator weights. For instance, in recent alternating-current generator designs, it has been possible by the introduction of vanadium-cobalt alloys and similar magnetic materials, the use of oil spray cooling, and the increase of rotor speeds from 8000 to 12,000 revolutions per minute, to reduce typical generator weights from 1½ lb/kVA to ¾ lb/kVA.

Figure 510-1 shows presently-available sizes of constant-frequency three-phase aircraft generators.

Reliability is the vital requirement. The vehicle and the lives of the people it may carry depend to an increasing extent upon the electric system, as does the mission which the vehicle is required to complete. Electric power may be used to operate the control surfaces, so that an electrical failure might render the vehicle unflyable. Reliability comes from sound design, careful manufacture, thorough inspection, sound application, proper installation, and correct maintenance.

511 Mechanical Considerations

Mechanical and electrical considerations are intimately related in the design of generators. Certain aspects of mechanical design are especially significant in the application of the generators and warrant discussion here. The many and severe vibrations of large engines result in a difficult design problem. The acoustic noise of jet engines causes severe vibration, extending to higher frequencies. Both high- and low-frequency vibrations are prevalent on turbo-prop installations. In all cases, acceleration loads resulting from maneuvering and aerodynamic flutter and turbulence must be considered. When generators are driven by hydraulic or pneumatic constant-speed drives, or by an auxiliary engine or gas turbine, special problems of torsional resonance near the natural frequency of the governor and/or voltage regulator may be encountered.

511.1 Mounting

The mounting-flange dimensions have been standardized by military specifications. Design strength, however, will vary depending on the type of service expected of it. Thus for mounting flanges on generators in a turbine engine, aluminum might be used,

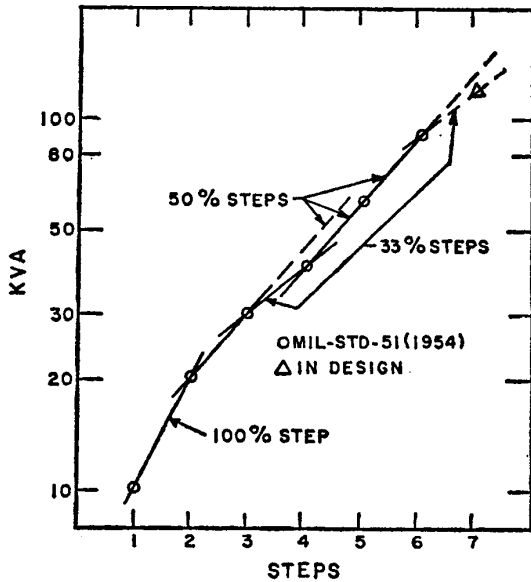


Figure 510-1 Standard Alternating-Current Generator Ratings.

while for mounting flanges on the same generator in a reciprocating engine, steel must be used.

511.11 The accessory drives of some engines are so crowded that special provisions are necessary to make it possible to replace a generator without disassembling much of the engine. This is especially true in some jet engines that pack two tiers of accessories in the nose cone. A simple design to ease the mounting problem is the "button-hole" which permits the generator to be removed by a slight rotation of the flange after the holding nuts are merely loosened. More elaborate quick-attach-detach (QAD) mounts are available that do not require accessibility to any of the mounting nuts, but only to one clamping ring nut which may be located in a position which is easy to reach.

511.2 Natural Frequency

The natural frequency of the entire generator should be well above the worst vibration frequencies of the engine or engine-propeller combination by which it is driven. When the generator is driven by an auxiliary engine or constant-speed drive, the generator torsional natural frequency should be well above the natural frequency of the speed governor. Pernicious cases of frequency and voltage modulation with such drives have been solved by raising the generator natural frequency to a value three or four times higher than the governor natural frequency.

511.3 Drive Shaft

Resilient couplings are generally incorporated in generators for use on reciprocating engines or auxiliary power units to absorb a large part of the torsional vibration of the engine. This often takes the form of

a long inner "quill" shaft which extends from the engine takeoff drive to the opposite end through the hollow outer shaft. The inner shaft is resilient, due to its long length, it is free to twist. This resiliency may introduce other vibration modes, especially in paralleled-generator systems.

In addition, some other means of coping with the torsional vibration of the engine may be necessary. This can take the form of a friction damper, consisting of some form of metal surfaces held together by spring force. One (or more) surface is fixed relative to the rotor of the generator and the other(s) to the input shaft, so that torsional oscillation in the resilient coupling results in rubbing of the surfaces, thereby absorbing energy and preventing build up to large amplitude.

The "clearance" drive has been very successful in some applications. It involves a rotational dead band that is relatively large compared to the amplitude of the torsional vibration experienced. Therefore the torsional impulses are not transmitted regularly and resonance does not occur.

Turbine-engine applications are not necessarily free of torsional vibration problems, as the vibration can be induced by the electric system, especially in systems involving paralleled generators. Transient loads can excite an unstable governor or initiate lightly damped shaft torsional oscillations, resulting in voltage and frequency modulation.

511.4 Bearings

Aircraft generators generally have grease-packed sealed-type ball bearings, with no provision for addition of lubricant. Bearing life is usually that specified for the generator, or at least for generator life-to-overhaul, typically 2000 hours. Aircraft generator bearings should be handled with care. Bearings that have been pulled off a shaft by the outer race may have brinnelled races and should not be reused. For high-temperature applications, special bearings and greases may be required. For very high speeds, oil lubrication may be used.

The pressure differential across a bearing should be very low, otherwise grease will be forced out of the bearing. In some cases, the drive-end bearing must be protected by holes through the mounting flange to equalize pressure.

Considerable difficulty has been experienced in bearing application design because of difference in the expansion of the shaft and the end bell, resulting in pinching of the balls of the bearing. This is caused by two factors:

- Difference in the temperatures of the shaft and end bell; the shaft is heated by the rotor, with very little cooling surface on the shaft, while the portion of the end bell at the bearing is fairly remote from the heat sources and may be well cooled.
- Differences in expansion coefficients of the shaft and end bell. The shaft is generally steel, and the end bell may be made of magnesium or aluminum.

The former problem requires very careful consideration of bearing fits and clearances. The latter problem can generally be solved by using steel inserts in the bearing housing of the end bell which are sturdy enough to absorb the differential compressive loading due to temperature changes, or by use of tangential supports which rotate the bearing housing instead of compressing it.

512 Cooling Methods

Forced air cooling is used on aircraft generators to increase the power that may be dissipated per unit mass of the installed equipment, and thereby greatly reduce the weight of a generator of a given output rating. The balance between the machine rating and the pounds of cooling air per minute required is affected by:

- a. The temperature and density of the cooling air.
- b. The maximum safe temperatures in the machine.
- c. The heat transfer characteristics.
- d. The machine efficiency (since this controls the losses which must be dissipated for a given power output).
- e. Efficiency of air distribution within the machine.

A consideration of these factors has led to the establishment of the requirements of Figure 3 of MIL-G-6162 which is based on sea level conditions.

High altitudes and high speeds are becoming more and more of a problem in cooling of equipment:

- a. Higher speeds result in greater ram rise in temperature of the cooling air, so that the cooling is less effective.
- b. Lower densities make necessary very high volume of flow to get enough cooling air through the equipment.
- c. Heat transfer characteristics vary with the density and rate-of-flow of the air over the cooling surfaces.
- d. Higher air velocities through the machines may change the distribution of the airflow through the various air passages through the machine.

The type of cooling system acceptable to the particular vehicle and its mission will determine the method to be used in the generator. The generator must be designed to meet the needs of the vehicle.

512.1 Fan Cooling

Fan-cooled machines are equipped with an integral fan; this is usually attached to and rotates with the rotor. Air flow is directed through the machine, discharge air should be baffled to prevent it from re-entering the air intake. Air in the compartment from which air is taken should be as cool as possible. The use of fan-cooled generators is limited to small machines and low altitudes, unless this cooling method is supplemented by use of ram air, or the electrical loads are of extremely short duration.

512.2 Blast Cooling

Blast cooling is the most common system at present. Generators are arranged so that a difference in pres-

sure exists between the two ends of the machine. Usually air enters at the anti-drive end, passes over the windings of the machine, and then exhausts at the drive end.

Ducting is generally required at one or both ends of the machine to establish this difference in pressure. Inlet ducting, connected to the generator through a "blast cap," may be run to a high-pressure area, such as a scoop to pick up ram-air pressure due to the speed of the aircraft. Bleed from the compressor of a turbo-jet engine offers another convenient source of high pressure. This compressor bleed air must, however, be cooled for use; this is generally done by using it to do work in an expansion turbine. Exhaust shrouds may be used around the drive end of the generator to gather the exhaust air into a duct leading to a low-pressure area. This might be on the surface of the wing, in the intake to a turbine engine, or elsewhere.

The combination of high-pressure and low-pressure areas and ducting used will be determined by the aircraft, the engine configuration, and the type of engine. Whatever the source of air, it must be of the proper temperature, pressure differential, and quantity. In cases where the generator has not been designed with inherent protection against moisture, it may be necessary to provide for removal of excess moisture from the air. Excess moisture has caused unstable commutation and exciter polarity reversal in some generators. However, such problems may be avoided by use of brushless machines.

The quantity of cooling air passing through the generator will depend on the difference in pressure in the openings of the intake and exhaust ducts, the pressure-loss characteristics of the ducts, the density of the air, and the characteristics of the generator. The above factors are affected by the speed and altitude of flight, the temperature of the air, etc. The particular aircraft configuration is very important. Some installations have encountered zero or reversed air flow under certain operational conditions.

Fans are sometimes built into blast-cooled generators to aid in cooling during operation on the ground. These must be used with great caution, as they tend to exhibit constant-volume characteristics, and are very apt to restrict the flow of air at altitude, where the volume for a given mass is very much increased.

The rotors exhibit some of the characteristics of a fan—sometimes in the wrong direction. The speed of rotation may increase or decrease the flow of air—or it may have little effect on the air flow—depending on the effective fan action of the rotor and/or the presence of a fan.

Usually the generator has been built to a detailed specification that specifies the duct configuration and pressure differential to be used in the evaluation of the machine. In the actual installation, pressure differential as well as temperature and density may be considerably different, and the effect on generator output must be evaluated as discussed below under Section 513, Rating.

At transonic and higher speeds, the ram-air pressure available is so high that special measures may be necessary to prevent damage to the generator or faulty operation. Such effects may include expulsion of grease from bearings, disturbance or breakage of brushes, rain erosion, or other results. The generator manufacturer should be consulted on such applications.

512.3 Cooled Air

Air obtained from a turbine-engine compressor may be too hot for effective cooling. This same condition may arise in high-speed aircraft using ram-air inlets. As the pressure in these cases is also usually higher than required by the generator, an expansion turbine may be used to reduce the temperature by extracting energy from the air. Shaft work might be utilized to drive a blower on the exhaust side of the generator.

Air may be cooled by spraying water into it. This might especially serve for an aircraft flying at low enough speeds for direct ram cooling most of the time, with water sprayed into the air during the short periods of high-speed flight.

High-speed aircraft may require refrigerated air for the pilot and for certain electronic equipment. After use for these purposes it may still be cool enough to be suitable for generator cooling, but allowances should be made for possible reduction of cooling effect caused by changes in the cooling circuit.

512.4 Expendable Coolant

The high heat of vaporization of some fluids, especially water, allows a large quantity of heat to be removed by the evaporation of a relatively small weight of fluid. This may be done by jacketing the generator, or by introducing the fluid to the heat generating parts of the machine. The vapor is allowed to escape. This is especially applicable to missiles and other short-time flights; on flights of long duration, expendable coolants may not offer any weight saving. This will depend on the relative cost in performance of obtaining ram air for cooling. As flight altitudes increase, the use of expendable coolants will become more attractive because the equipment can be made to be relatively independent of ambient air conditions.

512.5 Liquid Cooling

There are several sources of coolant liquids that might be used for generators. The aircraft may have a recirculating refrigerant system for cooling the crew and electronic equipment. Some additional heat load from the generator might require relatively little additional weight. Or the generator might be provided with cool oil from either the engine oil-cooling or from a separate oil-cooling system.

Especially on turbine engines, the fuel may be a heat sink of large capacity. Under high-speed flight conditions, when ram cooling is least effective, the fuel flow is very high and would be able to absorb all

generator losses. Use of a heat exchanger may be desirable utilizing fuel, or even cabin exhaust air to remove heat from the generator cooling medium.

513 Rating

The rating of a generator depends on many factors which must be appreciated and evaluated by the user. These are imposed by the wide range of operating conditions inherent in flight vehicle operation. There are limitations arising from the necessity of designing for minimum weight. There are considerations of desired life and of duty cycles. All this makes rating a subject worthy of thorough study by those concerned with flight-vehicle generators.

Because the engineer is faced with the problem of adapting standard machines to non-standard conditions, it is very important that the manufacturer be prepared to furnish him with sufficient performance data to enable him to analyze properly the provisions he must make to meet the peculiar problems of his application. The desired types of data are listed in Section 519.

513.1 Factors Limiting the Rating

In generators, as in other electric machinery, temperature limitations of the insulation limit the rating of the machine. Nevertheless, the relatively short design life permits higher temperatures. Furthermore, specifications call for performance rather than specifying operating temperatures. Solder used to make connections, or for balancing, may set a temperature limit. Because of this, silver solder or brazing is often used for connections where high temperatures will be encountered.

Commutation in direct-current machines is a load-limiting factor. Even though adequate cooling may be available to insure low temperatures, the output cannot exceed what may be commutated without producing sparking severe enough to cause progressive deterioration of the commutator surface or shifting of the commutator bars. Brush life also is affected by load current. However, with the advent of brushless machines, commutation need not be a load-limiting factor.

A generator cannot handle equally well a given load at all speeds. Operation at low speeds may be limited by flux and by field excitation or field heating. Operation at high speeds involves increased losses due to windage and friction and can involve also high-frequency effects; in some blast-cooled machines, there may be a reduction in air flow due to adverse effects. Therefore, wide-speed-range generators often are not capable of continuous operation at rated load over the speed range, but instead are generally rated for continuous operation at the worst speed condition, and sometimes a second rating at a cruise speed condition.

513.2 Altitude Rating

The continuous rating of a blast-cooled generator at altitude is approached from the standpoint of determining the loads at various mass flows of air through the generator and various air temperatures which will give the same total temperature in the generator

as will normal rated load at sea level under rated cooling conditions at the same generator speed. The mass flow of air is a function of the air density (altitude), of the pressure differential, and of the air-flow resistance of the machine. It should be noted that this air-flow resistance varies with altitude and volume flow, especially in machines with internal fans. This approach leads to the permissible output of the generator for constant insulation life at all altitudes. Data sheets showing these calculations as a family of curves applicable to a large number of generators are available. These have been substantiated by test and experience over a moderate range of altitude and pressure differential. Further study for very high differentials and for high temperatures is in progress. In rating generators, all applicable conditions must be considered. A generator can transfer heat to a cool engine pad, but may receive much heat from a hot pad, and thereby be capable of less output. High ambient temperature surrounding a generator may reduce the output of the generator, regardless of the method of cooling employed. Figure 512.2-3 shows the form of a typical altitude rating chart for blast-cooled generators. It has been taken directly from "Interim Method of Presenting Blast-Cooled Generator Rating Data" prepared by the Airborne Electric Apparatus Rating Subcommittee of the Air Transportation Committee in July, 1954. The complete "Interim Method of Presenting Blast-Cooled Generator Rating Data" is included in the "Standardization of Presentation of Aircraft Generator Characteristics" prepared by the AERM Subcommittee.

On oil-cooled machines, the altitude effects involve mainly corona considerations and sometimes oil sumping provisions.

514 Overload Capacity

Overload requirements cover short-time ratings which tend to increase machine temperature above safe limits but, because of the short time involved, do not dangerously reduce machine life. The short time required may also permit poorer commutation in direct-current machines during overload.

514.1 Overload Requirements

Overload requirements arise from several factors. The load analysis of a typical aircraft system will show numerous short-time high load conditions in various portions of the flight plan. For instance, these may be caused by operation of the landing gear, wing flaps, water injection pumps, gun turrets, or other large intermittent loads. It is economical in weight to use the short-time thermal capacity of the generators to supply such loads. In a system of parallel-operated generators, it is a general requirement to design the system to supply all loads with at least one generator out of service. Under emergency conditions, when the number of working generators has been reduced to the design emergency number, some monitoring of non-essential loads is usually necessary. In this case it is important to allow time for the crew to meet the emergency and perform the necessary load monitoring before the damage point is reached on the re-

maining good generators. Aircraft have been lost because of inadequate allowance for this factor. Automatic indication and/or reduction of overloads should be considered.

Typical overload requirements for alternating-current machines are 150 percent rated load for two minutes and 200 percent rated load for five seconds. Direct-current overload requirements have not been standardized. Where given, they range from 150 to 200 percent for thirty seconds and 125 to 150 percent for two minutes. The two-minute overload ratings are intended to take care of the normal short-time loads and the emergency monitoring time. The five-second overload rating for alternating-current generators provides capacity to handle large motor-starting in-rush currents and to clear faults on the longer low-current distribution circuits. The clearing capacity for heavy faults is discussed in Section 516.2.

Overload requirements usually apply after the generator has stabilized in temperature at full rated load. To avoid too great a penalty in weight, the requirements usually do not apply to base speed on variable-speed machines, but to a higher speed so that the flux-carrying ability of the generator is not determined by the overload requirement. Even when such a precaution is taken to avoid having the overload requirement dictate the size of the generator, it may well determine the size of a prime mover such as an air turbine. Therefore, care should be exercised in specifying overload requirements and proper minimum fault clearing currents.

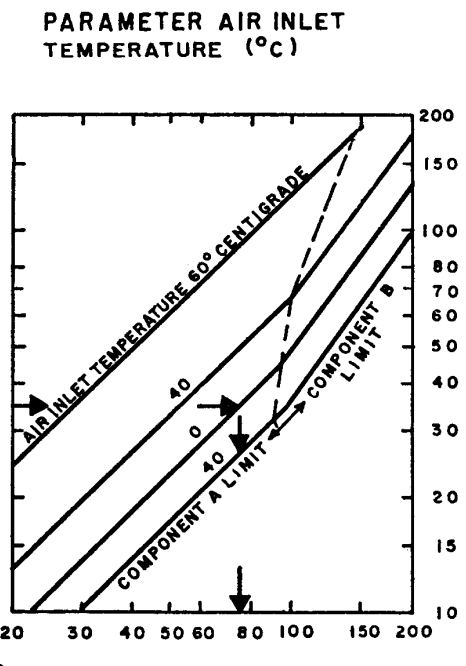
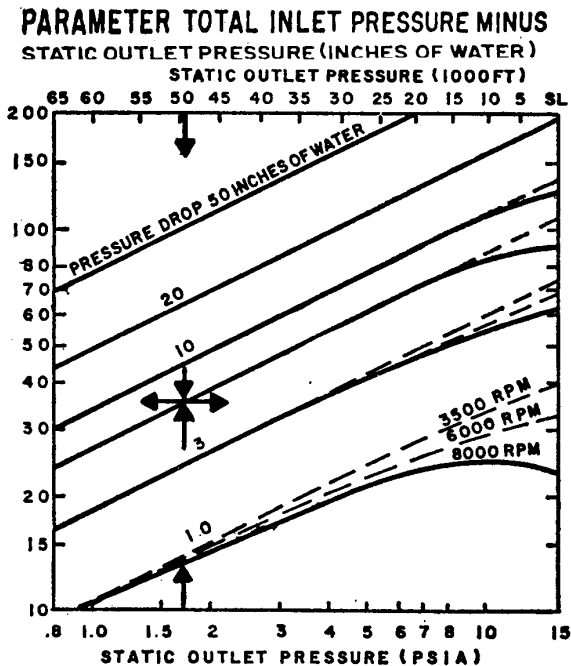
514.2 Thermal Limits

A generator designed for minimum weight will operate at close to the maximum safe temperature of its insulation. Therefore, it inherently does not have much thermal overload capacity. This is especially true of direct-current generators, where much of the weight is in copper carrying load current (armature winding, commutator, compensating field, and commutation-pole winding). In a 120/208 volt alternating-current generator a smaller proportion of machine weight is in armature copper as compared to direct-current machines, so that it is relatively easy to provide sufficient copper to carry the overload required without exceeding safe temperatures. This is why direct-current requirements have not been specified to the extent that alternating-current requirements have.

In general, machines are not self-protecting in the matter of overloads. Except at minimum rated speed, variable speed direct-current machines are usually capable of putting out load currents that will quickly cause destruction. Even at minimum speed the excitation circuit may be destroyed.

514.3 Volt-Ampere Limit

The maximum power which a generator will supply is shown by the external characteristic of the generator. A typical curve for a direct-current machine is shown in Figure 514.3-1. The volt-ampere charac-



GENERATOR RATING CHART
 MANUFACTURER X
 TYPE NO. Y
 NAME PLATE DATA
 DC AC
 VOLTAGE 30 VOLTS
 KVA _____ CURRENT 300 AMPS
 PF _____
 SPEED 3000 - 8000 RPM
 REFERENCE VALUES
 AIR WEIGHT FLOW 925 LB/MIN
 HEAT REJECTION 4200 WATTS
 OUTPUT _____ KVA OR 300 AMPS
 AT 30 VOLTS
 AIRFLOW CONFIGURATION
 INLET DUCT DIA. 3 INCHES
 INLET BLAST CAP RADIAL
 EXIT DESCRIPTION NO EXIT SHROUD
 OTHER PERTINENT DATA

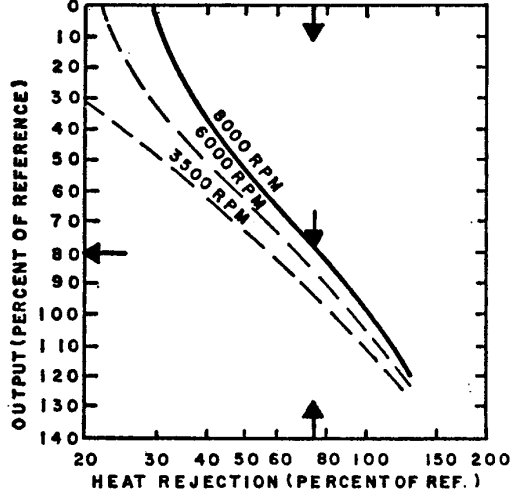


Figure 512.2-3 Generator Rating Curves.

teristic varies with speed and with the resistance in the shunt-field circuit, in this case 0.75 ohm is in the field circuit external to the generator. These characteristics are used to determine system behavior under fault conditions, they may also be used to determine the required strength of the components of the generator drive. Curves for alternating-current generators are similar except that power factor is another parameter. Also, as alternating-current generators have exciters of some type, the curves usually do not fold under as do the direct-current curves taken on self-excited machines.

515 Operation Under Subnormal Conditions

Some operating conditions may require that the generator provide power at less than rated speed and/or less than rated ventilation.

A blast-cooled generator may be required to supply power at less than normal ventilation, particularly when an aircraft is taxiing or stationary. In some cases, the use of separate blowers or an integral fan to supply adequate ventilation may be necessary during operation on the ground.

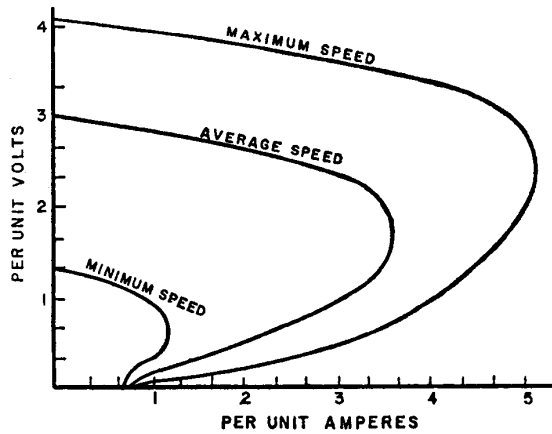


Figure 514.3-1 Direct-Current Generator Volt-Ampere Characteristic Curves.

With some engine and nacelle configurations it may be found that negative differential air pressures will exist under certain taxi or low-speed flight conditions. This is detrimental to proper cooling and will require careful study. A possible solution is to provide an alternate duct inlet and/or outlet, with an automatic flapper valve operated by differential pressure to select the desired air path.

516 Transients and Fault Clearing

To permit calculation of system behavior under transient conditions, generator characteristics must be known. These will be considered for direct-current and alternating-current generators separately.

516.1 Direct-Current Generator Transient and Fault Current Performance

The imposition of a shock load on a direct-current generator results in an initial peak current followed by a steady-state value of current and voltage determined by the generator external or volt-ampere characteristic. The initial peak current and its associated terminal voltage may be determined for any load by the use of the generator "transient" volt-ampere characteristic. This "transient" characteristic may be derived from the curves and can be simulated by assuming the presence of an internal resistance equal to $\Delta E/\Delta I$ (Figure 516.1-1) which is equal to armature circuit resistance, plus a component which is a function of generator speed. Thus the transient resistance is a fictitious value of resistance considerably greater than real armature resistance and dependent on generator speed. This fictitious resistance may be used to calculate maximum system short-circuit currents for selecting interrupting devices. The initial peak current is reached approximately 0.01 second following imposition of the load and the transition from the initial peak current value to the steady-state value has been observed to fall consistently in the region of 0.05 to 0.10 second. The steady-state value will be maintained for a period dependent on the thermal and commutating ability of the generator.

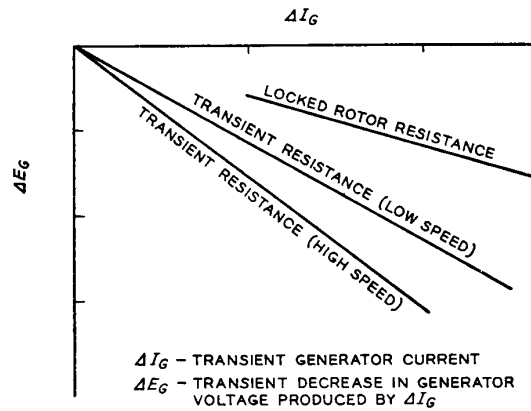


Figure 516.1-1 Transient Volt-Ampere Characteristic Direct-Current Aircraft Generator.

516.2 Alternating-Current Generator Transient and Fault Current Performance

Minimum steady-state short-circuit current is usually specified to insure proper operation of protective devices. Commonly specified is 300 percent rated current at average rated speed for narrow-speed range machines and 250 percent rated current at minimum rated speed for wide-speed-range generators.

Transient performance is calculated from the generator impedances involving the synchronous, transient, subtransient, negative-sequence and zero-sequence reactances. Unbalanced loading and single-phase operation can be analyzed, using these constants. Maximum transient recovery voltage should be considered.

517 Direct-Current Generators

Direct-current primary systems predominated in the past, but are now generally specified only for small aircraft. The standard direct-current system voltage is 28, with 30 volts the generator rating. Smaller generators are available for the 12-volt systems. Some 120-volt generators have been used, although there has been only limited interest in direct-current systems over 30 volts because of commutation and switching problems. Thirty-volt generators are available in many ratings, typical being 100, 200, 300 and 400 amperes; and several speed ranges, such as 3000 to 8000 revolutions per minute, 4000 to 8000 revolutions per minute and 2500 to 4500 revolutions per minute. (But see Section 513.1.)

517.1 Generator Field Design

Fields of most 30-volt direct-current generators were originally designed to operate with a carbon-pile voltage regulator having the following characteristics:

Minimum resistance, including wiring	1.25 ohms
Maximum resistance	35 ohms
Maximum current, steady-state	8 amperes
Maximum power dissipation	90 watts

Present-day transistor regulators, which in most cases have replaced the carbon-pile regulators, were designed to operate with these same field windings.

518 Alternating-Current Generators

The alternating-current generator has become the predominant primary electrical power source on modern aircraft. Increased electric loads on aircraft have required the use of higher-voltage systems. With many of the loads requiring alternating-current power, the use of alternating-current generators has been desirable.

Consequently, for the sake of standardization, there has been considerable development on three styles of alternating-current generators: (1) 120/208-volt, 3 phase, 380-420 Hz, (2) 120/208-volt, 3 phase, 400-800 Hz, and (3) 120/208-volt, 3-phase, 320-480 Hz; (4) for missile work, 3200 Hz has been proposed, no voltage or phase standard has been adopted. Common machine ratings are: 9, 15, 20, 30, 40, 60, 90 and 120 kVA.

Formerly, the most widely used generators included an integral direct-current exciter on a common shaft with the rotor of the alternating-current generator, or were self-excited with a portion of the output of the generator being rectified to supply controlled field current. Many of these generators are still in use.

Present-day brushless alternating-current generators consist of three sections driven by a common shaft. A permanent magnet generator employs a multi-pole rotating permanent magnet to develop alternating current in its stator. This is rectified to supply regulator power and excitation power for the exciter field on the stator of the exciter section. The rotor of the exciter develops alternating current which is rectified by rectifiers to supply excitation to the rotating field of the main alternating-current generator section. The generator alternating-current output is developed in the stator of the main section. Permanent-magnet-type pilot exciters, serving sometimes also as a control power source for the generation channel, are finding increased application.

518.1 Regulating Field Design

Whereas formerly the regulating fields of integral direct-current exciters were designed to operate with carbon-pile, magnetic-amplifier, or transistor-voltage regulators, present-day brushless alternating-current generators employ transistor or silicon-controlled-rectifier voltage regulators almost exclusively. Regulators are usually designed to work with a given generator. This is necessary to optimize the transient performance of the generator-regulator combination as well as provide other specified performance requirements such as fault current limiting and power limiting.

Generating systems being designed for use on large aircraft, with long runs for the permanent-magnet generator and exciter field cables, are employing higher voltage permanent-magnet generators than those used for smaller aircraft. By working the entire excitation system at a higher voltage, the required field current levels are reduced. This permits the use of smaller lighter cables without sacrificing overload performance.

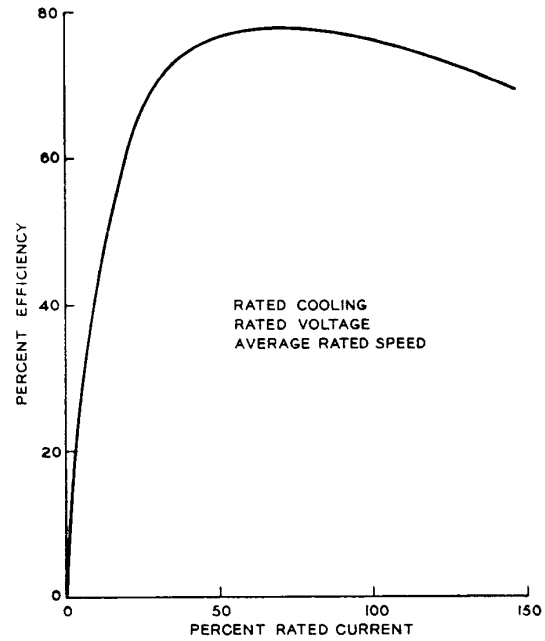


Figure 519.2-1 Efficiency versus Load.

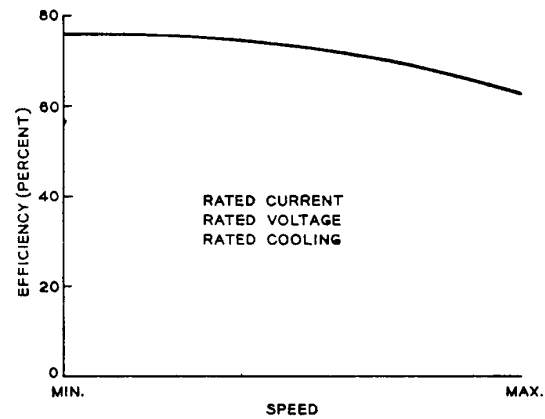


Figure 519.2-2 Efficiency versus Speed.

519 Performance Data

To evaluate a generator application, the user needs performance data covering important factors. The following lists are typical of the data desired. Obviously some factors apply only to particular types of machines. Many of the items have been discussed in the sections above.

519.1 Direct-Current Generators

The following information is generally desired:

- Brush life at various altitudes, speeds, and loads.
- Airflow versus head at various speeds.

Regulation curves, field current versus load at various speeds.

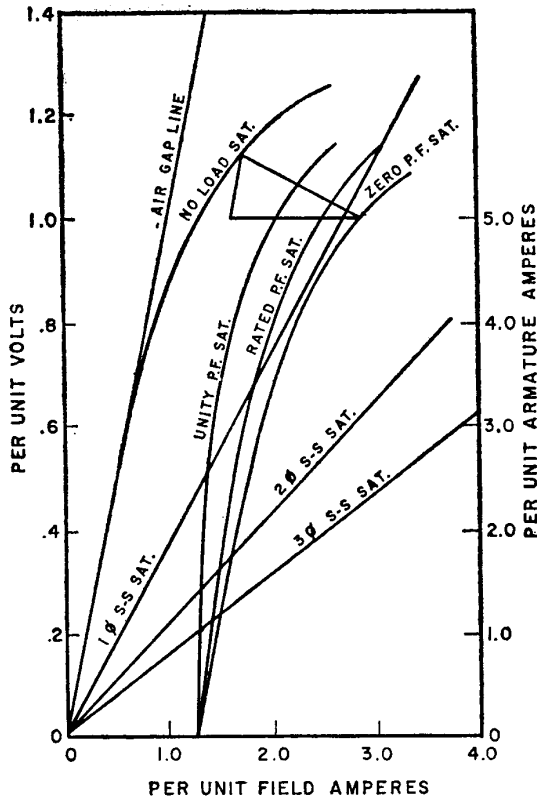


Figure 519.2-3 Alternating-Current Generator Saturation Curves.

Unregulated volt-ampere characteristic (Figure 514.3-1).

Efficiency at various loads and speeds.

Underspeed performance.

Altitude, temperature and air pressure rating data (Figure 512.2-3).

Short-time overloads.

Saturation curves, voltage versus field current at no load and rated load.

Resistances.

The following additional data may be useful in making more complete and accurate system studies:

Short-circuit oscillograms.

EMI and ripple voltage.

Shunt field time constant.

Maximum speed for regulation.

519.2 Alternating-Current Generators

The following information is generally desired:

Brush life at various altitudes, speed and loads if brushes are used.

Airflow versus head at various speeds.

Heat rejection if liquid cooled.

Voltage regulation under various operating conditions.

Corona.

EMI content.

Harmonic content (wave form).

Voltage unbalance under unbalanced loading.

Short-circuit oscillograms.

Parallel operation.

Efficiency at various loads and speeds (Figures 519.2-1 and 519.2-2).

Underspeed performance.

Steady-state short-circuit current (Figure 519.2-3).

Synchronous reactance in direct and quadrature axes.

Negative-sequence impedance.

Zero-sequence impedance.

Altitude, temperature and air pressure rating data (Figure 512.2-3).

Short-time overloads.

Saturation curves (Figure 519.2-3).

Unregulated volt-ampere characteristics.

Resistances, hot and cold.

The following additional data will be useful in making more complete and accurate system studies:

Transient and subtransient reactances in direct and quadrature axes.

Time constants.

Maximum speed for regulation.

Amplitude modulation.

Frequency and voltage modulation.

520 PRIME MOVERS AND CONSTANT-SPEED DRIVES

521 Main Propulsion Engines

521.1 Reciprocating Engines

The reciprocating engine is normally provided with one or more 5-inch-diameter bolt-circle round mounting flanges, rotating clockwise, on which generators of up to approximately 65 pounds in weight, 15 inches in length, and 6.5 inches in diameter can be mounted. These mounting pads are usually as described by Government Design Standard AND-20002. The axes of rotation of these mounting flanges are usually parallel to the axis of rotation of the engine; however, in some instances these axes are at other angles and most aircraft generators are capable of operating at any angle including the vertical. The gear ratio between the generator drive and the crankshaft on current reciprocating engines is usually about 3:1, which results in the following approximate operating speeds of generators:

Engine idling	1500-1800 r/min
Aircraft minimum cruise	3300-5300 r/min
Aircraft takeoff	8000-9000 r/min

Some applications involving sustained high-speed engine operation require a lower gear ratio to permit full-capacity output of the generator. Older large reciprocating engines and some current small engines are provided with a variety of drive means and ratios

for generators, predominate among which are the 5-inch diameter bolt-circle drive with a 1.5:1 ratio to crankshaft speed and a four-stud square drive with the same ratio. The operating speeds of generators on these drives are one-half these indicated in the tabulation above.

521.2 Turbo-Jet Engines

This type of engine is normally provided with one or more 5-inch and/or 10-inch bolt-circle round mounting flanges for generators. The 5-inch flange has the same capabilities as for reciprocating engines, and the 10-inch flange, whose rotation is also clockwise, can mount generators with constant-speed drives of up to 225 pounds in weight, 20 inches in length, and 11 inches in diameter. Some types of engines have a single 5-inch mounting flange on which must be mounted a combination starter-generator. These mounting pads are usually as described by Government Design Standards AND-20002, AND-20006 and AND-20007. The axes of rotation of the generator drives are usually parallel to the axis of rotation of the engine, and the drive is frequently located in the engine air inlet duct, thus complicating the cooling and inspection problem. The gear ratio between the generator drive and the engine rotor varies considerably due to the wide range of rotor maximum operation speeds which are primarily limited by turbine blade tip velocity; however, the generator drive input speed is usually over a 2-to-1 speed range with 6000-6400 revolutions per minute at 75 percent nominal sea level static output of engine. The speed versus thrust characteristics of turbo-jet engines are such that the generator drive input speeds are approximately as follows at SEA LEVEL STATIC CONDITIONS:

Idling	1700-2900 r/min (28-45%)
Minimum Cruise	3800-5000 (63-78%)
75 per Output	6000-6400* (100%)
Full Power	6200-7400 (103-115%)

As air speed and altitude are increased, the engine speed approaches the maximum for all operating conditions, including idling; hence, the generators may operate at a substantially constant speed under most aircraft flight conditions.

521.3 Turbo-Propeller Engines

The turbo-propeller engine is normally provided with the same generator drive facilities as described for turbo-jet engines above; however, the drives are usually located on a gear box which also drives the propeller. This gear box is sometimes clutched to the engine after it has been started, accordingly electric power from engine-driven generators may not be available until the gear box is clutched into the engine. Some turbo-prop engines are substantially constant-speed with steady-state speed being maintained with an accuracy of the order of one percent under all normal flight conditions. During takeoff the speed may be as much as 10 percent above normal but this will

*This is a tolerance in engine-to-generator-drive gear ratio rather than a speed variation.

not occur when maximum power is being delivered by the engine at appreciable flight speeds, as the speed is raised at the takeoff for the purpose of increasing propeller efficiency at zero and low flight speeds.

The so-called constant-speed alternating-current and direct-current aircraft generators can be driven directly from such turbo-propeller engines and attain nearly the same performance as when they are driven by a constant-speed drive or an auxiliary power plant. Nevertheless, it should be noted that direct-driven alternating-current generators cannot be paralleled because it is considered to be impractical to control the engine speed and phase angle with accuracy sufficient for this purpose. Although essentially constant frequency may be obtained in this manner, the attainment of any *particular* frequency, such as 400 Hz, will require close coordination of engine governed speed and gear ratio. Further, not all turbo-propeller engines are constant speed; in particular, the twin-spool or free-turbine engines tend to be wide speed range.

522 Auxiliary Power Units

522.1 Reciprocating Power Plants

The auxiliary reciprocating power plant is often used to drive aircraft-type generators to supply power during ground operation of the aircraft and also to provide electric power at low altitudes, particularly as a standby for main-engine-driven generators during landing and takeoff operations. Operation at altitudes above a few thousand feet requires either super-charging or a reduction in output. In some applications of auxiliary power plants, only stowage is provided and the power plant is always removed to the ground prior to operation. The relatively high fuel consumption of reciprocating power plants (0.6 to 0.8 pound per horsepower hour), when compared to that of main propulsion reciprocating engines which is approximately 0.5 pound per horsepower hour, usually makes continuous in-flight operation of auxiliary power plants uneconomical from the weight standpoint. Where the capacity of the auxiliary drive engine is inadequate to drive the generator at overload conditions, control means must be provided to limit the generator output to the capacity of the drive engine. The main propulsion engine can usually provide this overload capacity when required without appreciably affecting its propulsion function. During main propulsion engine idle and let-down flight conditions, the main-engine-driven generator has little or no overload capacity available due to the low speed of operation. Typical reciprocating type auxiliary power plants are as follows:

Continuous Rated Output*	Gen. Drive Speed	Wt. with Generator
2 kW	3400 r/min	113 lbs
5	6500	122
10	4800	205
30	3600	525

* Little or no overload capacity available.

522.2 Turbine Power Plants

522.21 The gas-turbine auxiliary power plant has the same applications as described for the reciprocating type above. However, this type has the advantage of lighter weight than the reciprocating engine; but the fuel consumption is higher (1.5 to 2.0 pounds per horsepower hour), the life expectancy is shorter, and operation at altitude more difficult than with the reciprocating engine. A typical gas-turbine power plant delivers 40 kilowatts continuously from a generator operated at 6000 revolutions per minute, and weighs 285 pounds.

522.22 Air-turbine motors may be used to drive generators when a source of compressed air can be made available, either by bleeding from the aircraft main-propulsion-engine compressor or from an auxiliary compressor. The compressed air is used at pressure ratios in the range of 6:1 to 8:1 and at a temperature of 250 to 350°F. Extraction of power from the main engine by airbleed is usually less efficient than by other generator drive means; however, in specific instances the airbleed system may be preferable for some of the following reasons:

- a. Propulsion engine has such a mismatch between compressor and turbine that it is necessary for some air to be bled, thus resulting in a power extraction at less penalty than from a more properly matched combination.
- b. Aircraft operating altitudes are below engine design altitude, which results in capability of airbleed without appreciable sacrifice in aircraft performance.
- c. The ability to manifold air from several engines to fewer generators results in reduced electric system weight.
- d. The combination of the air-driven generator system with a starting system, and/or a system to provide power when main engines are not operating, results in a combined system saving.
- e. A short flight time requirement makes the light weight of the air-drive components, rather than their efficiency (fuel weight), the governing factor.

The air-turbine motor can be governed to nearly any reasonable steady-state accuracy; however, it is relatively "soft" drive due to the compressibility of air and the inertia of the air in the line from the air source. It does not have much overload capacity unless deliberately designed oversize. With a turbine designed to match the overload rating of the generator, during 100 percent load change the speed may change 3 percent and take one second to return to rated value. A typical air duct for a 70-horsepower air turbine is 5.0 inches inside diameter, 40 feet long, is thermally insulated and weighs 34 pounds. The 70-horsepower air turbine, complete with governor and 10-inch bolt circle drive, operating at 6000 revolutions per minute (turbine speed about 35,000 revolutions per minute), weighs 57 pounds and requires 105

pounds per minute of 217°F air at 78 inches of mercury absolute inlet pressure for full output at sea level.

522.23 Gas-turbine motors are practically identical to the air-turbine motor except that fuel is injected and burned, thus increasing the efficiency and output per unit size and decreasing the weight considerably in the larger sizes. The same considerations are involved in the application of gas-turbine motors as for air-turbine motors. The use of gas-turbine motors may have greater advantage at higher horsepowers above, say, 50 horsepower. A typical gas-turbine motor of 125 horsepower output with a 10-inch bolt-circle drive, operating at 6000 revolutions per minute, weighs 85 pounds and requires 67.5 pounds per minute of 330°F air at 90.5 inches of mercury absolute inlet pressure and 1.1 pounds of fuel per minute for full output at sea level.

522.24 A gas-turbine compressor is a gas turbine with an oversized compressor from which air is bled to operate air or gas-turbine motors to drive generators. The combination of the compressor and the motor comprises an auxiliary power system which is independent of propulsion engine operation. The output air of the gas-turbine compressor may be used for propulsion-engine starting (with air-turbine starters) or for other auxiliary uses, such as air conditioning. A gas-turbine compressor capable of supplying sufficient air to operate a 25-horsepower air-turbine motor or a 75-horsepower gas-turbine motor at full load at sea level weighs 175 pounds and requires 1.61 pounds of fuel per minute to deliver 43 pounds of 337°F air at a pressure of 86 inches of mercury absolute at sea level.

523 Transmissions

The term "transmission" is applied to an assembly which forms a link between the main propulsion engine and the driven generator. It is variously known as a generator drive, a remote shaft, or a torque converter.

523.1 Constant-Speed Transmissions

This type of transmission has the characteristic of relatively constant-speed output over a range of input speeds. Its primary purpose is to achieve a so-called constant-frequency electric system, using the main propulsion engine as a prime mover over its operating speed range. The output speed is normally 6000 or 8000 revolutions per minute due to the predominance of generators designed for operation at these speeds. Output speeds of 12,000 revolutions per minute are also available at the present time.

The output speed can be held to any reasonable steady-state accuracy, and speed transients due to 100 percent load changes can presently be limited to less than 5 percent with a duration not to exceed one second. Present constant-speed transmissions are predominantly of the hydraulic or combination hydraulic-mechanical type, with development work being done on pure mechanical types. Hydraulic pressures of up

<i>Configuration</i>	<i>Continuous Output</i>	<i>Typical Dry Weight*</i>	<i>Input Speed</i>	<i>Output Speed</i>	<i>Efficiency</i>
Cartridge	85 hp	57 lbs	3000-9000 r/min	6000 r/min	77-90%
Sandwich	50	65	2800-6500	6000	75-88
Package	85	85	2800-8500	6000	72-88

*Parallel operation requires additional drive components weighing approximately 11 pounds per drive.

to 5000 pounds per square inch are used in some hydraulic types. Non-flammable fluid is also used.

523.11 In unit-type constant-speed transmissions the primary functions are accomplished within one assembly. The unit may be a cartridge inserted into the engine, using engine services such as oil cooling; it may be mounted on the propulsion-engine drive as a sandwich between the drive and the generator; or it may be a separately-mounted package driven by a constant-ratio transmission.

The cartridge-type drive is probably the most desirable, for it actually results in an engine with a constant-speed power takeoff for generator operation. The cartridge-type drive is presently confined to turbo-jet engines, and generators are mounted directly on the output end of the cartridge which is in reality a portion of the engine rear section. It is doubtful whether generators of the size normally required for constant-frequency systems could be directly mounted on a cartridge-type drive incorporated into a reciprocating engine because of weight and overhang problems under the vibration conditions encountered; however, a constant-ratio transmission might be used to operate a generator remotely from the cartridge. The sandwich-type drive can be used as a substitute for the cartridge when engine design cannot be changed and when total overhang of the drive and mounted generator do not exceed engine limits. This latter limitation usually eliminates consideration of the drive for use in reciprocating-engine installations; however, the use of a constant-ratio drive to operate the generator remotely from the sandwich will considerably reduce the overhang moment. The package-type drive is also in common use and can be used with any type of engine; however, it is the heaviest of the unit-type configurations.

523.12 In split-type constant-speed transmissions the functions of a constant-speed and a remote transmission are combined into one system, usually consisting of one or more hydraulic pumps mounted on the main propulsion engine(s) connected by hydraulic lines to one or more hydraulic motors which drive generators. Either the engine-mounted pump(s) or the hydraulic motor(s) driving the generator(s) must be of the variable displacement type, and both may be in some systems. The use of a variable-displacement engine-mounted pump, rather than a fixed-displacement pump, results in more efficient utilization of hydraulic system components due to operation at approximately the same maximum pressure at all input speeds. However, variable-displacement pumps are

larger and heavier than constant-displacement pumps. In addition, output-speed governing by means of controlling the displacement of input pumps in a multiple-pump installation is a rather complex problem.

The split-type transmission may also be used as a starting system either by introducing hydraulic power into the system and operating the system input pumps as hydraulic starting motors or by operating the generator(s) as starting motor(s) and reversing the hydraulic cycle.

The advantages of a split-type hydraulic drive are most apparent in the following situations:

- Space limitations prohibit use of a unit-type transmission.
- A combination starting and generator-driving system can be utilized.
- A multiple-pump installation will enable a reduction in the number of generators without a sacrifice in the number of prime movers available for generation of electric power.

The following are typical split-type transmissions:

<i>Continuous Output</i>	<i>Dry Weight*</i>	<i>Input Speed</i>	<i>Output Speed</i>	<i>Efficiency</i>
35 hp	120 lbs	2500-9000 r/min	6000 r/min	75-83%
70	206	2500-9000	6000	75-83

*This dry weight includes all components such as intercoolers, reservoirs and valves; however, it does not include fluid or lines. In a typical installation having 10-foot separation between pumps and motors, the working weights would be approximately 45 pounds and 80 pounds above the dry weights for the 35- and 70-horsepower transmissions respectively.

The 70-horsepower transmission comprises two separately-mounted 5-inch mounting-flange input pumps connected hydraulically to two hydraulic motors geared together and driving two 10-inch diameter generator mounting flanges.

On present split-type hydraulic transmissions, a gear box is incorporated into the hydraulic pumps and motors, as it is not possible to operate them at the high speed required for good generator design. The hydraulic components are being improved with regard to high-speed operation, and an appreciable weight saving will be gained when the gearing is eliminated.

523.13 Co-axial Transmission. A more recent development in constant-speed drives has been the co-axial drive. In this configuration, the drive mounts on one side of the engine gear box and receives its input power through the outer of two co-axial shafts. The constant-speed output appears on the inner of the two shafts. This runs back through the gear box and drives the generator which is mounted on the other side. The advantage of this configuration is that either the drive or the generator may be removed for servicing without removing the other.

523.14 Integrated Drive-Generator (IDG). In this recent development, the constant-speed drive and the generator are integrated into one unit resulting in a weight saving because of the packaging economics and the elimination of a bearing. Further weight savings are realized by the use of oil-sprayed cooling and higher speed (12,000 revolutions per minute plus) generators.

523.2 Constant-Ratio Transmissions

523.21 The simplest method for driving a generator remotely from a main propulsion engine, not capable of mounting it directly, is by the use of a drive shaft. When a shaft is to be used, space must be found for both the shaft and the large generator in close proximity to the engine. The design of the shaft must be such that it will allow for engine movement but at the same time neither introduce nor amplify torsional vibrations. These two requirements add up to the necessity for the use of constant-velocity universal joints in most applications. The engine movement and installation allowance is usually of the order of 1.50 inches for axial variations and 10 degrees for misalignment between input and output ends of the shaft. The torsional requirement indicated above dictates that the natural frequency of the shaft must be low, and it is usually below 15 Hz on shafts designed for driving generators from reciprocating engines. This natural frequency is established under the condition that the shaft be mechanically loaded with the smallest polar inertia it will be driving when installed.

Several types of constant-velocity joints have been used in various shaft designs, such as spherical gears (Barcus), floating balls (Rzeppa) and diaphragms. It is necessary to provide oil circulation and cooling for some of the more complex types of joints because of their losses. Typical weights of remote shafts incorporating two diaphragm-type joints and having a 5-inch bolt-circle input flange and a 10 inch bolt-circle output flange are as follows:

<i>Horsepower</i>	<i>Speed</i>	<i>Length</i>	<i>Weight</i>
180	4000-9000 r/min	18 in.	25 lbs.
180	4000-9000	36	30
250	4000-9000	18	30
250	4000-9000	36	35

523.22 When engine limitations prevent direct mounting of a generator, and space limitations preclude the use of a remote shaft, it is possible to drive genera-

tors remotely using a system similar to that described above through split-type constant-speed transmissions, except that all pumps would be of constant-displacement type. This saves weight and gains simplicity in applications when constant speed is not essential. A typical hydraulic constant-ratio transmission delivers 30-horsepower continuously over an input and output speed range of 4000 to 8000 revolutions per minute, and has a dry weight of 100 pounds, with an efficiency of 78 to 86 percent.

In a typical installation having a 10-foot separation between pump and motor, the working weight would be about 45 pounds more than the dry weight.

523.23 In many installations it is necessary to provide gear boxes to alter the engine drive configuration to suit the aircraft requirements. These gear boxes may be used in conjunction with a transmission of some sort or may be in the form of a sandwich between the engine and generator(s). If they are of the latter type, particular attention should be given the weight and overhang-moment limitations of the engine which cannot be exceeded by the resultant combination of generator(s) and sandwich gear box. In particular installations, however, it may be possible to exceed the recorded engine limitation in those instances where the airframe G limitations are less than those for which the engine limitation was established (usually 10G). In the design of gear boxes, the effect of torsional vibrations, either introduced or amplified by the gearing, should be considered, as they may have detrimental effects on the generator. If the gear box requires external lubrication, consideration should be given to providing an individual lubricating system rather than possibly compromising the integrity of the main engine lubrication system by utilizing it for the gear box. The efficiency of a gear box can be approximated by assuming one percent loss of power per gear mesh.

523.24 On certain aircraft applications, particularly helicopters, the only apparent means for driving generators has been by the use of belt drives. In such installations, it is essential that the generator be installed so that radial belt load is not applied directly to generator bearings unless the generator is specifically designed to withstand such loads. In addition, the effect of various service conditions on belt performance should be evaluated, as should the effect of torsional vibrations in the system comprising the drive, the belt, and the generator.

524 Speed Governing

In order to obtain "constant frequency" from generators of conventional design, they must be operated at fairly constant speed. The accepted steady-state frequency range for a "constant frequency system" is 380-420 Hz, although the present trend is toward 400 ± 5 Hz or narrower limits. Some devices, such as gyros and computing equipment, require a much narrower frequency range; however, they are normally supplied from a "private" power supply having frequency precisely controlled, sometimes to within one part in ten thousand. The constant-frequency

system may involve only one power source, in which event the governing problem is not complicated by paralleling requirements. On the other hand, the system may contain two or more sources driven by relatively constant-speed prime movers, such as turbo-propeller engines, where parallel operation may not be possible without introducing disadvantages outweighing the advantages of parallel operation. The predominant type of constant-frequency system is one having multiple sources operating in parallel, governed to share the real load within 5 to 10 percent under steady-state conditions, and to maintain frequency between the steady-state limits of 390 and 410 Hz under all operating conditions. Regardless of whether or not the system is paralleled, the frequency transients due either to normal system load changes, or to causes external to the electric system, must be minimized and should not exceed the order of 4 percent frequency change, with recovery within 0.5 percent of steady-state frequency in about 0.6 second. This transient performance is difficult to achieve without using some sort of "anticipation" principle in the governor, and it is further aggravated in the case of some prime movers because of their own acceleration rates, which, in the case of air and gas-turbine motors, may be limited by the inlet air-duct size and configuration.

525 Vibration

525.1 Torsional Vibration

The operation of engines, transmissions and gear boxes usually produces torsional vibrations which are impressed on the driven device. The driven device may be either built strong enough to withstand the torsional, as is done in the case of some small engine-driven generators and a few large transmission-driven generators, or built using a flexible drive and damping mechanism, usually operating above resonance. above 10-35 Hz. This latter approach is used in most generators as it can be accomplished with less weight than by using a sufficiently-strong rigid drive; furthermore, the modulation of the generator output is lessened during normal operation of the drive above resonance. A version of the damped flexible drive is the so-called "clearance damper" which allows a few degrees of relatively-free torsional motion of the drive input before the flexible drive comes into play. By using this principle, it is not necessary to provide a damping device capable of continuously absorbing the torsional energy because the clearance provided exceeds the amplitude of the torsional vibration encountered during normal continuous operation, and the flexible drive operates only during rough operating conditions such as starting, misfiring, and perhaps idling. It should be recognized that any shaft flexibility or freedom introduces the probability of having small-amplitude frequency modulation under variable load or variable driving torque conditions, which may contribute to or initiate instability in parallel generator operation. Current practice is to use a rigid stub-shaft on generators associated with turbine engines.

There are some types of generator driving devices which are relatively free of torsional vibrations, such as gas turbines and air turbines. This condition leads

to the consideration of generators specifically designed for such devices with simple rigid-type drives, thus saving some weight and complexity. The same result is sometimes achieved by designing the flexible drive mechanism in such a way that it can be added or removed as the installation requires.

The torsional amplitudes encountered during normal continuous operation of reciprocating engines are of the order of 0.5 to 2.0 degrees double amplitude, with peaks of up to 6 to 8 degrees encountered during idling and exceptionally rough engine operating conditions. The torsional amplitudes encountered in turbo-prop engines, where the generator is mounted on the propeller gear box, do not exceed 0.5 degree double amplitude.

525.2 Translational Vibration

Some of the most difficult problems in the design and operation of engine-mounted generators arise from the detrimental effects of translational vibration. The most generally accepted method of minimizing such problems is by designing the generator so that its natural frequency as a rigidly-mounted beam, and the natural frequency of its component parts, are as high as practicable, with a minimum tolerable value of 200 Hz. Accelerations measured on reciprocating-engine-mounted generators are of the order of 20 to 50G under various engine operating conditions, while those measured on generators mounted on the propeller gear box of the turbo-prop engines are of the order of 5 to 30G.

526 Continuous High-Speed Operation

Most of the available designs for engine-driven generators were intended for use only under the operating speed conditions encountered on reciprocating engines, which are usually below 6000-7000 revolutions per minute for all periods of operation in excess of 15 minutes, with higher speeds up to 8000-9000 revolutions per minute encountered for only short periods, such as during takeoff. Turbine engines and reciprocating engines in special applications such as helicopters, have the characteristic of continuous operation at or near their maximum speed rating. If the generator drive ratio is selected such that the top continuous engine speed corresponds to the top generator design speed for reciprocating engine service, then it is usually necessary to reduce the rating of the generator for the turbine-engine service. The reduction in rating is of the order of 25 percent for continuous operation at 8000 revolutions per minute, using a generator designed for operation over a range of 3000 to 8000 revolutions per minute in reciprocating engine service.

530 VOLTAGE REGULATION AND LOAD DIVISION

531 Voltage Regulation

Choice of operating voltage and frequency is discussed in Section 300. Maintenance of system voltage within tolerable limits is discussed in Section 140. Generator voltage is maintained at a predetermined level within limits at a selected point by a generator voltage regulator. The voltage at any other point in the system is the regulated voltage minus the IR or vector IZ drop between this

point and the point of regulator sensing. In a three-phase system, an additional voltage deviation is caused by unbalanced loads acting through the system impedances. The generator voltage regulator has no control over voltage unbalance between phases, resulting from this effect. (Section 451)

In special cases it may be desirable to have the regulator maintain a given voltage at some point other than the point of connection of the sensing circuit. This is often desirable with ground power supplies to compensate for the impedance drop in the connecting cables. The use of compensator circuits for this purpose is discussed in Section 532.51.

In general, the present design generator voltage regulator is required to maintain the voltage at the point of regulator sensing within limits of approximately ± 1.5 percent, including all environmental factors. On direct-current systems, the desirable voltage level may be affected by battery operating conditions as discussed in Section 560. Figure 531-1 shows the generator voltage variation expected in 28-volt direct-current electric systems. Figures 531-2 and 531-3 show the generator voltage variation expected in 115-volt alternating-current electric systems.

532 Voltage Regulators

Specifications usually define requirements for operating conditions and, for unlimited service in all types of air-

craft, require continuous duty under wide variations in altitude, temperature, humidity, sand and dust, salt spray, vibration, and operating position. Specification performance requirements define warm-up period, permissible steady-state voltage variation, recovery period following generator load changes, and ripple voltage initiated by the regulator. The unit is required to operate satisfactorily with a given generator, or resistance range and heat dissipating ability may be specified where the regulator is required to be interchangeable among several generator designs. In this case it is usually necessary to take precautions to prevent the possibility of regulator "hunting" when the regulator is controlling some generators. Mounting dimensions, weight and space limitations, voltage adjustment location, and voltage adjustment range may also be specified.

Voltage regulators used in aircraft are usually of the transistor type for direct-current systems. Regulators for alternating-current systems generally are of three types.

- a. Direct magnetic amplifier output.
- b. Silicon controlled rectifier (SCR) output.
- c. Transistor.

Semiconductor advancements in recent years have made the SCR and transistor regulators the most common types. Generally lower cost and lighter weight are realized with these types.

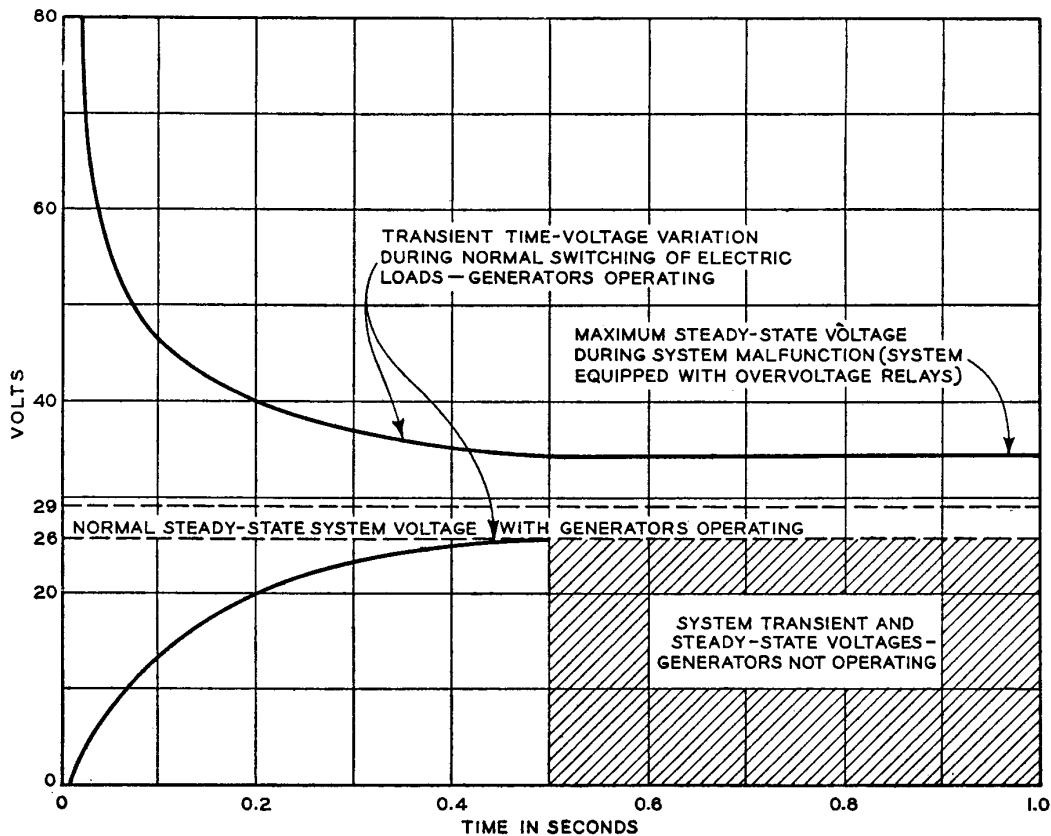


Figure 531-1 Typical Time Voltage Relationships in Direct-Current Systems.

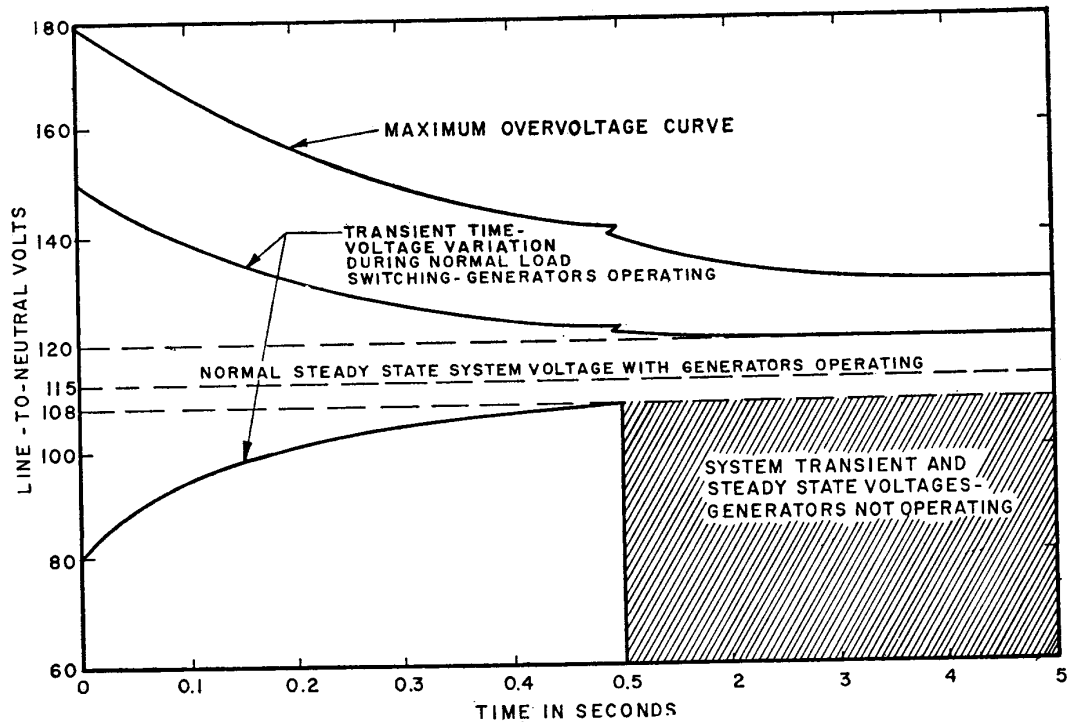


Figure 531-2 Typical Time-Voltage Relationships in Alternating-Current Systems Using Carbon-Pile Regulators.

All three types exhibit high gain characteristics and consist of completely static circuitry.

532.1 Carbon-Pile Voltage Regulators for Direct-Current Systems

The use of high-field-current generators (maximum field current of nine amperes) resulted in the adoption of carbon-pile voltage regulators for use in older aircraft. These regulators are variations of a type developed by the Newton Brothers, Ltd., Derby, England. The electric circuit of the Newton regulator is shown in Figure 532.1-1. The regulator consists of: a magnet case containing the voltage coil, a tapered ring for support of the armature spring assembly, an armature and radial spring leaf assembly, a carbon pile in a ceramic or glass tube, a pile housing and an adjustable pile-compression screw.

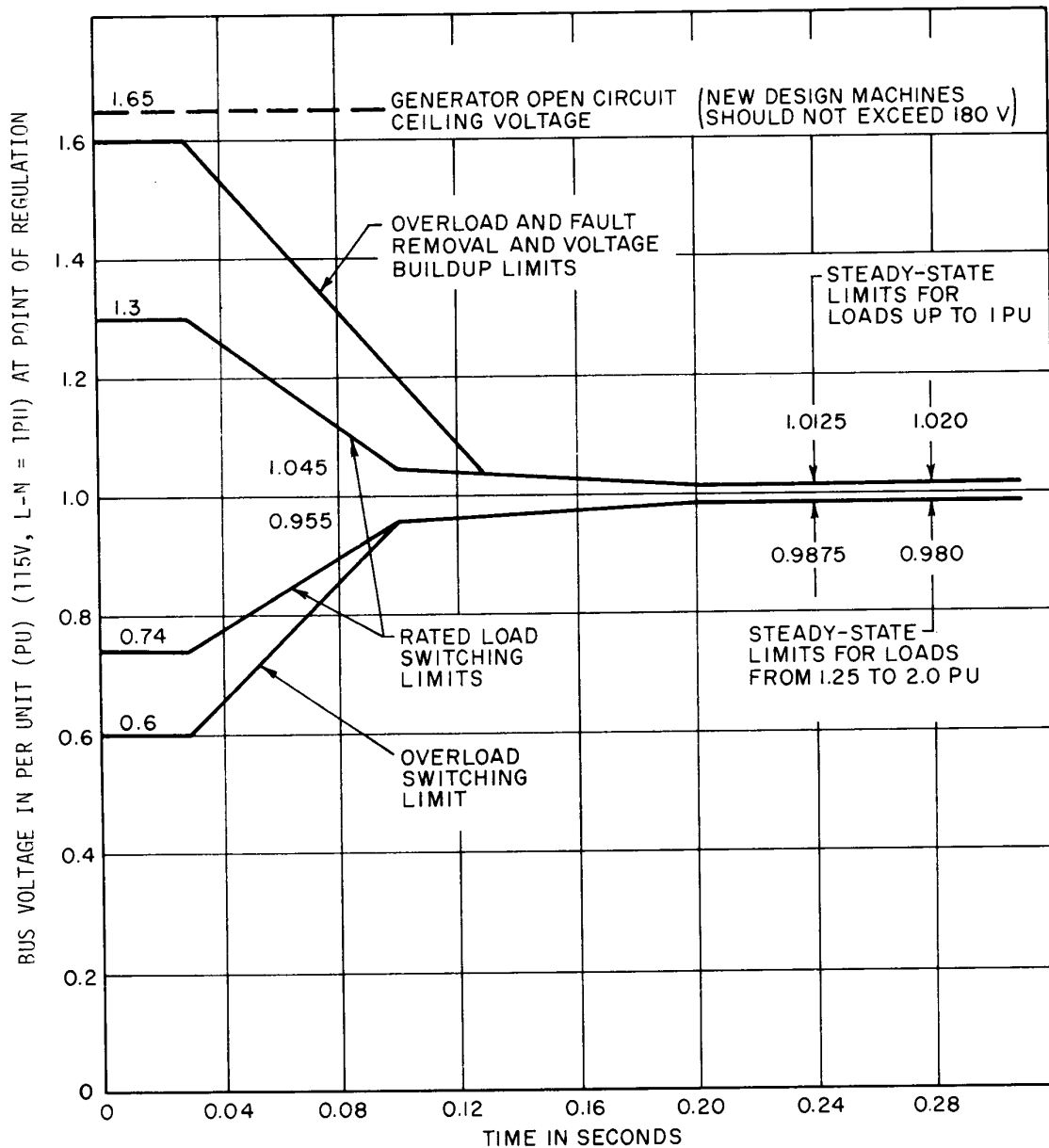
When the voltage coil is unenergized, the armature is pushed against the carbon pile by the radial springs, compressing the pile to the static resistance value. As the generator speed is increased, the generator voltage will increase in accordance with Curve B of Figure 532.1-2. Curve A shows voltage versus speed for a full shunt winding. In the carbon-pile regulator, the application of even low voltage produces a magnetic force on the armature, thus reducing the pressure on the carbon pile and increasing the pile resistance. Sufficient generator speed will raise the voltage to the regulated value, and thereafter the combined force

of magnet and carbon-pile pressure acting in one direction must be balanced by the equal and opposite force of the radial springs, if regulation is to be maintained.

532.11 In general, it is desirable to determine performance of a voltage regulator when it is controlling the generator or unit to which it has been designed so that the overall performance of the combination is obtained. In those cases where the regulator is interchangeable among several generator designs, testing becomes more complex as the characteristics of each combination should be determined.

Adequate tests should be made to determine the effect of operating conditions upon the performance characteristics. Simultaneous imposition of several adverse operating conditions during laboratory test of the regulator is usually difficult, but adequate field testing of a sufficient number of units should reveal defects. If field testing is impractical, intensive laboratory testing or close and frequent inspection in service is mandatory.

532.12 Carbon-pile voltage regulators are adversely affected by lack of ventilation and by excessive vibration. They are easily damaged by rough treatment and should be accessible for inspection and replacement during ground servicing. On certain aircraft it may be necessary to locate the regulator where voltage adjustment may be made during ground servicing operations or flight, although ground adjust-



Notes: The following modern design data also applies in addition to the above.

1. Regulator adjustment increment (largest error) = .25 V L-N max
2. Meter error for adjustment of regulator = .45 V L-N max
3. Unbalance volts between highest and lowest phase volts due to 1/3 load unbalance = 3.0 V L-N max

For utilization equipment terminal voltage limits see MIL-STD = 704

Figure 531-3 Typical Time-Voltage Relationships in Modern Alternating-Current Systems Using Transistor Type Regulators.

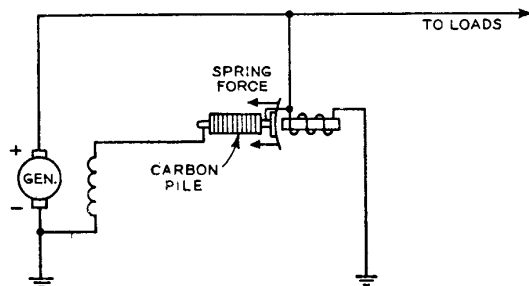


Figure 532.1-1 Electric Circuit of Newton Carbon-Pile Voltage Regulator.

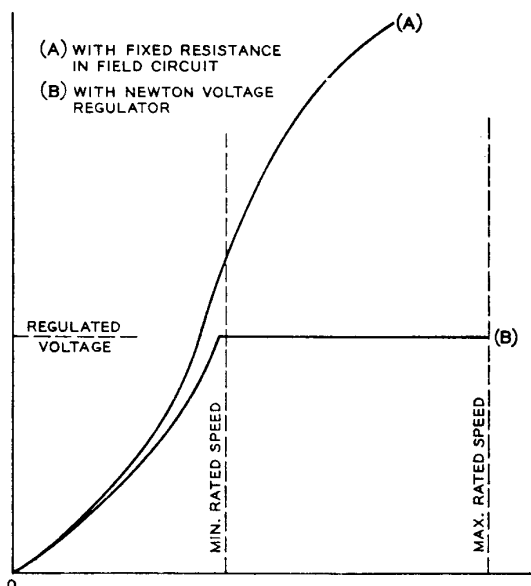


Figure 532.1-2 Generator Voltage versus Generator Speed.

ments should be made only when all conditions are controlled, and flight adjustment should be made only in case of an emergency.

Great care must be exercised in adjusting regulators during ground run-ups, as generator and regulator cooling create adjustment errors that later show up in flight. Any such ground run-up adjustments should be made only after generator and regulator temperatures have stabilized and equalized, and an accurate voltmeter used.

Carbon-pile regulators should be installed where adequate ventilation is provided for carrying heat away from the regulator by convection or by blast cooling. The heat dissipated by the regulator is largely a function of the machine whose voltage it is controlling. The maximum heat dissipated by a regulator controlling a direct-current self-excited generator is

equal to the heat dissipated in the voltage coil plus the maximum heat dissipated in the variable resistance which is a maximum when the voltage across the variable resistance is equal to the voltage across the generator field. Adequate tests should be made in actual flight to determine that the safe operating temperature of the regulator is not exceeded. It should not be possible to block ventilation by placing articles on or about the installation. Blast cooling should be uniform for regulators controlling generators operating in parallel, and concentrated flow of air should be avoided on one section of a regulator because of the danger of effecting improper temperature compensation. Blast cooling from outside air is also likely to impose severe temperature compensating demands upon the regulators. Regulator manufacturers' installation specifications should be carefully followed.

It is advisable to vibration-mount the regulator when vibration frequencies and amplitudes exceed 1G acceleration. The resonant frequency of the vibration mount should be less than 15 Hz for general application.

The regulator should be located where it will not be damaged by accidental bumps from crew members or passengers and where heavy articles will not be placed on the unit. It is advisable to locate regulators where voltage adjustment may be made both during flight and ground servicing, although where regulated voltage level is adjusted by varying the resistance of the voltage-coil circuit the variable resistance may be located on the engineer's or pilot's instrument panel. If this is done extreme care should be exercised in installing the connecting wire since opening of this circuit de-energizes the regulator and maximum field current will flow.

With generators operating in parallel, care must be exercised when adjusting voltage regulators for correction of load division to prevent raising the voltage of that generator which is carrying the least load to a value that would result in a rise of the system voltage above its nominal value.

532.13 Much carbon-pile voltage regulator difficulty can be avoided by proper maintenance practices. The regulators should be inspected and tested periodically at 500- or 1000-hour intervals and if defective, overhauled and readjusted. Both the periodic test and the overhaul and readjustment should be made in strict accordance with manufacturers' instructions or with proven data, and deviation from these instructions by shop personnel should not be permitted until adequately proven.

532.14 *Transistor Regulator for Direct-Current Systems.* All new direct-current regulators use the transistor as the controlling element for generator field excitation. The output transistor is usually operated in a switching mode in order to keep transistor dissipation to a minimum.

Electrical and mechanical integrity of transistorized regulators is far superior to the carbon-pile regulator.

Generally, the transistor regulator can stand relatively high levels of vibration and wide variance in temperature with little effect on system performance.

532.2 Voltage Regulators for Alternating-Current Systems

Modern alternating-current generators have evolved primarily to the brushless-rotating field type most commonly used today. Regulators for these generators essentially consist of at least three stages. These stages are the sensing circuit, reference circuit, and power output stage. All recent regulator designs employ completely static construction thus eliminating all moving parts.

532.3 Power Output Stage

Variations in power output stage circuitry are quite numerous but generally are of three types, magnetic amplifier, silicon controlled rectifier (SCR), and transistor.

532.31 Magnetic Amplifier. Magnetic amplifier regulators have found wide usage in aircraft systems. The magnetic amplifier is used to directly control the generator exciter field excitation level. Due to the nature of the circuitry this type of regulator is usually heavier and larger than regulators employing semiconductor output stages. The magnetic amplifier regulator has a slower response than the SCR or transistor type.

532.32 Silicon-Controlled Rectifiers. Silicon controlled rectifiers (SCR's) employed as the output stage of a regulator provide extremely high gain and fast response. Changes in the level of exciter field excitation are accomplished by the regulator varying the conduction angle of the output SCR's. Gating for the SCR is usually provided by a magnetic amplifier or transistor gating circuit.

532.33 Power Transistor. With the advent of high-performance power transistors control of exciter excitation with these devices has become commonplace. The transistor is operated in a switching mode which makes the transition from the "full-off" to the "full-on" state quite rapid. This fast switching operation allows the transistor to control large amounts of power while keeping the power dissipation in the transistor at a low value.

532.4 Reference Circuit

Reference circuits for all new regulator designs employ Zener diode circuitry. The circuit is quite simple consisting of one or two Zener reference diodes and a biasing circuit.

532.5 Sensing Circuit

The voltage sensed in these regulators can be of many different kinds. Some of these are single-phase average, single-phase root mean square, the arithmetical average of the three-phase root mean square voltages, the highest of the three-phase voltages and average sensing for normal operation with a change to highest phase sensing on overloads or faults. The

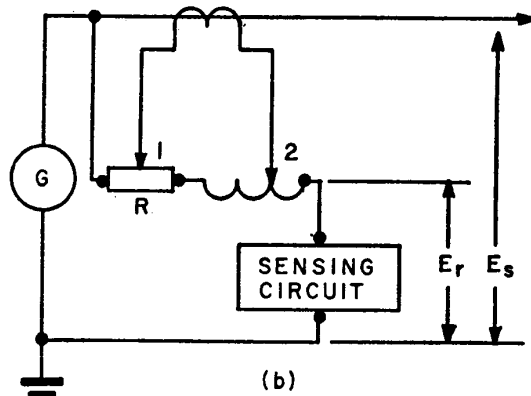
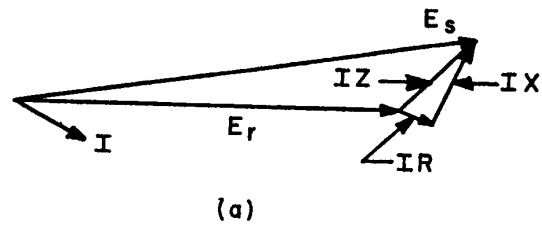


Figure 532.5-1 Alternating-Current Regulator Voltage Compensation Circuits.

last three types of sensing circuits are more generally used for the main three-phase power systems in existence on present-day aircraft, the choice of a sensing circuit depends upon the system operation desired. An example of this effect of the type of sensing circuit on overvoltage protection is given in Table 5-1.

True high-phase sensing should not be used on any system supplying induction motors in which unbalanced voltages are used to the extent allowed by MIL-G-6099A, as the other phase voltages may be low enough to seriously reduce motor torques and to increase motor heating.

532.51 By introducing into the sensing circuit a signal proportional to generator output current, the regulator may be caused to maintain a given voltage at some system point other than the point of connection of the sensing circuit. This may be useful when it is impractical to extend the sensing wires to connect them at the desired regulating point. A case in point is that of ground power supplies, where the connecting cables may be 30 feet long or longer.

In the compensation of an alternating-potential voltage regulator it is necessary to take into account not only the resistance and reactance of the circuit between the sensing and regulating points but also the load power factor. The required vector relationships for the single-phase case may be produced by the circuit shown in Figure 532.5-1 (b), wherein a current transformer in the generator output circuit circulates current through a resistance and reactance

Table 5-1—Comparison of Various Combinations of Voltage Regulator and Overvoltage Relay Sensing Three-Phase Alternating-Current Systems

	(1)	(2)	(3)	(4)	(5)
Voltage Regulator Sensing	Three-Phase Average	Three-Phase Average	High Phase	High Phase	High Phase
Overvoltage Relay Sensing	Three-Phase Average	Three Separate Phases	One Phase Only	Three Separate Phases	Three-Phase Average
Number of Sensing Leads (Excludes Ground)	6	6	4	6	6
Type of Fault	Result				
VR Sensing Lead Open (Overexcitation)	OVR Operates	OVR Operates	Less than 105% Voltage	Less than 105% Voltage	Less than 105% Voltage
Overexcitation with 1 OVR Lead Open	Excessive Voltage	OVR Operates	Excessive Voltage	OVR Operates	Excessive Voltage
L-N or L-L Fault	Probably High Voltage on One or Two Phases	OVR Operates	Less than 105% Voltage on High Phase	Less than 105% Voltage on High Phase	Less than 105% Voltage on High Phase
L-N or L-L Fault with 1 OVR Lead Open	Probably High Voltage on One or Two Phases	Two-thirds Probability OVR will Operate	Less than 105% Voltage on High Phase	Less than 105% Voltage on High Phase	Less than 105% Voltage on High Phase

network in series with the input to the regulator voltage sensing circuit. By proper choice of R and X , the potential between points 1 and 2 will be equal in magnitude and phase angle to vector IZ in Figure 532.5-1(a) and, therefore, the regulator sensing circuit is deceived into thinking that it is connected directly to the distant regulating point. Appropriate variations of this circuit may be adapted to three-phase circuits, but it is important to sense all three line currents if it is expected that appreciable unbalance in the generator load will be encountered.

532.52 Power supplies for these regulators may be obtained in many different ways. Some of the possibilities are as follows:

- a) Generator Three-Phase Output
- b) Single-Phase Output of a Three-Phase Generator
- c) Current Boost Transformer
- d) Permanent-Magnet Generator
- e) Separate Excitation

Often the power supply for the regulators is obtained from various combinations of the above types. The choice of excitation depends upon the coordination desired with starting, protective features, load equipment, and fault performance.

532.6 Reactive Load Division

When two or more alternating-current generators are operating in parallel, a change in the field excita-

tion of one machine has little effect on the relative division of the real (kilowatt) load between the generators. The division of real load between synchronous machines is purely a function of the adjustment of the speed governors. The field excitation, however, does have a direct effect on the reactive (wattless, or kilovar) load supplied by each machine. A generator which is underexcited will carry less than its share of the reactive load of the system. The transfer of its reactive load to the other machines will increase their heating. An underexcited machine has less than normal synchronizing torque and is, therefore, more likely to pull out of synchronism on a heavy load transient. Thus both heating and stability considerations demand that the voltage regulators automatically equalize the reactive load components of all paralleled generators.

It is possible to place a current transformer in one phase of the generator and connect its secondary to a phase-shifting network whose output is applied in series with the alternating input voltage to the regulator. If the network is properly chosen, its voltage will have negligible effect on the regulator input when the generator operates at unity power factor. If the power factor is less than unity, then the input to the regulator is altered by an amount depending on the reactive load. In this manner, the regulator is made sensitive to changes in reactive power but remains practically insensitive to changes in real load.

In the simplest scheme of reactive-load compensation, each regulator is given a drooping voltage characteristic with increase in reactive load. If this characteristic is the same for each machine on the system, the generators will all carry equal reactive loads since they must operate at the same terminal voltage. This scheme is similar to that of paralleling direct-current generators by directly compounding the regulators so the voltage droops as the load increases. Because of the adverse effect on voltage regulation, this method has not received much use.

A series current transformer loop is frequently used to provide the reactive load equalization function. In this system a voltage proportional to the unbalance in reactive current between generators is used to bias the regulator output to provide equalization of all generators in the system.

532.7 Real Load Division

Where any type of generator is used in a parallel system, some type of load sharing or equalizing system must be employed to fully utilize the installed capacity of the generators, and to prevent generator overload. In direct-current systems, it has been the practice to sense current differences between generators and apply a corrective signal to the voltage regulator, but this cannot be done in alternating-current systems, since voltage control here affects reactive load division mainly, real load division must be accomplished by controlling the power input to the generator. In present alternating-current system designs, current differences between generators are sensed and applied to a load division controller for each generator, where, by phase-shifting means, the real power associated with the current difference is sensed. From this, a signal is applied to the governor of the constant-speed drive to increase or decrease the power output as necessary to equalize the real load between generators. In order to keep the frequency within assigned limits while this is being done, a signal is obtained from some type of comparator which adds or subtracts from the load division signal to the constant-speed drive governor, so that the frequency as well as the load division is controlled.

The manufacturers of the various types of constant-speed drives have their own methods of accomplishing the above results, their literature should be consulted before planning a specific application.

533 Variable-Speed Constant-Frequency Systems

A typical variable-speed constant-frequency (VSCF) system aircraft engine. Its design is similar to constant-load division circuits if it is a parallel system, and a protection and control panel.

533.1 Generator

The generator is usually high speed (10,000 to 20,000 revolutions per minute) and is driven directly by the aircraft engine. Its design is similar to constant-speed brushless alternating-current generators, and

the bearings are oil lubricated. The overhung moment appearing at the engine pad may be considerably less than constant-speed drive systems.

533.2 Converter

There are several types of VSCF converters, but the one most used is a cycloconverter which changes the variable-frequency power from the generator into constant-frequency power using silicon-controlled rectifiers as the control devices. The cycloconverter's output wave contains ripple which is produced by the rectifier circuit. This ripple is reduced to a low value by use of a power filter in the output.

The frequency of the output is controlled very accurately by an oscillator using low drift elements or a crystal. The frequency is held within a very close band even under transient conditions. This precise control of frequency makes synchronized, isolated operation very practical. It also allows the VSCF system to synchronize with ground power after the engines are started and a no-break power transfer from ground power to aircraft power can be made. This feature may also be attained on constant-speed drive systems by using synchronizing techniques and momentary paralleling of the generator output with the ground power source.

Normally, a cycloconverter is provided for each output phase. These phases are displaced 120 degrees, and the output of each phase is regulated independently so that much better voltage regulation can be obtained with single phase loads.

The transient response of a VSCF system may be considerably faster than other systems.

The output current of a VSCF system is usually limited by design to approximately 3.0 amperes per unit. This gives ample current to clear faults but limits the worst current handled by circuit breakers and wiring. This current limit also reduces the maximum power that must be taken from the aircraft engine. These characteristics may also be obtained for other systems by current limiting techniques.

The generator or converter can be oil or air cooled; however, the generator is usually oil cooled and the converter air cooled.

533.3 Load Division

VSCF systems can be designed to operate in parallel with very close load division. This division is accomplished by biasing the frequency and voltage of each system.

533.4 Protection and Control

The protection and control of a VSCF system is accomplished with a panel which can be separate or combined with the converter. The usual protection functions are provided; the undervoltage and overvoltage protection is provided for each phase since these are regulated independently.

540 MOTORS AND ACTUATORS

541 Aircraft Engine Starters

Numerous devices are used in starting an aircraft engine, both for piston, turbine, and turbo-prop engines. One is the pneumatic starter that is used mainly on turbo-jet and turbo-prop engines. This operates from compressed air supplied by a ground power source, such as a gas-turbine power unit. In starting multiengine aircraft after one jet engine has been started, the pneumatic starter for the remaining engine can utilize bleed air from the engine or engines already in operation.

Another form of starter is the cartridge type. This is used both on reciprocating and turbine engines. In these starters, both solid and liquid propellants are used. The products of combustion are used to move either the piston or turbine drive which gives the necessary rotation to induce starting.

Another means is the starter-generator. In this group, the starter-generator functions as a motor to drive the engine until after the engine is in operation; then the unit becomes a generator. Starter-generators are usually direct-current devices. The unit, as a generator, must essentially possess the characteristics outlined under section 510 (Aircraft Generators). The effect of current inrush on brushes and commutators should be studied in cases where the starter-generator is feasible.

Another method of providing necessary energy to the engine to induce starting is the electric-motor starter. This is used on both piston engines and turbo-prop or turbo-jet engines. The electric starter on piston engines can be either direct cranking, which is the latest development in the series of electric starters, inertia, or combination inertia and direct cranking. The inertia starter incorporates a flywheel which stores enough energy to crank the engine sufficiently for starting. This was satisfactory on small engines. Later, the starters were equipped with a combination electric inertia-direct-cranking starter. In this type the electric motor does more than build up electric energy in the flywheel. As the starter jaw is engaged electrically with the engine jaw, the motor continues to supply power and assist in cranking the engine. Further development resulted in the present-day, widely-used direct-cranking electric starter, which depends solely on the electric motor to rotate the engine. A few of the inertia or combination inertia electric starters are still in service, although all new starters are direct cranking.

541.1 Piston-Engine Starting—Direct Cranking

An electric starter must be designed and built to obtain the greatest possible output for its weight. It is required to give trouble-free operation between normal engine overhauling periods. A minimum of 800 starts would be the normal requirement on a starter. Most starters are designed to operate on a 28-volt direct-current system, although future installations may require alternating-current starters. For example, one installation now requires a 200-volt, 3-phase, 400-Hz motor. The electric power used to operate the starter is usually from a ground power supply,

although on some installations batteries are used. This means that the starter must be designed to give good performance at low voltage.

541.11 The starter can be broken down into roughly four groups—motor, gear reduction section, torque limiter, and jaw actuating device. The motor usually has only a single terminal with a ground return through the engine pad. The terminal is located either on the side of the motor or in the end, depending somewhat on the application and installation requirements. On some installations where the terminal is mounted on the side of the motor, a scavenging unit—a starter accessory—can be mounted readily on the end of the starter. This scavenging device rotates the starter at a slow speed. This is used to facilitate the removal of accumulated engine oil (hydraulic lock) and raw gasoline in the engine cylinders. It also can be used to assist the mechanic in obtaining proper setting for valves. Starters are designed to rotate either clockwise or counter-clockwise, depending on the engine requirement. The duty cycle of a starter is comparatively short—10 to 30 seconds sustained cranking—which allows the use of a motor that is very compact and smaller than that required in industrial equipment for the same rated output.

541.12 Between the motor and the engine jaw is a gear reducing unit, torque limiting device and an actuating jaw. The torque limiter is usually a multiple-disc-type clutch lubricated with grease or oil. This device is in the system to prevent the starter from damaging the engine if the engine locks up. It also will prevent motor failure in case the torque required to crank the engine is excessively high and there is no current limiting device in the system. The torque limiter must be able to hold its setting through the whole ambient temperature range (-65°F to $+160^{\circ}\text{F}$) in which a starter must operate.

The engine jaws have been standardized throughout the aircraft industry and are either three or twelve tooth. The starter jaw is designed to mate with the engine jaw and must be strong enough to withstand the impact conditions which arise when the starter is initially energized. At this time, the jaw is actuated forward, usually by a cam or other positive means, so that it is in engagement with the engine jaw after a fraction of a revolution. As soon as the engine starts to fire, the engine jaw overrides the starter jaw and, until the starter is stopped, the jaws will ratchet on each other. Provisions must be made to allow the jaw to slide back and forth during this time without damage.

All starters must be of such construction as to withstand vibration, exposure to sand and dust, salt spray, and other adverse environmental conditions, as well as sustain no damage when exposed to temperatures from -75°F to $+200^{\circ}\text{F}$. They also must be of such design that they can operate in any altitude because both horizontal and vertical mounts are common.

541.2 Turbo-Prop and Turbo-Jet Engine Electric Starters

The applications for these starters differ somewhat from that of a piston-engine starter in that turbine-engine starters must accelerate a given inertia load to a specified speed in a relatively short time, as well as assist in cranking the engine until such time as the engine is self-sustaining. Most applications require direct-current starters, although occasionally an application requires an alternating-current starter. Usually, starters are required to perform 600 starts between overhauls, with each starting cycle having from 30 to 60 seconds duration.

With very few exceptions, standard AN pads are used by the engine manufacturer and normally a five-inch bolt circle with six studs is provided to mate with the starter. Starters are provided with either a buttonhole mount or a quick-attached-detached (QAD) mechanism. The buttonhole mount permits the starter to be removed by a slight rotation of the flange after the holding nuts are loosened. The quick-attached-detached mounts require only the tightening or loosening of a single bolt, screw, or pinion to either install or remove the starter from the engine pad.

On many aircraft the power supply to operate the starter is from a ground power unit equipped with a variable-voltage device which reduces the voltage initially and then, as the starter comes up to speed, increases the voltage to around 34 volts. This gives a soft start which eliminates some of the slippage of the torque limiter during the first few seconds of operation of the starter.

541.21 The turbine-engine starter can be broken down into roughly the same four groups as the piston-engine starter. That is: motor, gear reduction section, torque limiter, and jaw actuating device. For most starters, the motor is a non-grounded unit with the terminals at the rear of the motor, although on some installations it is required that the terminals come out the side of the stator. Most applications require that the motor be explosionproof.

541.22 The mechanical problems for the jet starter are similar to those mentioned earlier for piston starters, and the designs are somewhat similar. During each start, the torque limiter slips for a very brief period of time until the starter jaw speed and the engine turbine speed coincide. Two factors which control this slippage time are the voltage which is applied to the starter and the torque limiter setting. The higher the setting, the faster the turbine will accelerate; and the lower the voltage, the less time it takes to equalize the difference in speed between the jaw and the turbine.

Jet-engine starters generally are required at the present time to operate between the temperature range of -65°F and $+160^{\circ}\text{F}$, all under all environmental conditions which exist for piston-engine starters. Storage life is another factor which must be considered. Usually two years storage is the requirement for starters

without requiring an overhaul before installation. This also means that the torque limiter must be designed to maintain its setting during these two years in storage.

542 Motors, General Applications

542.1 Basis of Rating

A motor is rated at the output it will deliver for its duty cycle under the worst specified conditions of ambient and altitude. Motors are usually designed for a specified life under normal operating conditions and a much shorter life under worse conditions. The power rating will depend principally upon the safe temperature rises that the particular type of construction and insulation permit.

Tests for motor ratings should be made in an environment similar to that which will be experienced in service. Wherever an external source of fan or blast cooling is required, pertinent data must be contained in the rating information relative to the pressure and volume of air required. If other than normal application is made, allowance in rating must be made to compensate for higher ambient temperatures, heat by conduction, or radiation from adjacent equipment, lack of ventilation, etc.

542.11 A continuous-duty motor is one which will operate continuously under all conditions of ambient and altitude for which it was designed, delivering rated load, and not exceeding the maximum permissible working temperature of any of its parts. Most of the continuous-duty direct-current motors are compound wound, and a few shunt or series wound.

542.12 An intermittent duty motor is one that will deliver its rated horsepower for a short time without exceeding the limiting temperature, but at the end of that time it must be allowed to cool before it can be operated again. Intermittent duty direct-current motors are series wound, unless speed regulation is a matter of importance, and for reversibility the series field is sometimes split, one winding being active while the other is inactive. Alternating-current motors are usually of the squirrel-cage induction type. Intermittent duty motors are usually enclosed and, therefore, can more easily be made dustproof, oilproof, or explosion resisting. Many are built with magnetic brakes (usually direct-current) and thermal protection.

542.13 For particular applications in which the details of operation are definitely known, weight saving can frequently be obtained and quality improved by special designs conforming to the operational requirements.

542.2 Characteristic Curves of Typical Motors

The characteristic curves (speed versus torque, current versus torque, power factor, efficiency) of aircraft motors are, in general, similar to corresponding curves of commercial motors. The difference in performance between a hot and a cold aircraft is more pronounced than for commercial motors, however, because the temperature rise is greater and the value of

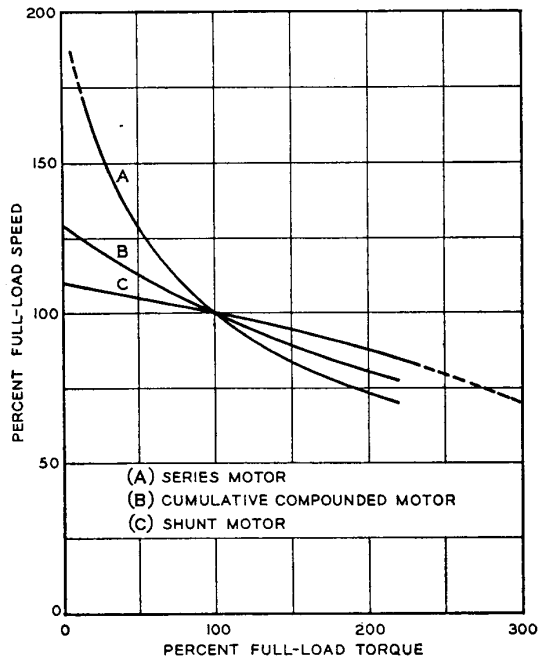


Figure 542.2-1 Typical Speed versus Torque Curves for Direct-Current Motors.

resistance is, therefore altered to a more pronounced extent.

It should be emphasized that the curves included to illustrate general performance were obtained by assuming a certain set of constants for these motors. To make any application study, a definite design curve should be obtained from the motor supplier.

542.21 Typical speed versus torque curves for direct-current aircraft motors are shown in Figure 542.2-1. Figure 542.2-2 gives typical torque curves for the two classifications of polyphase induction motors. These curves have been smoothed out. Under ordinary conditions, the curves for these individual motors are not smooth, but are filled with small ragged variations caused by the distribution of flux in the motor, and the winding distribution of the motor.

542.22 The differences between the current versus torque curves of the various types of direct-current motors are not so marked as the differences between the speed versus torque relations. Typical current versus torque curves for polyphase induction motors are shown in Figure 542.3. As the motor starts from rest, the current decreases along the current curve while the speed is increasing until it becomes stationary at the torque representing the load.

542.23 The power factor of an induction motor is influenced primarily by the number of poles and the type of duty. If the motors are not selected which will operate close to their full-load rating, the power factor will be lower than for a correct application.

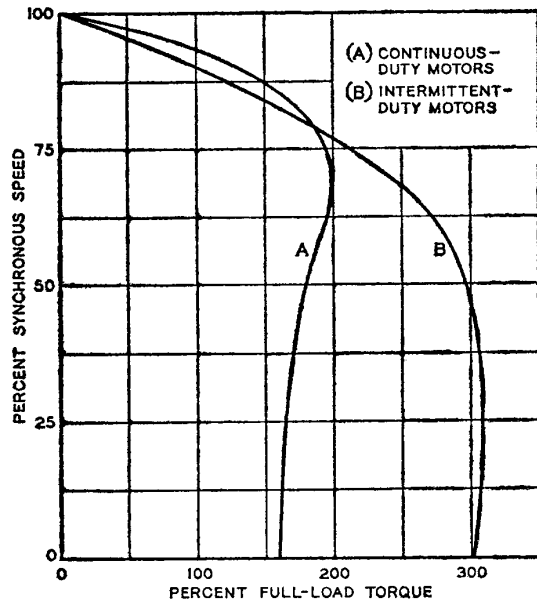


Figure 542.2-2 Typical Smoothed Speed versus Torque Curves for Induction Motors.

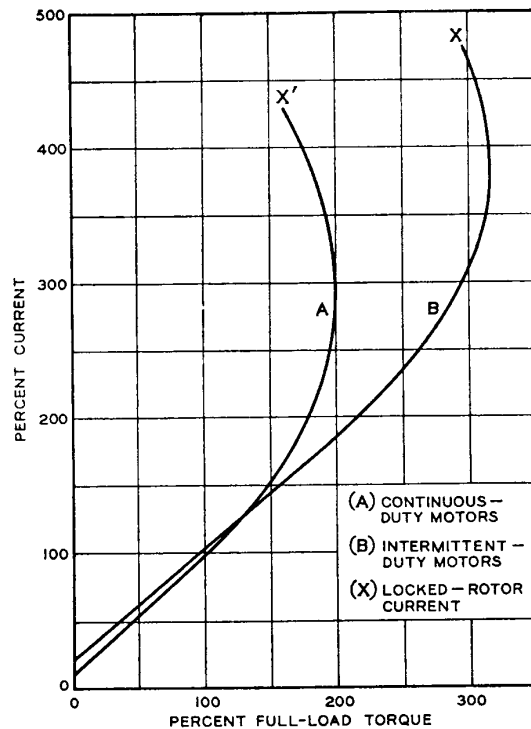


Figure 542.2-3 Typical Current versus Torque Curves for Induction Motors.

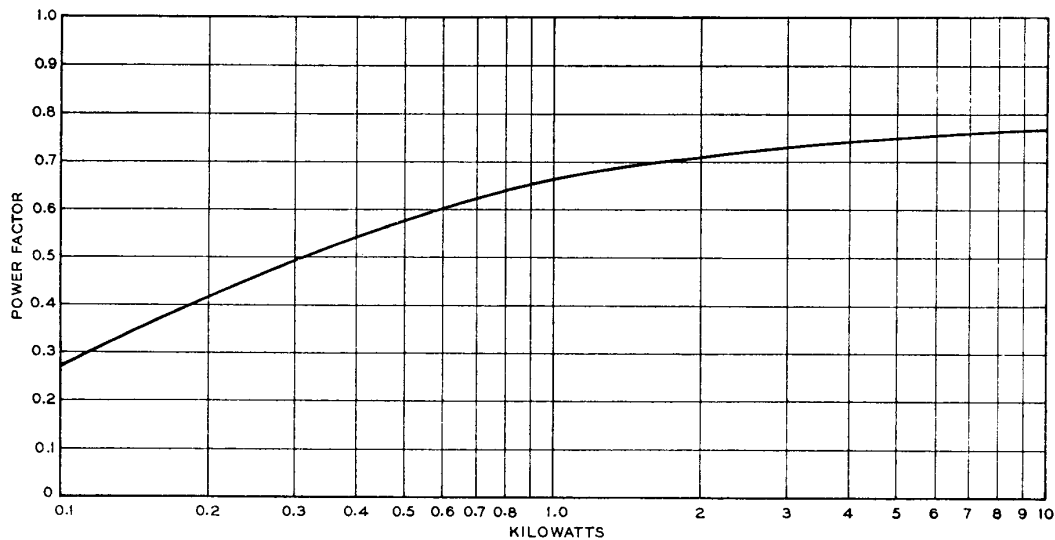


Figure 542.2-4 Power Factor for 400 Hz Continuous-Duty Motors at 75 Percent to 125 Percent of Full-Load Rating.

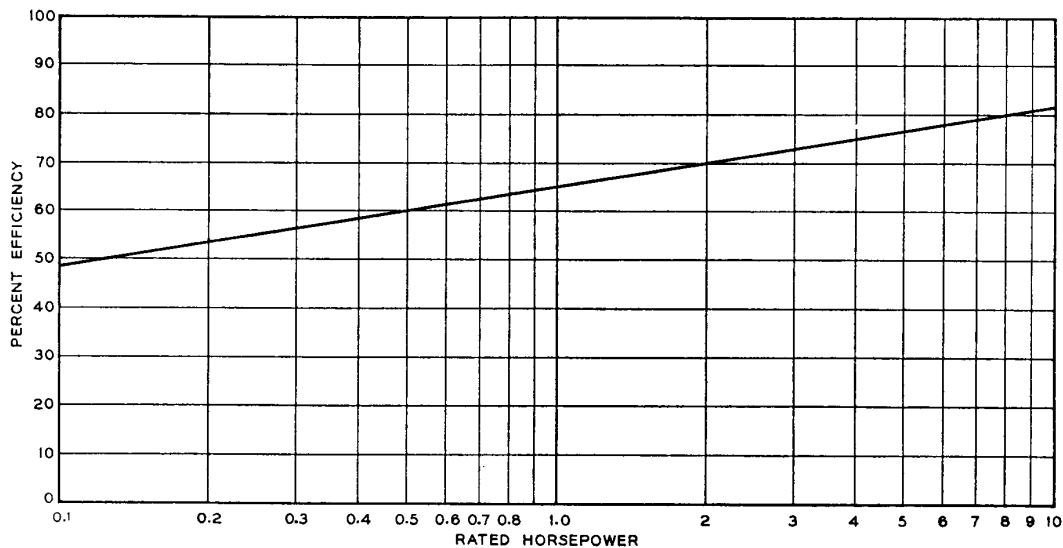


Figure 542.2-5 Efficiency of 400 Hz Motors.

Figure 542.2-4 shows how the power factor varies with the rated size of the motor.

542.24 The efficiencies of aircraft motors range from 10 percent for the smaller units up to 85 percent for the larger ones. An efficiency greater than 85 percent cannot be expected without excessive weight in copper and iron in the motor. For properly designed motors, the efficiency is dependent primarily upon the horsepower rating. Figures 542.2-5 and 542.2-6 show how

the efficiency varies with the horsepower rating for alternating-current and direct-current motors, respectively. Little difference in efficiency of continuous-duty motors should be noticed for the same horsepower rating despite the fact that the motors may have other performance characteristics that are widely different. Intermittent duty motors, with widely different characteristics and duty cycles may vary considerably in efficiency. Comparisons of intermittent duty motors should be made for similar applications.

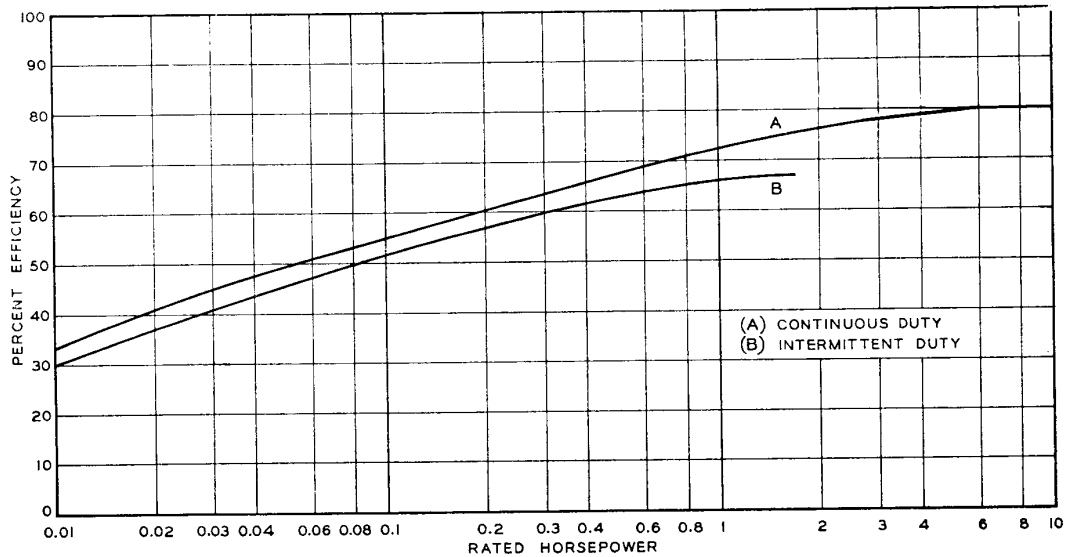


Figure 542.2-6 Average Efficiencies of Direct-Current Motors.

542.3 Overload Ability

An aircraft motor will operate under overload conditions as shown by its characteristic torque curves. These maximum torques are available to take care of high torque points in the load cycle, lasting for a few seconds.

542.31 Thermal capacity of the motors is the time limiting factor. In general, the thermal capacity is small, since the motors are worked near their peak temperatures at normal rating. Any overload will cause the temperatures of the parts to exceed safe limits within a minute or two for continuous-duty motors. The thermal limitation of an intermittent-duty motor is dependent upon the normal duty cycle it is designed for, and abnormal performance information should be obtained from the manufacturer.

542.32 In general, commutation remains satisfactory up to 150 percent of full-load output, although the brushes will not give their normal life expectancy if run at this load at their rated duty cycle.

542.4 Effect of Departure from Normal Rated Conditions on Characteristic Curves and Load

542.41 Aircraft motors are normally designed to operate with the ambient temperature varying according to some curve of ambient temperature as a function of altitude. If the ambient temperature varies above this curve, the motor must be derated. Some manufacturers feel that a satisfactory motor is one that will provide a suitable total life when the damaging effects to the insulation are integrated through the time and temperature conditions that exist in actual usage. An alternative is to include inherent thermal overload protectors which respond rather closely to a particular temperature at one or more points within the body of the motor.

542.42 For a specific torque requirement, there will be quite a pronounced variation in speed of direct-current motors to correspond with a variation in voltage. Since most aircraft motors are designed under conditions close to magnetic saturation, the variation of speed with voltage for a given torque for direct-current motors is usually but slightly less than linear.

The speed of induction motors varies very little with input voltage throughout the normal torque range.

Figures 542.4-1 and 542.4-2 show the approximate amount of variation that can be expected in continuous duty and intermittent duty induction motors, respectively.

542.43 The speed of an induction motor is regulated almost entirely by frequency. The speed of a direct-current shunt motor at full load may vary plus or minus 7.5 percent within a group of motors; whereas for the induction motor the speed variation among a group of motors is apt to be more nearly in the region of one-half of one percent. However, a variation of approximately plus or minus 5 percent can be expected because of frequency changes in the normal supply system.

542.5 Starting Conditions

Starting torque and starting current values, even for a particular class of field winding, vary to a large extent. For direct-current shunt motor starting, current values will in general be in the order of 10 to 15 times the full-load current. For compound-wound motors, the starting current values will be slightly less in general, and for series-wound motors they will usually be in the range of 6 to 10 times full-load current. Intermittent and continuous alternating-current induction motors have a starting current from 3.5 to 5.5 times full-load current.

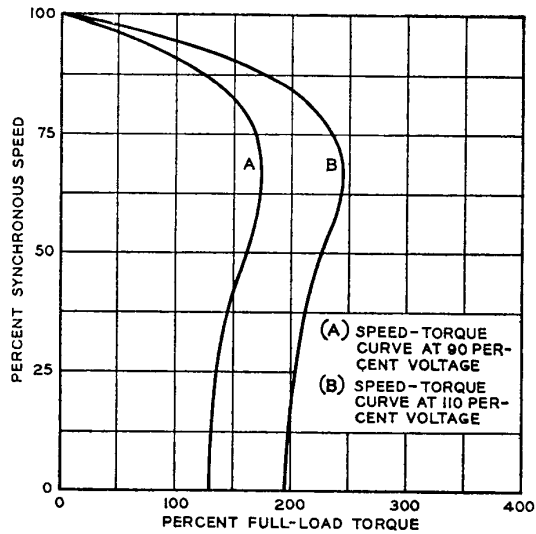


Figure 542.4-1 Speed versus Torque Curves Showing Variation in Torque Due to Voltage Variation for Continuous Duty Induction Motors.

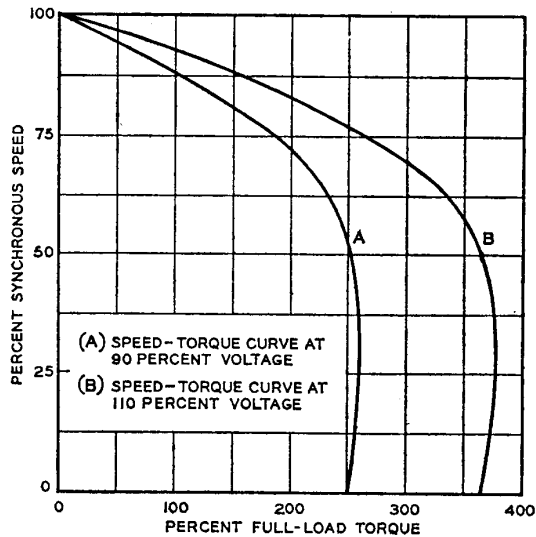


Figure 542.4-2 Speed versus Torque Curves Showing Variation in Torque Due to Voltage Variation for Intermittent Duty Induction Motors.

542.51 The current versus time relationship, while bringing any motor up to speed, is dependent upon the inertia of the motor and the inertial and torque requirements of the load on the motor. The curves in Figures 542.5-1 and 542.5-2 show the current versus time curves of various aircraft loads. The regulation of the power source and the resistance of the feeder to the motor may become important factors in the peak current and accelerating time of the motor, especially if the motor is of relatively large size with

respect to system capacity or the major load for its respective feeder.

542.511 Low voltage will decrease the starting torque of the motor such that it will come up to speed more slowly or remain stalled. Motors must be so selected that sufficient starting torque is developed under low voltage to break away the load. The effects of low voltage may be summarized thus:

1. It decreases starting and maximum torques.
2. It usually increases power factor.
3. It may increase or decrease operating efficiency depending upon whether the increase in copper loss is offset by a decrease in iron loss.
4. It may increase or decrease the operating temperature depending upon whether the sum of the iron losses and copper losses increase or decrease as explained under Item 3.

542.512 The load torque affects the accelerating time and the operating speed of the motor. The effect of load torque varies with the type and characteristics of the motor used. It is desirable and generally necessary to use motors definitely suited to the load factors involved. Loads representing high static or breakaway torques must have motors that develop sufficient zero speed or stalled torque to start the load, even though the running torque required may be moderate. The opposite may be true in the case of certain types of blower or fan loads which generally require a higher torque at speed than at starting.

542.513 While running load torque (speed considered), in general, determines the power requirements of motors, the effect of load inertia becomes a factor requiring consideration when it becomes of such proportion as to appreciably affect the time required to reach normal speed.

Examples:

- (a) An aircraft engine possesses a large effective moment of inertia. To bring such an engine up to starting speed in a few seconds requires a torque application considerably in excess of that required for rolling torque.
- (b) A hydraulic system that possesses a considerable mass (both fluid and solid).

If such a system must respond to control or signal devices, high transient accelerations are involved and adequate starting and accelerating torques must be supplied.

- (c) Very light loads, such as indicating systems, signal devices, or controls that must act almost simultaneously as to start-stop or reversal.

In this case, the moment of inertia of the motor armature or motor may become important. In extreme cases, the motor stack may have to be designed somewhat longer, and the rotor or armature of smaller diameter. The usual design trend

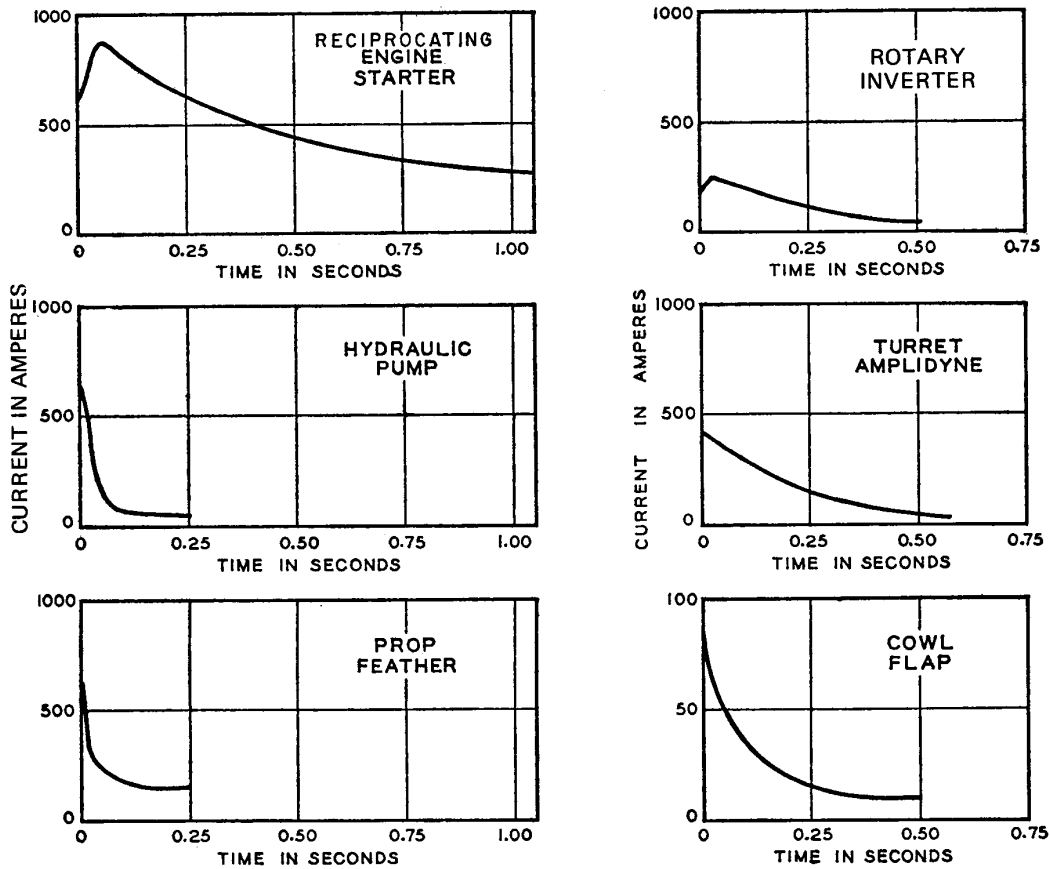


Figure 542.5-1 Starting Characteristics of Direct-Current Motors.

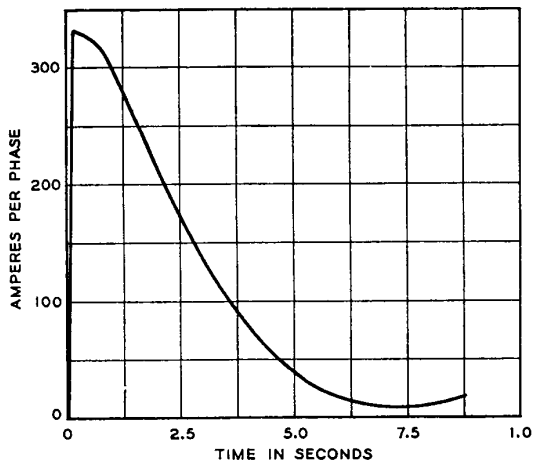


Figure 542.5-2 Alternating-Current Hydraulic Pump Motor Pumping into Accumulator Starting at Zero Pressure.

is to large diameter, short motors for cost, commutation and application reasons.

Tables 5-2 and 5-3 give typical values of WR^2 for aircraft motors although they do not apply to any particular motor design.

542.52 All parts of the motor should be designed to absorb the torque and momentum loads imposed by sudden stoppage of the armature due to jamming of the driven load at the highest service voltage without damaging or loosening of parts. This may not always be possible, especially if the motor must stand substantially instantaneous deceleration.

Thermal capacity of the motors is the time-limiting factor. The thermal capacity of aircraft motors is small. Any abnormal condition will cause the temperature of the parts to exceed safe limits in the course of seconds or minutes. The question of whether or not thermal protective devices should be required on all motors is very controversial. For critical circuits, it is obviously unwise to include a protective device which will prevent operation of the motor just because it is five degrees above the established "safe"

Table 5-2—Open Fan-Cooled Direct-Current
Aircraft Motors

Horsepower Rating 7500 rpm	WR^2 lb ft ²
1/20	1×10^{-3}
1/15	1.30×10^{-3}
1/10	1.8×10^{-3}
1/8	2.2×10^{-3}
1/6	2.7×10^{-3}
1/4	3.8×10^{-3}
1/3	5.0×10^{-3}
1/2	6.0×10^{-3}
3/4	11.3×10^{-3}
1	17.0×10^{-3}
1 1/4	21.5×10^{-3}
1 1/2	26.0×10^{-3}

Table 5-3—Open Fan-Cooled Alternating-Current
Aircraft Motors

Horsepower Rating 7500 rpm	WR^2 lb ft ²
1/8	0.35×10^{-3}
1/4	0.46×10^{-3}
1/2	1.5×10^{-3}
3/4	2.0×10^{-3}
1	4.75×10^{-3}
1 1/2	6.2×10^{-3}
2	7.75×10^{-3}
3	16.0×10^{-3}
5	23.0×10^{-3}
7 1/2	77.0×10^{-3}
10	95.0×10^{-3}

temperature of the motor windings when unrestricted operation of the motor, even though it is severely damaged in the process, would eliminate a dangerous flight condition. On other motors not supplying "time critical" functions, built-in thermal switches protect the motor against unintentional or unsuspected overloads by cutting the motor off the line until it has cooled to a safe temperature. The cycling of the motor due to automatic reclosing of the protective devices gives warning to the crew that something is wrong with either the motor or its load, and they may either clear the trouble in flight or cut the circuit off the line to repair at the next ground stop.

542.53 Normally small series and shunt-wound motors are started across the line with no method used to limit the starting currents. The greatest difficulty in reducing the starting current is that the starting

torque is also reduced by the same amount unless special features are incorporated in the design. If it is desired to limit the starting current for an available motor, it could be accomplished by the use of starting relays which would be automatic in operation.

542.54 There are some applications wherein it is necessary to limit the starting torque of the motor drive in order to insure against malfunctioning of the driven mechanism. Two methods which have been attempted with fair success are a slip clutch arrangement, and a highly-saturated magnetic circuit under starting conditions. The latter method entails the design of a rather inefficient machine as a result of the high density conditions. The slip clutch mechanism usually varies in its slip qualities as the coefficient of friction varies between the clutch members. By proper selection of the clutch facing materials, it is possible to obtain either an increase or a decrease in the coefficient of friction. Slip clutches will carry the designed torque with little or no slipping, but will slip when the torque reaches a certain value. The torque transmitted while slipping is normally less than the breakaway torque.

542.6 Special Motor Loads — Electrical Characteristics

On new applications, it is very important to select the best type of motor and the best motor and control combination while the design is in the formative stage. In the final analysis, the selection of the exact motor frame size, operating speed, enclosure, degree of compounding, etc., must be given consideration. The final selection can best be made by the motor designer after carefully weighing the operating conditions involved.

542.61 A load which is encountered quite frequently and has many variations is that which makes the motor a driving means for a motor-generator set. One variation of this is a motor-generator set feeding a constant resistance load. Under this condition as the motor speeds up, the generator builds up until it reaches a point where saturation occurs or a regulator takes control of the output voltage. When this regulator takes control, the output of the generator from there on is practically a constant amount of power. Under this condition the torque varies inversely as the speed, and it is possible for the generator torque-speed curve to intersect the motor torque-speed curve below the pullout torque point, and run at this loading continuously. A reasonably typical condition would be 50 percent speed and 200 percent torque, for example, and failure would soon occur.

Another variation of the motor-generator set application is one in which the motor-generator set feeds a variable-type load, and the motor-generator set is controlled in such a way that under starting conditions the maximum demand can be put on the generator. This type of motor-generator set is often used in certain control circuits for actuating devices.

542.62 Friction loading is usually considered to have constant friction or torque over a large range of speed. Because of the inconsistencies of lubricants and rubbing surfaces, it must be remembered that only if all conditions of temperature and surface are maintained constant can it be expected that friction loads will be constant. In making any application of a motor to a friction load, the maximum torque required should be determined for the worst conditions of temperature and surface that can be expected. Most friction loads are characterized by having a relatively high breakaway torque; that is, the coefficient of friction is higher under static than under running conditions. Because of the relatively low starting torque of continuous duty induction motors and some shunt motors, this may become the limiting factor.

542.7 Special Problems

542.71 Bearing sizes used on commercial motors of equivalent physical size are too small to withstand the loads and vibration encountered in aircraft applications.

In general, ball bearings have proved more satisfactory in service than sleeve bearings, and sealed-type ball bearings are preferred, particularly for the higher speeds. Bearings must be designed to take thrust from both directions. Oil impregnated bearings have not proved too satisfactory. Excessive lubricant must be avoided. The type of lubricant must be such that it will provide lubrication at the extreme high and low temperatures encountered. Enough lubricant should be provided for 500 hours operation without attention, with the motor operating in any position.

542.72 Gears for aircraft motor applications present a difficult design problem because of the small weight and space allowed for them and the difficulty of providing satisfactory lubrication over the wide range of temperatures encountered. Sintered iron gears, impregnated with oil have given satisfactory service on fractional-horsepower motors. Hardened steel gears with low-temperature grease have been fairly satisfactory for larger geared motors, but no low-temperature grease yet available is entirely satisfactory at high temperatures.

Clutches are specified when the momentum of the armature must be removed from the load to prevent overshooting of the output shaft when the brake is applied, or when the frictional load of the armature and its associated gearing is to be removed from the system to facilitate hand crank operation. Clutches are also used in motors for starting applications where torque limiting features are desired.

Brakes are used in motors where motion of the device is not desirable except when operation is called for. Many of these applications are actuators and positioning devices. Brakes can be and are used to prevent overshooting with at least equal success to clutch brake combinations.

542.73 Some applications, such as landing-gear actuators, require that means for hand operation be pro-

vided in case of failure of the electric system for any reason. The hand crank extension should not turn when the motor is driving the mechanism, nor should it be necessary to turn the motor armature when operating the mechanism with the hand crank. The torque required to turn the hand crank should be low enough that one man can continuously turn the crank without requiring the advantage of his full weight. Each application of this kind requires individual consideration to establish the most suitable design.

542.74 To provide the utmost reliability of operation, limit switches should be mounted on the mechanism being operated. It is common practice to mount limit switches in separate switch boxes sometimes attached to the motor, or more frequently to the gear box. Switches used for this purpose must be extremely resistant to vibration and must have adequate current and voltage breaking capacity at sea level and at high altitudes. Snap-action contacts are necessary and compactness is important. Means of adjusting the setting of the limit switches must be provided, and the setting adjustment locked against changes due to vibration or continued operation of the motor. Solid state, proximity and other static sensing devices can be used to advantage in lieu of electromechanical limit switches. These devices are small in size, highly reliable, extremely resistant to vibration and shock with minimal or no adjustment required during operation. Static sensors are best used in low-power-level logic control circuits where current and voltage breaking capacity are not considerations.

542.75 The type of mounting is determined by the individual application. Flange mountings are lighter than base mountings, but are subject to high stress due to bending moments, particularly if resonant vibration is encountered. Flange mountings must provide sufficient space to permit insertion and removal of bolts or nuts and adequate wrench clearances for tightening them. Tapped holes directly in aluminum or magnesium are not satisfactory, and such applications should employ plated steel inserts.

542.76 Leads for small motors not subject to severe vibration may consist of a multiple-pin receptacle. For leads on large motors when suitable connectors are not available and for all motors on which severe vibration makes connectors unsatisfactory, terminal studs should be provided.

542.77 Although the terms are often used interchangeably, acceleration and vibration are not the same. Vibration always gives rise to acceleration, but acceleration can exist without vibration. Values of acceleration and vibration vary widely from one type of aircraft to another, and even in different sections of the same aircraft. The problem is further aggravated by motor mountings which may be flexible enough to permit resonant vibration, in which case the acceleration may increase as much as 20 times. If resonance is not present, ability to withstand accelerations of 12G applied at the center of gravity, in any direction will be generally satisfactory for aircraft applications, including the acceleration value obtained by landing impact.

542.78 Use of light metals such as aluminum and magnesium, to reduce weight, has aggravated the corrosion problem, since steel, copper, and other metals lower in the galvanic series in sea water must also be used in the motor, often in intimate contact. Effective and durable protective finishes must be provided between dissimilar metals, otherwise any condensation or salt spray will form an electrolyte and the aluminum and magnesium will be destroyed rapidly by galvanic action. Care must be taken when the dissimilar metals are protected by a protective layer to provide a good contact between parts for bonding purposes. This contact area must be protected from all substances which assist corrosion. Severe condensation occurs when a descent is made from the cold air of high altitudes into the warmer air near ground. Global operation subjects motors to fine sand and dirt. This sand will eventually penetrate any seal except the hermetic type, given sufficient time. These abrasive particles grind away bearings, brushes, commutators, switches, and gears once they have gained entrance. The nearest approach to the solution at present is to design as effective a seal as possible and to keep the seal effective by periodic cleaning or replacement.

542.79 It must be noted that the use of magnesium may increase the fire hazard since thin magnesium could ignite under some conditions surrounding motor failure. Its use must be carefully evaluated in terms of its potential danger and corrosion tendencies.

Ambient temperatures for motors mounted in exposed locations range from -65°C to 120°C , and this complete range may be encountered within a few minutes. Location in cabins or other semiprotected locations does not necessarily mean more favorable ambient temperatures, since aircraft are frequently stationed at operating bases where hangars are not available.

Ambient atmospheric pressures vary from 14.7 pounds per square inch at sea level to 2.72 pounds per square inch at 40,000 feet altitude. This reduction in pressure, although slightly offset by the reduction in temperature as the altitude increases, results in decreased weight of air per cubic foot. The decreased weight of air per minute will not be adequate unless the necessary allowance is made in calculating cooling air available. Motors located in supercharged compartments ordinarily will not be subject to ambient pressures lower than 9.5 pounds per square inch. Creepage distances satisfactory at sea level must be increased 300 percent for satisfactory operation at 40,000 feet. In general, corona aspects must be considered at altitudes above 30,000 feet when voltage is 400 volts peak; at higher altitudes lower voltages can cause corona.

Ambient humidities will vary from zero percent to 100 percent. Service reports from the South Pacific areas disclose that the humid, warm climate is particularly conducive to the creation and rapid development of fungus growth on textiles and all other

organic materials, including those used for electrical insulation, unless prevented by a fungi retardant included in the insulating varnish or applied over the varnish. Under ideal conditions for growth, enough fungi will develop in one week to completely fill the airgap and prevent the armature or rotor from turning.

Some fungicidal treatments are effective for protecting equipment in storage, but after a few hours at motor operating temperatures the treatment loses its effectiveness. Fungicides are being developed which will retain their effectiveness under motor operating temperatures. More recently the problem has been avoided by making use of the newer synthetic insulating materials which are completely fungus inert. See Military Specification MIL-T-152.

Motors located in compartments where an explosive mixture may accumulate must be provided with suitable explosionproof housings and have excellent electric bonding between all parts of the motor enclosure and the supporting structure to eliminate any possibility of igniting such mixtures by an electric discharge between the motor and structure.

550 CONVERSION EQUIPMENT

Conversion equipment is operated from the primary electric system on the aircraft and is used to deliver relatively small amounts of power to other equipment which requires power with an electrical characteristic differing from that of the primary electric system. The following types of conversion devices have been developed for use on aircraft:

550.1 Direct-Current to Alternating-Current Conversion Equipment

A device for changing direct-current power to alternating-current power is an inverter. The usual type is one which is powered by a direct potential of 26 to 29 volts and delivers 390 to 410 Hz, three-phase or single-phase power at an alternating potential of 110 to 120 volts. The static type is in most common use, although there are some vibrator and some rotary types in use. At the present time, static types are being used for new application. Either single-phase or three-phase inverters are available. However, most three-phase rotary inverters are designed so that they may be loaded single-phase to at least 83 percent, and some designs up to 100 percent, of their three-phase rating. Typical ratings of rotary inverters in use today are 10, 100, 250, 750, 1500, and 2500 volt-amperes which would weigh, respectively, approximately 2.5, 10, 20, 30, 48 and 60 pounds. Static inverters of the same ratings weigh less, have higher efficiency, longer life, and higher reliability.

550.2 Alternating-Current to Direct-Current Conversion Equipment.

550.21 A rotary device for changing alternating current to direct current is called a converter. A typical unit will deliver 27.5 to 28.5 volts or 22 to 29 volts,

depending upon whether the unit incorporates a regulator or not, when powered by 380 to 420 Hz three-phase power at an alternating potential of 102 to 124 volts. Units of 50, 100 and 200 ampere capacity are in use today.

550.22 Various types of rectifiers are in use, the usual types are:

- a. The semi-conductor rectifiers (usually silicon) are generally employed when conversion from alternating current to direct current is required. Appropriate transformers are used to obtain the desired direct-voltage output.

In small sizes, these rectifiers are used extensively in control circuits and magnetic amplifier systems. Large power rectifiers are being used to convert alternating current to direct current when the primary power source is alternating current. Fifty to 200 ampere units are in common use.

- b. In certain devices, control power in reasonable amounts (up to approximately 500 watts) has been rectified, and in most cases controlled, by semiconductor devices. These devices fill a great variety of needs, particularly in the communication and navigation fields. In a few cases, grid-controlled thyatron tubes have been used for rectifying and controlling the field power of direct-current motors and alternating-current generators. However, power semiconductors are being applied more extensively.

550.3 Alternating-Current to Alternating-Current Conversion Equipment

550.31 Frequency converters are sometimes called frequency changers. Frequency converters can be classified as devices which will convert alternating current of a variable frequency with a constant ratio, convert alternating current of a constant frequency with a constant ratio, or convert alternating current of a variable frequency to constant frequency. A typical unit will deliver alternating-current power at 399.6 to 400.4 Hz. A typical unit will deliver three-phase ac power at a potential of 113-117 V, when powered by 102-124 V, 250-470 Hz three-phase power. The normal use for this type of device is to obtain a small amount of alternating-current power having much closer voltage and frequency regulation limits than the prime alternating-current power system can produce. Units of various volt-ampere ratings are under development. They may be either rotary or static devices.

550.32 A voltage stabilizer is a device which accepts alternating-current power with one voltage characteristic and delivers alternating-current power with another voltage characteristic, and has no effect on the system frequency. A typical unit will deliver 250 to 470 Hz, three-phase power at an alternating potential of 113 to 117 volts when powered by 250 to 470 Hz, three-phase 102 to 124 volts.

550.33 Potential and current transformers are used in alternating-current systems but in general are used in, or as an accessory to, component devices in the system.

550.34 Phase adapters are occasionally used to provide small amounts of three-phase alternating current for the operation of instruments from a single-phase power supply—usually an inverter.

One commonly-used method is a resonant circuit which establishes the third corner of a voltage delta. This type of phase adapter gives fairly accurate balance of voltages for one value of load impedance and for one frequency only. Consequently, the use of phase adapters for situations involving input frequency variation and/or variable impedance loads, such as motors, gives rise to unsatisfactory operation. Rotary phase adapters are not commonly used on aircraft, it being simpler to supply three-phase inverters on direct-current systems. Most aircraft with basic alternating-current systems have three-phase systems.

550.4 Direct-Current to Direct-Current Conversion Equipment

550.41 Dynamotors were common devices, until recently, for converting direct-current power at one voltage to direct-current power at another voltage. Dynamotors now available operate from power sources with direct potentials of 12, 28, and 115 volts and supply direct-current power at a variety of voltages. Dynamotors are not normally used in aircraft as general purpose power supplies, but are integral components of some utilization equipment, such as electronic or armament equipment, and supply power to some single load. Thus there is little uniformity in ratings or sizes in use today.

550.42 Static devices for direct current to direct current conversion use transistors or other solid-state devices as conversion elements. These units are characterized by their high efficiency and the lack of maintenance required, since no moving parts are involved.

551 Application of Conversion Equipment

In the application of conversion equipment in aircraft the following factors should be considered:

551.1 Electrical Considerations

551.11 The load presented to rotating conversion devices producing three-phase alternating-current power should be balanced for satisfactory operation. Units now available, in general, are regulated on but one phase and since, in an effort to save weight, the magnetic material in the unit is held to a minimum, variations in the load per phase result in the unit producing an unbalanced voltage. Unbalanced voltages caused by load unbalance have been found detrimental to aircraft instrument and electronic equipment. In order to keep the voltage balance within acceptable limits the loads should be balanced within 10 percent of the rating of the unit.

551.12 To insure immediate availability and eliminate the warm-up period usually required for conversion equipment to be in specified operating condition, it has been found desirable in certain instances to operate standby units whenever the primary power supply is in operation. In the use of rotating equipment utilizing output brushes, it has been found desirable in some instances to operate the equipment at approximately ten percent load to prevent overfilming of the commutator or slip rings.

551.13 In applying conversion equipment, it is important that provisions be made to insure that the input voltage will be within the required limits. Failure to design or apply conversion equipment to conform with the primary system voltage, transient and steady-state, has on occasion caused failure of the load equipment used on the secondary power system.

551.2 Physical Considerations of Conversion Equipment

551.21 Equipment should be positioned in an installation as specified by the equipment specification. If it is necessary to use the equipment in a position for which it was not designed, special consideration or tests may be necessary to determine if the equipment will operate satisfactorily. Static devices can normally operate in any position.

551.22 The shock and vibration conditions under which conversion equipment will operate satisfactorily varies with the type of equipment. Specifications for a particular equipment should be consulted prior to application. Although operational conditions from which shock and vibration specifications are derived are continually in a state of flux, MIL-E-005272B, Environmental Testing, Aeronautical and Associated Equipments, may serve as a guide for qualification continually in a state of flux, MIL-STD-202 and MIL-E-5272 may serve as a guide for qualification testing.

551.23 In the application of conversion equipment, provision for cooling is probably the most important single physical consideration. A few types of units are either blast-cooled or convection-cooled; however, for the most part, this type of equipment is fan-cooled.

Rotating units normally have the cooling fan mounted on the main shaft. Static units usually incorporate a motor-driven fan. In either case the fan moves substantially a constant volume of air. As the altitude in which the unit operates is increased, the air density and its effectiveness as a cooling medium decreases. For propeller-driven aircraft, the decrease in cooling air density is offset to a degree by the reduced compartment temperature at the higher altitudes.

Solid-state conversion devices frequently utilize convection and sometimes blast cooling. Silicon type semiconductors are in common use.

For high-performance jet aircraft, this is not true. Due to the increased velocity of the aircraft at the

higher altitudes, the compartment temperatures tend to increase as the speed is increased. It is therefore, imperative that the temperature-altitude conditions under which a particular piece of conversion equipment must operate be determined and assurance be made that these temperature-altitude conditions do not exceed those covered by the applicable equipment specification.

The installation of conversion equipment is usually in compartments with other heat-rejecting devices, and as a result it is sometimes necessary experimentally to verify thermal adequacy by an installation mock-up and a survey of the critical operating conditions.

552 Transformers

552.1 Power Transformer

Transformers increase the ability to use alternating-current power by providing an efficient means for transforming power from one voltage to another voltage in both single-phase power systems and three-phase power systems. The transformer may be used as a component for transforming voltage of the system or as a component within a component for magnetic-amplifier voltage regulators, transformer-rectifiers, control and protective devices, etc. Single-phase power systems permit the use of only single-phase transformers while three-phase power systems utilize both the single-phase transformers and three-phase transformers. Important uses of three-phase transformers are to isolate power from ground, and to reduce harmonics.

The important requirements that must be specified for a transformer are:

- kVA Rating
- Frequency Range
- Transformation Ratio
- Voltage Regulation
- Efficiency
- Temperature
- Altitude
- Means of Cooling

The requirements given above are only a partial list because vibration, mounting and specific envelope are frequently peculiar to a specific application.

552.11 Aircraft transformers are usually rated for a nominal frequency of 400 Hz. Constant-frequency systems have a frequency range of 380-420 Hz, and variable frequency systems have a frequency range of 380-1000 Hz. If the additional size and weight can be tolerated, good quality transformers designed for 60 Hz may be used in a 400 Hz application, but transformers designed for 400 Hz are smaller, lighter, and more efficient than those designed for 60 Hz. These savings are somewhat reduced as the range of frequency reduces the minimum frequency.

552.12 The true ratio of transformation is defined by

$$\frac{N_1}{N_2} = a$$

where N_1 = primary turns
 N_2 = secondary turns
 a = turn ratio

The turn ratio (a) is approximately equal to the ratio of the primary voltage to the output voltage.

552.13 Voltage Regulation may be defined as:

$$\text{Voltage regulation (in percent)} = \frac{V_t \text{ no load} - V_t \text{ full load}}{V_t \text{ full load}} \times 100$$

where V_t is the output voltage. With loads having reasonable power factors, 8 percent regulation is usually specified for transformers up to 500 VA. For ratings greater than 500 VA, 6 percent regulation is usually required.

552.14 Transformer efficiency is the ratio of its output power and input power. Since output plus losses represent input, the efficiency equation becomes

$$\text{Efficiency (in percent)} = \frac{\text{output}}{\text{output plus losses}} \times 100$$

The minimum efficiency of an aircraft transformer is usually 75 to 82 percent for very small transformers and from 86 to 92 percent for transformers rated 100 VA and above.

552.15 Three-phase transformers in the simplest form consist of three groups of primary and secondary windings, one group for each phase, that are connected in delta or wye on either the primary or secondary. The wye connection may be used with the neutral grounded or ungrounded. Usually one winding is delta connected to reduce the third or multiples of the third harmonic. Where requirements make it difficult to connect either winding in delta, the third or multiples of the third harmonic may be reduced by connecting a tertiary winding in delta. The tertiary winding is an additional winding for reducing harmonics and in general is not connected to any supply or load.

552.16 Nearly all aircraft transformers are designed to meet their ratings over a temperature range of -55°C to 71°C or 120°C . The most critical design point is the high operating temperature where the type of insulation and size of the transformer is affected. Most heat loss is dissipated by radiation when normal air convection is the cooling medium. When blast cooling is used a lighter transformer may be designed because the blast air increases the amount of heat load that may be removed by convection and makes it possible to design a transformer that has more losses. Transformer weight in some ratings can be reduced if high temperature insulation is used to increase the permissible hot spot temperature of the transformer above the ambient.

552.17 In addition to the high operating temperature the altitude and the time at this altitude which the transformer must operate affects its size and weight.

552.18 The system designer must specify complete information on ambient temperature, altitude and mounting for the most efficient installation with respect to size and weight. For example, if a small transformer is mounted on a surface that can be considered a heat sink, a smaller transformer may be used as the losses are more efficiently removed from the unit.

552.2 Autotransformers

A special type of power transformer is the autotransformer having a single, tapped, winding per phase to step up or step down voltage. These transformers are not generally used in the power generation system but are used more in the distribution system to provide better utilization of power. Autotransformers have been used in conjunction with windshield deicing, aircraft lighting and windshield defogging. They are made for both single-phase and three-phase applications.

The autotransformer is used primarily because it is the most efficient type of transformer. As there is only one winding, the transformer is required to handle only the power requirements between the input and output voltage. The method for determining the amount of power handled by the autotransformer is

$$\text{Power Transformed} = \frac{\text{High Voltage} - \text{Low Voltage}}{\text{High Voltage}} \times \text{Output Power}$$

Since the autotransformer does not handle full power transfer as does a two-winding transformer, it can be made smaller, lighter, and more efficient. Its disadvantage is that it cannot be used to isolate the voltage from ground if one side of the input voltage is grounded.

552.3 Potential Transformers

The potential transformer is connected across the lines of the circuit on which a voltage measurement is to be made. The secondary circuit contains the voltmeter, voltage coil of a wattmeter, relay, or other device. Such a transformer differs very little from a power transformer except in size. The ratio of voltages is not exactly equal to the turn ratio owing to the impedance drops of the winding. If these drops and the no-load current are small, only a slight ratio error is introduced at loads within the rating of the transformer. A phase-angle error is introduced because the output voltage is not exactly 180 degrees out of phase with the input voltage. In general, phase-angle errors may be neglected but ratio error must be considered for determining accuracy.

The potential transformer should be compensated where high accuracy is required. The impedance burden, in terms of $R + jX$, should be specified.

552.4 Current Transformers

Current transformers are used in alternating-current circuits, to step down current in an accurate, known,

ratio for purposes of metering and for the operation of protective and regulating devices. The primary winding of a current transformer is connected in series with the circuit, and the secondary is short circuited through the impedances of the devices on which it is used.

A current transformer will have phase angle and ratio error for a specified load impedance. It is possible to compensate for the ratio error by making the actual ratio of turns different from the nominal current ratio. Some phase-angle correction can be made by designing a short-circuited winding on the core.

An alternating-current system may require a large number of current transformers to provide signals for load division, protection and metering circuits.

553 Rectifiers

553.1 Selenium Rectifiers

The selenium rectifier is known as a metallic-plate rectifier. It is made by depositing selenium material on aluminum plates. These plates act as heat radiators in addition to being one of the elements of the rectifying cell. The plates are spring-loaded together to form a complete rectifier. Cells are used in series or in parallel to obtain various current and voltage ratings. Groups of cells or "legs" are connected to make up bridge circuits, doubler circuits, etc. After the complete rectifier is assembled, it may be coated with a protective material so that moisture and other foreign materials may be kept out. It is difficult for this coating to be made good enough to withstand the requirements of missile equipment. Therefore, many selenium rectifiers are either encapsulated or hermetically sealed.

553.11 Until several years ago all selenium cells were rated at 26 volts root mean square. However, when required, these cells are now available in a 40-volt rating. Even with the 40-volt rating, however, a number of cells must be used in series if a selenium rectifier is to be connected directly to the 115/200 volt output of an alternating-current generator. Cells with current ratings of from fractions of a milliampere to several amperes may be obtained. Several suppliers of selenium rectifiers now have rectifiers which are capable of operating at their full rating up to above 100°C. With some derating these special rectifiers are capable of operating up to 150°C.

553.12 Selenium rectifier cells are obviously nonlinear devices. Considering the characteristics with an alternating voltage applied, they are nonlinear in that they pass current in one direction and block current in the other direction. It is for this reason that they are called rectifiers. In addition, when either the forward or reverse characteristics are taken separately they are still nonlinear. In the forward direction the cells exhibit a threshold voltage which must be exceeded before any current flows. From this point, the forward resistance rapidly decreases until approximately a one-volt drop appears across the rectifier at rated load current. In the reverse direction low leakage

current flows until the rated voltage is approached. At this point the leakage current increases rapidly.

553.13 Selenium rectifiers are the least expensive rectifiers available. They are the largest of the rectifiers available and require considerably more space than other types. In the coated form their weight is not excessive; however, when encapsulated or hermetically sealed their weight increases several times. One of the disadvantages selenium rectifiers have is an aging characteristic. Their forward drop increases with age and therefore their efficiency decreases.

553.2 Silicon Rectifiers

Silicon is one element in the family of semiconductors which has been brought into the rectifier field and is used extensively for new aircraft rectifier designs. A semiconductor rectifier cell or "diode" is made by fusing an element such as aluminum or arsenic to a wafer of pure silicon. These fused or alloyed junction diodes are the type generally used. The point contact type of diode is not satisfactory under rough mechanical environmental conditions. In general, it is not necessary to use silicon cells in series because they do not have the voltage limitation per cell that selenium has. All silicon rectifier cells are hermetically sealed. Moisture has such a detrimental effect that it must be kept out. Most of the lower ratings of silicon cells are constructed similar to small resistors with pigtail leads. The higher ratings are usually constructed with a threaded stud on one end so that they may be mounted on a heat sink.

553.21 Silicon rectifier cells can be obtained in almost any voltage rating from a few volts to 1500 volts. Current ratings range from a few milliamperes to 250 amperes, at the present time. The maximum current rating obtainable depends on how large a junction area can be obtained, how good a heat sink is used and the ambient temperature. The state of the art in silicon devices is such that the maximum allowable temperature for operation changes with every new device put on the market. In general, all silicon devices may be used up to 150°C, most may be used up to 200°C and a few still have some ratings above 200°C. The rating of a silicon device must be studied very carefully for the particular application. The actual limiting factor is the temperature which the rectifying junction reaches. Since this cannot be measured directly, the temperature of the heat sink or the case of the device must be measured and allowance made for the temperature gradient between that point and the junction. This temperature gradient is not a constant even for one rectifier cell in one application but varies with the power being dissipated at the junction.

553.22 All rectifiers have the nonlinear characteristics described under selenium rectifiers. Silicon has the feature of having an extremely low leakage current in the reverse direction at room temperature. It is also different from selenium in that it maintains this very low leakage right up to rated voltage of the cell whereas the selenium cell has a very round knee in this area. The leakage current in silicon increases

rapidly with temperature, doubling in value for every 10°C increase in temperature. This rapid increase of leakage current would be very detrimental were it not for the fact that the leakage starts out at such a low value.

553.23 Silicon rectifiers have several distinct advantages. They are relatively small, they are high-temperature devices and they do not exhibit an aging characteristic which is in any way comparable with that of selenium.

553.3 Germanium Rectifiers

The description of silicon rectifiers cells applies to germanium cells except that germanium cells are available only in medium voltage ranges (100 to 200) and they have the serious disadvantage of a limiting temperature of something less than 85°C. Germanium cells have the advantage of having a somewhat lower forward voltage drop than silicon cells. This is important in some applications but can only be used if the maximum temperature is limited as indicated above.

554 Transformer-Rectifiers

554.1 General

A device combining the characteristics of the alternating-current transformers and the power rectifier is used to convert alternating-current power from the prime source to direct-current power. Most large direct-current power supplies are built with three-

phase primary windings and multiphase secondary windings on the transformers. The output of the secondary is rectified by selenium or silicon rectifiers. The transformer-rectifiers are classified as:

1. Regulated—Contains provisions for regulated output voltage and parallel operation.
2. Non-regulated—Does not include provisions for regulated output voltage and will depend on the inherent regulation characteristics of the transformer and rectifier to maintain voltage and provide paralleling within the specified limits.

554.11 Fan or blast air cooling is generally used with large ratings while small ratings are convection cooled. Forced-air cooling is accomplished by a motor-driven fan or by supplying an air duct for ram-air cooling.

554.12 The ratings vary from several amperes used in protective relay circuits to 200 amperes or greater in large direct-current power supplies.

554.2 Regulated

A typical large power rating of transformer-rectifier might have the following requirements if used to convert alternating 115/200 volt, three-phase power to direct 27 volt power.

- a. Input power—Shall be capable of operating on a three-phase, 400 Hz four-wire, wye-connected alternating-current power system.

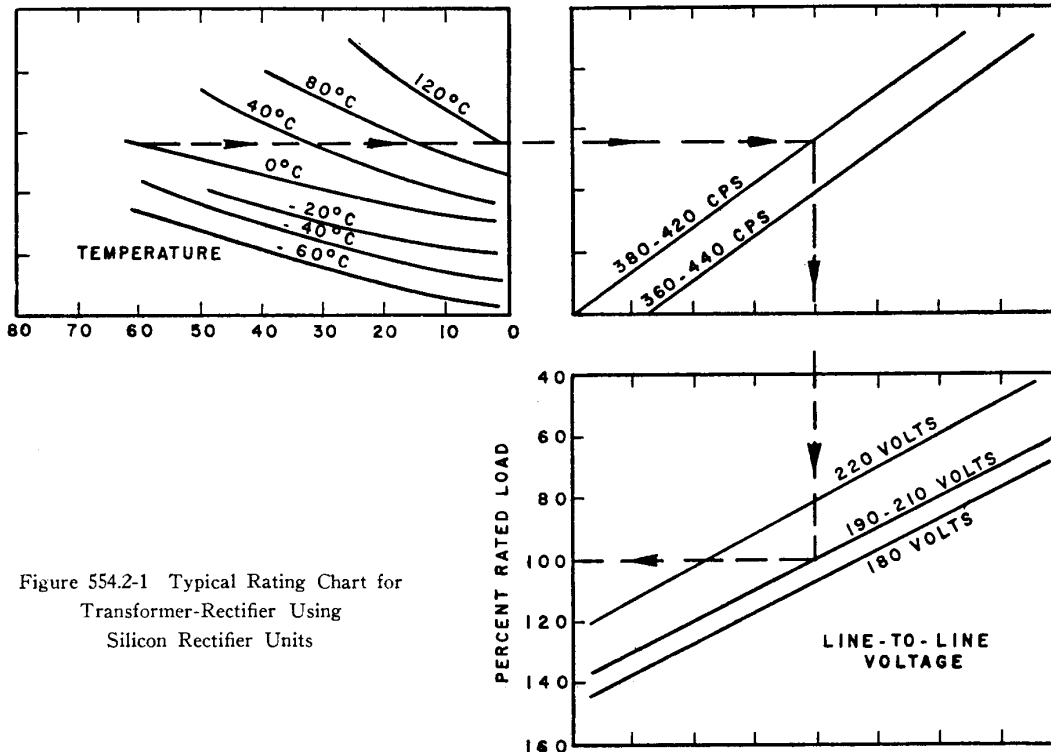


Figure 554.2-1 Typical Rating Chart for Transformer-Rectifier Using Silicon Rectifier Units

- b. Input voltage—Per MIL-STD-704.
- c. Input frequency—Per MIL-STD-704.
- d. Continuous Rating—Shall be capable of delivering a continuous output in accordance with the rating chart. (An example of a rating chart is shown in Figure 554.2-1 for a transformer-rectifier using silicon rectifiers.)
- e. Overload—Shall be capable of delivering :
 - 150 percent rated current for 5 minutes.
 - 250 percent rated current for 1 minute.
- f. Efficiency—Shall not be less than 80 percent at full load.
- g. Power Factor—Shall not be less than 70 percent at full load.
- h. Ripple Voltage—Shall not be greater than 1.0 volt peak maximum. A filter will probably be required to obtain so low a ripple voltage.
- i. Response Time—Shall not exceed 0.1 second after application or removal of full load.
- j. Regulation—Shall maintain an output voltage of ± 1.5 percent maximum at any voltage within the adjustable range, when the load is varied from no load to full load and the input voltage and frequency are maintained within the requirements specified by paragraphs b and c of this section.
- k. Parallel Operation—The transformer-rectifier shall be so designed such that when two or more units of the same style are operated in parallel, the load division between the transformer-rectifiers shall not show a greater deviation than five percent of the full-load rating of one unit based on the value of current that would normally be supplied to the common load by each unit during perfect load division.

554.3 Unregulated

The unregulated transformer-rectifier could have all the requirements specified for the regulated except response time and voltage regulation.

- a. The non-regulated transformer-rectifier shall be designed that the output direct voltage shall remain within the limits of 24 to 31 volts when load is varied from no load to full load, and the input voltage and frequency are maintained within the limits of 190 to 210 volts and 380 to 420 Hz.
- b. The transformer-rectifier shall be so designed that when two or more units of the same style are operated in parallel, the load division between the transformer-rectifiers shall not show a greater deviation than ± 10 percent of the full-load rating of one unit based on the value of current that would normally be supplied to the common load by each unit during perfect load division.

560 BATTERIES

570 CONTROL AND PROTECTIVE EQUIPMENT CHARACTERISTICS

571 Relays and Contactors

The American National Standard definitions covering contactors and relays are as follows:

Relay—A relay is an electric device that is designed to interpret input conditions in a prescribed manner

and after specified conditions are met to respond to cause contact operation or similar abrupt change in associated electric control circuits.

Contactor—A contactor is a device, operated other than by hand for repeatedly establishing and interrupting an electric power circuit under normal conditions.

In the aircraft industry it has been common practice to apply the term relay to all magnetically-operated switches.

571.1 General Types and Construction

Relays and contactors fall into two basic mechanical types—the solenoid type in which the movable member of the magnetic circuit is drawn inside the operating coil, and the clapper type in which the movable member is hinged and the magnetic circuit is closed by movement around the hinge point.

The choice of construction depends somewhat upon the kind of motion to be transmitted to the contact mechanism but probably more often by the design concepts of the individual designer. The clapper magnet type generally lends itself more readily to balanced construction because of the ability to counterbalance the weight of the contact mechanism about the hinge point while the solenoid type generally provides better space utilization due to its inherent symmetrical construction. Because of greater magnetic efficiency, stronger springs can be used with the solenoid type to increase resistance to vibration and shock comparable to that obtainable with the balanced clapper type.

Relays and contactors are available unsealed with dust-tight and explosion-resistant covers, and they are also available hermetically sealed for applications involving greater environmental extremes and explosion hazards. Hermetically-sealed relays and contactors generally employ metal-to-metal and metal-to-glass seals, although in some cases pressure-type seals have been able to meet performance specifications. Relay and contactor mechanism in a sealed enclosure are not affected by changes in altitude or pressure, or by salt spray, moisture condensation, or sand and dust. The contacts always operate in the same atmosphere which is usually an inert gas or mixture of inert gases.

An almost limitless number of contact arrangements are available in standard contactor and relay types from simple single-pole normally-open and normally-closed devices to multi-contact devices with various combinations of normally-open and normally-closed contacts. Contact ratings are available from a few amperes to hundreds of amperes.

In specifying contactors and relays the "normal" position is always considered the position with the operating coil de-energized—thus a single-pole normally-closed relay is one in which a single contact is open when the coil is energized and closed when the coil is de-energized. Latched devices are usually noted as such and their position must be determined by notation on the wiring or elementary diagram.

571.11 Many contact materials may be used successfully in aircraft relay and contactor construction, the choice depending largely upon the service requirements of the device. Where high continuous current-carrying ability is desired fine silver is generally used but where ability to close high in-rush currents is necessary, one of the alloys or refractory contact materials having high anti-welding characteristics is selected. It should be understood that a given material on one design of device will differ radically from that on another design due to conditions of contact slide, contact roll, contact bounce, etc.

571.12 Opinions differ as to the relative advantages of sliding action, rolling action and butt action between contact surfaces but all designers agree the contacts must come together with minimum tendency to bounce.

Sliding action is advantageous in keeping contact surfaces clean and, for low-current devices is generally accepted as the preferred contact design. On heavy-current devices also sliding contact is advantageous as long as the contact surfaces remain smooth but when pitting and roughening occur—a natural result of circuit interruption—there is a tendency toward contact stubbing with resultant failure of the contacts to seal. Sliding action also tends to increase contact wear because of the abrasive action between the two surfaces.

Rolling action between tips provides some assurance of closing and opening the circuit on one section of the contact surface and carrying current on another section. In addition, this construction provides the advantage of keeping the contacts in motion with respect to each other during the period of closing when the contact material is molten and therefore in condition to weld. The roll also offers some lever action tending to break any slight weld which might occur.

Butt action of contact surfaces is generally not used on devices having very low operating forces because of the possibility of closing against accumulations of foreign matter with resultant insulating of the circuit. On heavy-current devices butt action makes the problem of welding more acute since there is no relative motion between the contacts to break the weld—however many very good designs have been produced using “nonwelding” materials.

571.13 The size of contacts used is not necessarily a measure of current rating but rather it is a measure of the life or number of operations for which the device is designed. Of far greater importance in determining current rating is the mass and shape of heat-conducting material backing up the contacts and the efficiency of the thermal path conducting heat away from the contact surfaces.

Long contact life can be obtained either by large surface contacts or by depth of the contact material provided, in the latter case, the device must have enough “wipe” or follow through that contact pressure is not lost as material wears away.

The actual current density of a contact cannot be considered as the contact area divided by the rated current since contact is rarely made over the entire surface. As material is consumed the effective area moves around the total surface.

Any contacting device, particularly those interrupting heavy current, will show signs of pitting or burning after repeated operation. Sometimes this condition is interpreted as justification for dressing the contacts with a file or replacing completely. Contacts should not be replaced unless enough of the active material has been burned away to materially reduce the contact pressure and/or wear allowance. Contacts should not be filed unless the roughening is sufficient to cause defective action due to interlocking of burned edges or where insulating films have formed due to the presence of sulphur or other unfavorable conditions. In the case of silver contacts the formation of silver oxide is in itself not detrimental to good contact action since the oxide is burned off at a relatively low temperature. Where no arcing whatever occurs at the contact surfaces silver oxide might cause insulating of the contacts. Where there is a tendency for insulating films to form on low-energy devices a conical contact against a flat surface frequently provides the necessary high unit pressure to break down the film.

571.14 Most contactors and relays have either single- or double-break contacts although in a few instances three, four, and six breaks in series have been used for high-potential direct-current loads or highly-inductive loads. The advantage of double-break construction for circuit interruption particularly at high altitude has been amply demonstrated and is now generally accepted. Tests have proven that for a given total tip gap, double-break construction will increase the interrupting ability as much as four to five fold. In other words, a double-break construction using 0.020 inch tip gap on each break is several times as effective as a single-break gap of 0.050 inch.

For devices having limited arc-interrupting requirements single-break construction is generally adequate. Double-break construction obviates the need for pig-tail leads from rigid-type movable contact members.

Magnetic blowout coils can be used to facilitate arc interruption on contactors and relays especially where direct potentials above 50 or 60 volts are to be interrupted. Both permanent magnet type and electromagnetic type blowouts have been used. Multiple breaks in series have also been applied successfully without magnetic blowouts.

571.2 Rating

The nameplate current and voltage rating of a contactor or relay rarely provides complete information covering its capabilities. Different applications require different emphasis on certain design features such as control voltage, continuous and short-time current rating, surge currents, etc. Thus a contactor rated 200 amperes and 24 volts, which is a nominal rating, might be completely satisfactory as a bat-

tery-disconnect device but might fail completely as a motor-starting device even though the full-load current of the motor is much less than 200 amperes. It is necessary therefore, in each application to compare the characteristics of the circuit-controlling device with the requirements of the load.

571.21 The maximum voltage to which the operating coil will be subjected continuously dictates the coil design from the standpoint of heating. There are several factors which dictate the power that can be dissipated—type of coil enclosure if any, heat-radiating ability of the coil surfaces, end flanges, etc., and the thermal path provided through the magnetic circuit.

571.22 The nominal or nameplate rating of a relay or contactor is generally based on the current it will carry continuously without exceeding a predetermined temperature rise on the contacts. There are exceptions to this where the nameplate specifically states that the current rating is an intermittent rating in which case the maximum time the device will carry its rated current should be specified.

571.23 Most devices, whether continuous or intermittently rated, will carry higher currents for periods shorter than their nameplate rating basis although there is no fixed relation between continuous and short-time ratings. In the case of a representative contactor rated 200 amperes continuously the following short-time ratings apply.

15 minutes	300 amperes
5 minutes	400 amperes
1 minute	500 amperes

Frequently it is possible to increase the short-time rating of a device by simply increasing the contact pressure. Since this entails higher operating forces the coil also must usually be redesigned for intermittent operation.

571.24 The surge current rating of a device bears little relation to the continuous or nameplate rating since the ability to close high currents depends upon many factors such as contact materials, contact action, contact bounce, etc. For application to motor circuits particularly, consideration must always be given to the fact that motor starting current might be as high as ten times the normal motor running current. It is not difficult to design devices having high surge ratings since there are many so-called "non-welding" alloys that can be used for contacts. It becomes more difficult however to obtain high surge ratings and also obtain high continuous ratings because in general, contact resistance, and therefore contact heating, increases with the use of non-welding materials.

Care must be exercised in rating a device for surge current without giving due consideration to the frequency of circuit closing. A contactor might be capable of closing a given current value on a slow operating cycle but will fail if the operating cycle is

increased above some critical value where contact heating causes the contact materials to weld. For this reason accelerated life tests must always be made on a basis of maintaining contact temperatures somewhere near normal. Highly-inductive circuits are sometimes less troublesome from the standpoint of making high surge current values than are non-inductive circuits due to the time of build-up in an inductive circuit allowing the contacts to firmly seal before maximum current is attained.

571.25 Except for highly-inductive circuits the problems of high current interruption on 24-volt devices are less troublesome than those of high current closing. On low-voltage devices wide contact gap, multi-gap construction and high-speed operation offer ready means of solution. In general circuit-closing devices used on non-inductive or moderately-inductive circuits can interrupt any value of current they can close from sea level to 50,000 feet. An exception to this general statement is found in the application of devices to shunt or series (not split series) motor reversing service where under conditions of plugging the motor from full speed forward to full speed reverse the delay in extinguishing the arc might cause a short circuit.

For highly-inductive loads such as solenoid coils, motor shunt fields, etc., either de-rating the device or some means of arc suppression such as capacitance across the contacts must frequently be resorted to.

571.26 The pick-up voltage must be low enough to allow for low battery or bus voltage, for voltage drop in the control conductors and for increase in coil resistance due to coil heating and high ambient temperature. For continuous-duty 24-volt devices it is standard practice to design for a pick-up of 18 volts with the coil subjected to maximum ambient temperature but without coil self-heating. For intermittent-duty devices it is possible to dissipate more power in the coil and therefore lower pick-up values are obtainable. For most services a pick-up value of 7.5 volts for an intermittently-rated 24-volt device is considered satisfactory.

The design of the device should always be such that the armature will seal at a voltage less than the pick-up value. If this principle is not followed, application of low voltage to the operating coil might raise the contacts to the kiss position but failure to seal will result in contact burning and probable failure of the device due to excessive heating of the contacts, contact springs and insulating materials.

571.27 Drop-out voltage must be low enough to insure the contact remaining closed or open, depending upon whether the device is normally open or normally closed, under the lowest conditions of line voltage yet high enough to insure against holding on residual magnetism. A high drop-out device might disconnect the load under momentary fault conditions before the fault is cleared. For continuously-rated devices for 24-volt systems, the drop-out is usually specified as

7 volts maximum and 1.5 volt minimum. For intermittent devices the values are usually 2 volts maximum and 0.5 volt minimum.

571.3 Adverse Operating Conditions

Few contactors or relays fail in service when operating under conditions for which they were designed. Too many failures occur under adverse operating conditions either due to accident or misapplication. An appraisal of these possible adverse conditions should be made for each application.

571.31 One of the most frequent causes of failure, particularly in the case of heavy-current devices, is that of low control voltage. If the device is properly designed, application of low voltage to the operating coil is, in itself, ordinarily not detrimental since the device should seal on any voltage which will cause pick-up. If, however, the circuit is such that closing of the contacts causes a further reduction in control voltage due either to line drop or limited power source the contacts might remain in the "kiss" position and failure due to contacts burning or welding is almost sure to result.

If the circuit or power source cause of this condition cannot be corrected the use of an intermittently-rated device having low pick-up and drop-out must be resorted to, provided the nature of the load is such that an intermittently-rated device is feasible.

When a reversing motor is switched off by either control or limit switch operation, it continues to rotate for some time. During this interval, if the motor is energized to operate in the opposite direction, a voltage is generated within the motor with polarity opposite to that normally present. The motor thus tends to establish a terminal voltage which is opposite in polarity to that of the power supply. With limited power supply capacity, the tendency may be sufficient to actually cause the bus voltage (and contactor voltage) to drop to zero or reverse its polarity. Effects of plugging of large motors must be limited for successful contactors or relay application.

571.32 While most devices designed for flight vehicles withstand normal conditions of vibration, extreme conditions such as those encountered in some parts of an engine nacelle might cause sufficient vibration of the contacts to result in severe burning or welding.

Low-energy type relays are particularly susceptible to this difficulty and where conditions are very severe shock mounting should be used. Where control voltage reduction occurs as explained under Section 571.31, vibration is likely to augment adverse conditions.

Most relays in the past have been designed to withstand 10 G vibration from 10-55 Hz. Now relays and contactors are being designed to withstand vibration from 10-500 Hz at 10 G. Frequencies of vibration up to 2500 Hz are being found at certain locations and therefore designs must be made suitable for these frequencies or the contactors and relays must be located in a more favorable area. The simultaneous

presence of all frequencies in a spectral band further aggravates the problem of relay design.

571.33 Under extreme conditions of low voltage or where the power source is limited, reduction of voltage when the contacts close may be sufficient to cause the device to return to the de-energized position, causing complete circuit interruption. Interrupting the circuits causes the control voltage to be restored and the contacts again close with a resulting "telegraphing" action which will continue indefinitely until either the device fails due to repeated contact action and sluggish extinguishing of the arc, or of possibly greater importance, failure of the load occurs. This condition is particularly likely to happen when heavy motor loads are controlled from a battery source.

The cure for this condition may be the use of devices having low pick-up and drop-out characteristics or it may be an increase in power supply capacity, or a reduction in the severity of the motor in-rush current by use of reduced-voltage starters.

571.34 Conditions are frequently encountered where a device is adequate in all respects for its own load conditions but voltage reduction on the system caused by switching of other loads might cause the difficulties explained under Sections 571.31 and 571.33. Where extreme voltage dips occur on an installation it is advisable to check the control voltage characteristics of all electromagnetic devices used on the system.

For the control of intermittent loads such as most flight vehicle motors represent, it is advisable to give consideration to intermittently-rated magnetic devices since their low pick-up and drop-out characteristics are generally of considerable advantage in any power system. Even though the power system might be adequate for all connected loads, the possible voltage reduction due to momentary faults should be considered.

571.4 Calibrated Relays

Calibrated relays are used to detect when limiting values of voltage, current, or frequency are exceeded in order to protect load equipment or perform some other switching function automatically.

571.41 Where extreme accuracy is not required, a simple relay can often be used as a calibrated device to sense voltage or current. The force produced by the relay coil ampere-turns causes the relay to pick up and drop out when it exceeds or is exceeded by the spring forces which act as a reference. Calibrated relays of this type do not generally exhibit good repeatability and are susceptible to changes in calibration and even false operation in the presence of large acceleration, shock, and vibration forces.

Time delay can be added to simple calibrated relays by the use of dashpots, external capacitors, inductors, or thermal elements.

Adjustment of simple calibrated relays is generally achieved by varying the external circuit impedance, the spring constant of the relay, or the air gap of the magnetic circuit in the relay.

571.42 Where present-day standards of accuracy and resistance to acceleration, vibration and shock are required, it is generally not possible to accomplish this with a simple relay. In order to improve the accuracy of the operating points, an accurate reference and comparison circuit are often used in conjunction with a magnetic amplifier or transistor to supply power amplification. The overall circuit is generally designed to have snap action, resulting in a rapid change from minimum to maximum or from maximum to minimum output when the operating point is reached. The output signal thus achieved may be used to energize and de-energize a standard output relay. Since this output relay is used only as an "on-off" device, it has the maximum possible resistance to acceleration, vibration, and shock. In some cases it may be possible to utilize the output of the amplifier directly to energize another circuit, thus eliminating the need for an output relay altogether.

Time delay can be achieved easily with calibrated relays employing magnetic amplifiers and transistors. Delay can be introduced by the use of capacitors or by the use of highly-inductive magnetic amplifier control windings. It can generally be arranged such that snap action occurs at the end of the time delay period, thus maintaining maximum resistance to environmental factors.

Adjustment of high-accuracy calibrated relays is generally achieved by varying the impedance of some circuit element, usually in the comparison circuit. Usually adjustment of the mechanical characteristics of the output relay is not required and hence a hermetically-sealed unit may be used.

571.5 Dry Circuit Operation

A fairly common cause of contact trouble has been operation under very low currents—this has come to be known as "dry circuit" operation. Applications where this may show up are those short-circuiting the secondary of a high-ratio current transformer, closing the grid circuit of a vacuum tube, etc. In all such cases, the potential available across the contact surfaces may be too low to break down a film formed either by previous arcing or by exposure to an organic vapor. The methods we have to improve "dry circuit" operation is to provide some type of contact action that will always result in clean metal-to-metal contact, elimination of operation in organic vapors, and the minimization of arcing and the consequent formation of non-conducting or semi-conducting films. Unfortunately, the very type of operation which is known as "dry circuit" also precludes the application of arc-suppression networks, for such circuits can be effective only when the minimum arc current is higher than the circuit current. Minimum arc currents may be as high as one ampere for clean metal surfaces but may be as low as 0.03 ampere for carbonized surfaces. Further, the discharge of capacitances forming a part of many arc-suppression devices may cause contact damage in dry circuit operation which is almost as severe as the erosion from a sustained arc in a circuit normally considered as high current. It is usually considered that arc-suppression devices

should not be installed in circuits where the current is less than 0.5 ampere.

572 Circuit Breakers

572.1 Variety of Types and Construction

A circuit breaker in the flight vehicle industry is constructed to be capable of automatic circuit interruption under fault conditions, and also capable of repeatedly performing this function when the prescribed set of fault conditions exist. Primarily these devices are used to protect cable and should be selected to match the thermal characteristics of the cable. Breakers are usually designed for frequent operation and are often used secondarily as emergency switches.

572.2 Method of Operation

Circuit breakers are classified by method of operation as thermal, magnetic, or combination thermal and magnetic. In addition, breakers may be manually operable or operated electrically, and may be trip-free or non-trip-free (see Section 572.52).

572.3 Remote Circuit Breakers

Remote circuit breakers usually consist of a solenoid-operated contactor with its coil circuit controlled through a snap action switch by a current-sensitive element. This combination is used in conjunction with a manual trip indicating breaker. When the current sensitive element detects a fault condition in the remote location, it causes the switch to open the contactor coil circuit, thereby opening the main circuit; and, at the same time, the switch applies an overload to the manual trip indicating breaker causing it to trip. Reclosing the trip indicating breaker will re-establish the main circuit. The trip indicating breaker should be trip free to prevent closing it in on an overload in the event that the remote breaker current sensitive element has not recycled. It should be noted that remote circuit breakers depend upon the solenoid contactor to open the circuit in the event of a fault. This requires that the contactor have an interrupting capacity equal to the full capacity of the system or that back-up protection, such as a limiter, be provided.

572.4 Rating

Circuit breakers are rated to continuous current carrying capacity, maximum interrupting capacity, and operating voltage of the system or systems on which they are designed to operate.

572.41 Circuit breakers are generally designed for use both on 28-volt direct-current circuits and on 115/200 volt 400-Hz alternating-current systems. In the case of magnetic breakers, however, the trip time may be different for the two systems, whereas with thermal breakers trip time is dependent on current and ambient temperature only and is independent of voltage.

572.42 Circuit breaker ratings are usually based on ability to carry 115 percent of rating continuously without tripping, and ability to trip within one hour

on 138 percent of rated load, and should be capable of carrying 100 percent of rated current in a 57°C ambient. Minimum and maximum trip times at 200 percent of rated load are frequently specified also. In addition, MIL-C-5809 contains calibration curves for trip time versus percent rated current and for effect of ambient on ultimate trip. Breakers must fall within the limits of these curves.

572.43 Interrupting capacities of manual circuit breakers are specified in MIL-C-5809 according to the ability of the breakers to rupture and close-in-and-rupture a calibrated fault current for two operations each at sea level and at 50,000 feet for both alternating-current and direct-current ratings. Available currents are measured at the breaker terminals prior to insertion of the breaker. The actual current values to be interrupted are specified on the individual military standard drawings.

MS 25017 has been established to provide push-pull breakers for high-capacity bus systems encountered on new larger military aircraft. MS 25017 calls for a close-in and rupture supply source of 6000 amperes direct current and 3500 amperes alternating current with recovery voltages of 30 ± 2 volts and 120 ± 5 volts. Consideration is being given to raising these values to 7500 amperes direct current and 3500 amperes alternating current with recovery voltages of 50 ± 5 volts direct potential and 300 volts alternating potential.

Because failure of a circuit breaker to isolate a fault presents an electrical fire hazard, careful consideration should be given to the class of breaker required, based on the available short-circuit current capacity and potential recovery voltages of the electric system under consideration.

572.44 Circuit breakers are available with the following tripping characteristics:

- a. Overcurrent— instantaneous or inverse time.
- b. Directional Overcurrent— instantaneous or inverse time.
- c. Current Balance— instantaneous or inverse time.
- d. Differential Current— instantaneous or inverse time.

572.5 Nature of Reclosure

572.51 Circuit breakers may be electrically resettable from a remote location or may be manually operable. Either type may be thermal, magnetic, or a combination of both in method of action. Manual circuit breakers are further divided into toggle-lever and push-pull. Toggle-lever circuit breakers have the advantage of ease of operation, and can be used conveniently as a combination switch and circuit breaker. Toggle-lever circuit breakers on critical circuits, however, should be protected by guards to prevent accidental opening or closure by bumping, snagging, etc. Push-pull circuit breakers have the advantage of being less susceptible to accidental opening, and are available with higher interrupting capacities. They are, however, difficult to operate with heavy gloves on.

572.52 A trip-free circuit breaker is one which cannot be maintained closed while a fault or tripping condition still exists. The trip-free circuit breaker can be reset against a fault, but will trip automatically as long as the fault still exists, even if the manual or electric operator is held in the reset position. Trip-free circuit breakers are generally recommended as giving the maximum amount of protection and safety. If properly applied, trip-free circuit breakers give maximum equipment utilization without the danger inherent in non-trip-free circuit breakers which can be "overridden" and forcibly held in against a fault. At one time non-trip-free circuit breakers were recommended for critical circuits which had to be maintained at any cost, but current thinking is that all circuit breakers should be trip-free (non-override) in the interests of safety.

572.6 Contact Pressure

572.61 On thermal-type breakers the contacts are latched closed. Contact pressure depends only on the contact pressure springs and wear on the contacts and is independent of system voltage.

572.62 If contacts are held closed magnetically, the contact pressure may depend on system voltage. It is possible, however, to design a mechanism such that positive contact pressure is applied on a magnetic circuit breaker, regardless of system voltage. Most magnetically maintained circuit breakers are designed so that positive contact pressure is applied on any voltage down to the actual drop-out voltage of the device.

572.7 Means of Indicating Operation or Position

On push-pull manual circuit breakers the position or condition of the circuit breaker is indicated by the pushbutton. A colored band will show when the button is out in the "off" or "tripped" position. Pushing the button in restores the circuit breaker to the "on" condition.

On trip-free toggle-lever manual circuit breakers the toggle moves to the center position when the circuit breaker trips. To reset the circuit breaker the toggle is moved to the full "off" position and then to the "on" at which time the contacts are reclosed. A tripped unit can readily be distinguished in a row of circuit breakers, some of which are on and some of which are off, by the center "trip" position of the lever.

572.8 Adverse Operating Conditions

Manual or electric reclosure of a non-trip-free circuit breaker on a fault is an undesirable situation from a safety standpoint. If a circuit is so critical that it must be maintained even under fault conditions, consideration should be given to the use of parallel circuitry with duplicate circuit breakers.

If magnetically tripped, circuit breakers may be subjected to nuisance trip-outs due to current surges and voltage dips associated with current surges. Application of a magnetically-tripped circuit breaker in a circuit with heavy motor starting inrush currents should be carefully checked.

Adverse ambient temperature conditions should be taken into account in planning circuit breaker instal-

lations. Although magnetic circuit breakers are somewhat independent of ambient in their action, the tripping time of thermal circuit breakers is significantly affected by ambient, both at or near rated load and under overload conditions. Use of a thermal circuit breaker thus permits the maximum utilization of circuits, when the temperature-time tripping characteristics of the circuit breaker approximates the temperature-time curve of the cable protected. If a thermal circuit breaker and the cable being protected are in widely-different ambients, derating or uprating the circuit breaker should be considered in planning the installation.

573 Fuses

573.1 Definitions, Principles and General Recommendations

A fuse is an overcurrent protective device with a circuit-opening fusible member directly heated and destroyed by the passage of overcurrent through it. A fuse is a thermal device and will therefore be influenced by ambient temperature variations. These variations affect to some extent the fuse minimum "blowing" current as well as its "blowing" time at higher currents. This characteristic should not be overlooked in applying fuses. The normal use of a fuse should be to provide circuit protection. To perform this function, they should be selected to match, insofar as practicable, the thermal characteristics of cable. In many instances, fuses are used to provide equipment protection as well as cable protection. See below for precautions to observe.

573.11 The overload characteristics of fuses generally differ from the overload characteristics of electric equipment; and fuses are seldom located or designed to respond ideally to changes in the ambient temperature of the equipment. Hence fuses generally do not provide good equipment protection *and* utilization.

573.12 In general, fuses should be selected on the basis of the highest rating that will adequately protect the cable. For emergency circuits (circuits the failure of which may result in the inability of the vehicle to maintain controlled flight) it is essential that the fuse be of the highest rating possible consistent with cable protection. For these circuits it is especially necessary that the cable and fuse combination supplying the power be carefully engineered, taking into account short-time transients (e.g., motor starting, abnormally-high current due to low temperature operation, etc.) in order to insure maximum utilization of the vital equipment without circuit interruption.

573.13 For non-emergency circuits it may be desirable to select the fuse on the basis of the lowest rating consistent with reliable equipment operation. Careful engineering and/or testing is recommended to demonstrate the effectiveness of such protection under service conditions.

573.14 Fuses should usually be located accessible for replacement in flight in manned vehicles and should be located as close to the bus as possible so as to achieve the minimum of unprotected wiring. There

will be instances, however, where fuse locations other than accessible in flight will result in the minimum of unprotected wiring, and provided that operation of the vehicle is not prejudiced, such locations are considered satisfactory.

573.15 Fuses, particularly high-capacity units, dissipate considerable energy and their installation should allow for heat rejection so that the temperature rise of the fuse(s) does not exceed that of the cables and so that the mutual heating of two or more fuses does not adversely affect the desired time-current curve or continuous rating of the fuse. Also, care should be taken to insure that the rejected heat does not cause an overheat condition on adjacent equipment coupled to the bus in the vicinity of the fuses.

573.2 Application of Fuses

Either fuses or circuit breakers may be used for circuit protection except that circuit breakers are preferable on any circuit whose failure endangers safety of flight. This preference is primarily due to the fact that resetting a circuit breaker is believed to be safer and quicker than changing a fuse. The hazard of replacing a fuse with one of the wrong current rating or of creating an accidental short circuit in an open fuse panel is increased during the stress of flight emergencies. Circuit breakers also provide more positive trip indication than do fuses. However, presently-available fuses provide a much wider range of ratings and trip characteristics than is now available with circuit breakers. In particular, the non-availability of circuit breakers rated at one ampere or less has led to the general practice of protecting equipment such as instruments, small transformers, etc., with low-rated fuses. When the nature of a circuit requires mixing circuit breakers and fuses in a cascaded system, extreme care should be used to insure proper protector coordination. Fuses may be affected by vibration or shock; therefore, care should be exercised in selection of types and locations such that a satisfactory installation will result.

573.21 For many years fuse types were covered by Army Specification 94-32271-A, 94-32272-A and 94-32084, all of which have been obsoleted, but there are still many references in the literature to them. These specifications have been superseded by MIL-F-15160 which contains in a single document the old specifications with more up-to-date requirements. Attention is called to the provisions of this specification for all types and ratings of fuses applicable for aircraft usage.

Note: Also see limiters, Section 574.

573.3 Fuse Materials

Fuses should be fabricated of fractureproof material and be specifically constructed to withstand aircraft vibration. They should have firmly attached ends and a convenient means of extraction.

573.4 Connections for Fuses

Fuse clips when used should be beryllium copper, silver plated. Bolted connections are preferable to spring clips and should be used for fuses rated at 50 amperes

and over. Loose or high-resistance fuse connections cause excessive heating with danger of nuisance circuit opening and possible arcing. Any substitute methods of attachment not conforming to the above recommendations should be thoroughly investigated and proven by test. It should be especially noted that dirty contacts and heating of the fuse clip tends to draw the temper of the spring material and further weaken its contact pressure.

- (a) The blowing characteristics of a fuse directly bolted to a high-capacity bus may be affected by heat transfer through the bolted connection. Specification tolerances on fuse-blowing characteristics are so broad that the above effect is probably negligible except for special cases where close coordination is being attempted on the basis of a particular manufacturer's product and special tolerances.

574 Limiters

574.1 Definitions, Principles and General Recommendations

A limiter is an aircraft fuse specifically designed with a high-temperature melting point to provide protection for electric power distribution systems against fault currents. It is manufactured to have a closely-controlled curve of melting current versus time, and the use of a silver or copper link having a high melting temperature makes it relatively more insensitive to wide ranges of ambient temperature than a normal fuse. The term "limiter" is drawn from usage in 60 Hz circuits, where the blowing time was less than a quarter-cycle, effectively "limiting" the fault current. Such operation does not occur on 400 Hz and higher frequencies and the limiter must not be considered to have limiting action.

574.1.1 Limiters are not appreciably affected by changes in ambient temperature normally encountered in aircraft due to the high melting temperatures of the fusible link used in the limiter construction.

574.2 Cable Protection with Limiters

Limiters are not designed to and do not match the thermal characteristics of aircraft electric cable. A limiter chosen to provide complete cable protection will have less short-time (high-current) overload capacity than either a circuit breaker or "slow-blow" fuse.

574.3 System Protection with Limiters

Limiters are designed specifically to isolate any portion of an electric power distribution system which may be drawing fault current quickly enough to prevent voltage collapse or damage to the generating system. The difference between fuse and limiter applications may be illustrated by two examples: Power leads from the bus to the engine starter are normally subjected to severe overloading for a short time only. Proper protection of such a cable, still allowing for maximum utilization of a small light cable, can best be achieved by a "slow blow" fuse or other protector designed with a current-time characteristic conform-

ing closely to that of the cable. In contrast, the power leads from a main bus to a sub-bus usually carry current continuously; voltage drop limitations and the nature of the loads usually result in conditions in which maximum utilization of the cable is not required. There is, however, the need for isolating this feeder should it or the sub-bus become grounded. This can be accomplished very well by a limiter, under short-circuit conditions the limiter will open and relieve the main bus and generating system more quickly than a "slow-blow" fuse.

574.4 Application

In summary, limiters are useful for isolating high-capacity cables whose short-circuit current might collapse or damage the generating system if cable protection were based on maximum utilization of the cable; while "slow-blow" fuses or circuit breakers are best for realizing maximum cable utilization. High-capacity limiters in general need not be accessible for replacement in flight, since the nature of the faults to be cleared generally makes it undesirable to be able to replace such devices, while their frequent location at the main bus would usually make it difficult and unsafe to attempt replacement until power is removed from the bus. Limiters should be installed to allow for proper heat rejection although excessive heat transfer to a high-capacity bus should be avoided; particular care should be taken to prevent installing high-rating fuses or limiters in such a way that this rejected heat may cause an overheat condition to develop in adjacent equipment or equipment to which the limiter may attach. Limiter installations should be arranged in such a way that undue mechanical strain will not be imposed in the limiter link or case.

574.5 Types of Limiters

Limiters are presently available in two types: (1) for 28-volt direct-potential systems and (2) for 208/120-volt, 3-phase, 400-Hz systems. The 28-volt direct-potential limiters have a current-rupturing capacity of 5,000 amperes; the alternating-current limiters are covered by Specification MIL-F-5372 and are rated to safely interrupt 4,000 amperes at 120 volts and 2,500 amperes at 280 volts, 400 Hz. These alternating-current limiters come in sizes from ten to 100 amperes. For specific time-current values, refer to the specification and the manufacturers' curves, which do not always agree. Refer to Section 132, Figure 132-13, for time-current comparisons between limiters and circuit breakers.

Neither of the two presently-available types are entirely suitable for 120-volt direct-potential applications.

575 Switches

575.1 General

Switches fall into four general categories: 1) manually-operated control switches, 2) mechanically-operated indicating switches, 3) mechanically-operated limit switches, and 4) special switches.

Toggle, rotary, and pushbutton switches all fall under the manually-operated control switch category.

While they are precision switches in one sense of the word, their operating points with reference to specific positions have rather wide tolerances. The simplest manually-operated switches consist of a conducting member which is pushed in between two contact points, thereby completing a circuit. More complicated manually-operated switches are composed of many precision, snap-acting switches which are so mounted that they may be operated from a single control.

Switches which fall under either the indicating or limit switch category have operating points and general characteristics which are quite consistently repeatable. This places these switches in a precision switch class.

A precision type switch assembly which is actuated as the result of impact or acceleration should perhaps be placed in the fourth category, along with other switches such as torque switches, mercury switches, and pressure switches.

For dry circuit switch applications, see Section 571.5.

575.2 Basic-Switch Types

575.21 Nearly all limit-switch assemblies fall under the category of precision, snap-acting switches. A precision, snap-acting switch should probably be defined as one in which the make or break of the contact always occurs at the same position of the actuator regardless of the speed at which the actuator has moved, the make or break of the contact points occurring very rapidly.

If a switch is installed in a circuit where snap-action is a requisite, the switch chosen should be carefully analyzed to determine if its snap-action is fast enough. Few, if any, switches called snap-action do not have a "dead" position or band where neither contact makes if the actuator is moved slowly, or is teased into position. Thus, it is entirely possible that a switch regarded as snap-action may not have this characteristic at all as a result of its installation. The term "snap-action" is insufficiently defined to permit a selection to be made without detailed knowledge of the switch itself and its installation.

Most limit switches consist of an actuator assembly and a basic precision, snap-acting switch. The actuator assembly provides for a certain amount of actuator travel before switching occurs and a certain amount of over-travel of the actuator after switching. For example, the basic switch used in these limit switch assemblies maintains contact until the actuating mechanism is depressed to a certain precise position. At that position one set of contact points is rapidly separated and another is rapidly closed. These basic snap-acting switches are manufactured with various circuit arrangements, such as single-pole single-throw, single-pole double-throw, double-pole double-throw, split contact, etc. Several basic switches are often ganged together and are operated by one common actuator which provides a multiplicity of possible control circuit combinations from the one assembly.

Many rotary and toggle switch assemblies also incorporate basic snap-acting switches.

Some pushbutton switches may be considered snap-acting types.

575.22 Some toggle switches do not possess fast snap action. If the bat handle is pushed from one position to another in a normal fashion, relatively fast snap action occurs in most toggle switches. However, in many types of toggle switches it is possible to grasp the bat handle firmly and move it to an intermediate position so the contact points can be teased. Momentary contact toggle switches are particularly susceptible to this teasing characteristic.

Many rotary switches utilize wiping or nonsnap-acting contacts. The operating knob of these switches can be rotated slowly enough to cause a slow make and break operation with consequent burning of the contact points.

Certain types of pushbutton switches have no inherently built snap-acting characteristic, and can consequently be teased. These normally provide no "feel" at the make and break contact positions of the pushbutton.

575.3 Environmental Conditions

575.31 Switches in flight vehicles are subjected to several different types of environmental conditions. For instance, switches in a cockpit or cabin of a modern aircraft are normally operated within the pressurized and heated zone of the aircraft. However, if the aircraft is of a combat type, emergency operation of the switches under adverse conditions of altitude and temperature must be possible in case combat attack causes a puncture of the cabin or malfunction of the pressurization or heating system.

Another type of environmental condition which affects cabin or cockpit switches occurs when food and liquid, such as orange juice, coffee, and water are accidentally spilled on panels which contain toggle or other manually-operated switches. Some of these switches are not subject to such treatment because they are located in an inverted position in the roof of the larger airplanes. Many of them are located on vertical instrument or flight control panels, but a large number of these manually-controlled switches are located on horizontal or nearly horizontal panels, and these are the ones which very often are subjected to spilled liquids or food. Unless these switches are provided with a fairly efficient seal around the operating mechanism they are quite likely to become internally corroded and fail to function.

Switches which are installed in an area affected by nuclear radiation must be carefully chosen. Some materials presently used in switches will not withstand the effects of nuclear radiation over extended periods of time.

Switches in wheel wells must withstand exposure to hydraulic oil, engine oil, mud, dirt, ice, and road oil from macadam runways. These switches must also stand the normal maintenance washdown procedure

which involves the use of a grease-cutting agent, such as Stoddard solvent and steam cleaning. These switches must be capable of operating reliably under conditions of a combination of exposure to the above-mentioned foreign materials and extreme temperature ranges. In slow-flying, high-altitude vehicles the switches may be subjected to extremely-low temperatures, while in fast-flying vehicles these switches must withstand extremely-high temperatures as a result of the heating of the wheel well compartment from skin friction.

It is desirable that switches and their actuators be completely environmental sealed. This prevents jamming of the actuating mechanism or failure of the switch points to make contact when altitude and temperature change rapidly such as in a diving fighter plane, causing serious condensation and eventual freezing to occur in actuator mechanism.

In flap limit, or indicating switches, the same temperature range as experienced by landing gear switches may be expected, but sand and dust normally represent some of the most critical materials present.

Engine compartment switches are required to withstand even higher or lower temperatures in combination with exposure to various fluids, sand and dust. Although vibration has not been mentioned in the previous paragraphs, switches must withstand vibration conditions, but switches in engine compartments are sometimes called upon to withstand vibration or shock loads many times higher than most other switches.

575.32 Limit switches in sea or amphibious vehicles are sometimes spared the environmental conditions involving sand and dust, but they often are called upon to operate in all the other environmental conditions heretofore mentioned, plus salt water spray or submersion in salt water.

575.4 Current and Voltage Ratings

575.41 Generally speaking, switches in small aircraft are called upon to carry larger currents than switches in large aircraft. This may seem odd, but small aircraft of the private aircraft category nearly all utilize a 12-volt system, while practically all large aircraft utilize a 24-volt direct-potential or a high voltage alternating-potential system. This automatically causes switching currents in the small aircraft to be higher than in the large aircraft if the same wattage equipment is involved. Navigation, communication, and lighting equipment fall into this class. Heavy-current-consuming items such as landing gears and flaps must be controlled by relays. The control switches for such items of equipment are then only required to carry the relay current.

The physical distance between the main power bus, the switch, and the equipment is small enough in most small aircraft that voltage drops through the wiring allow direct switching. In large aircraft the distance between the supply bus, the control switch-

ing position, and the equipment is so large that relays have to be installed to allow direct runs of power-carrying wires from the supply bus to the equipment.

Although military fighter aircraft are considered small aircraft in one sense of the word, they are still large aircraft in many respects, and relays have to be employed in many instances to reduce the voltage drop in the power wiring. It is, however, true that the cockpit arrangement and many of the power-consuming pieces of equipment are close enough to the pilot and his control switches that the equipment current can be switched directly without the use of relays.

To summarize these paragraphs, it might well be stated that a row of toggle switches in a large aircraft will carry very small currents, while a row of toggle switches in a small commercial-type aircraft will probably be working at or near their maximum capacity, and a similar row of switches in a fighter aircraft will be split so that part of them will carry high current and part very low current.

575.42 In one four-place private aircraft recently produced, all of the landing gear and flap limit switches carry and break the full landing gear and flap motor loads. The propeller-pitch limit switches in part of the installation carry and break the full propeller motor load.

In one of the large bombers recently built, with two exceptions, no switch is required to carry or break more than a relay-coil current. In this bomber a 1/2-ampere, 24-volt rated switch would be more than adequate.

In military fighter aircraft a mixed set of conditions exists in the current requirements of limit switches which matches the general pattern already mentioned regarding toggle switches.

To summarize these paragraphs, it might well be stated that electric load currents are low enough and distances are short enough that limit switches can do a direct switching job instead of a control switching job in small aircraft. On the other hand, in larger aircraft the electric load current requirements are too high for the limit switch and power distribution can be more efficiently accomplished by having the limit switch control relays, contactors, or solenoid valves.

575.43 Although most control and limit switches are called upon to control currents in the fraction-of-an ampere to many-ampere range at voltages of 12, 24, or higher, there are a few applications where these switches are required to control units of only micro-amperes, or a few milliamperes at most, at voltages varying from almost zero to only a few millivolts. Special attention must be given to the selection of these switches, and the switch manufacturer must be made well aware of all of the conditions surrounding these special switches.

There are certain emergency switches, such as acceleration switches, which are almost never called upon

to operate. These applications should again be called to the attention of the switch manufacturer so special contact materials can be installed to match the requirements.

575.5 Examples of Special Switches.

575.51 Commercial airliners are equipped with emergency lighting systems which are automatic in their operation. An impact or deceleration switch operates the lighting system if the aircraft is subjected to a sudden change in velocity such as is experienced in the case of a crash. Some of these switches sense deceleration only in the forward direction, while others sense accelerations or decelerations in all directions.

These decelerations or impact switches are sometimes used to control relays which in turn shut off oil, fuel, hydraulic oil, generators, and batteries, and perform other operations automatically which are strictly emergency operations. This relay is sometimes connected so it automatically discharges the fire extinguishing system.

575.52 Another form of acceleration switch is often called the "G" switch. It is arranged to detect positive and negative G loads. At certain limits this type of switch will operate and disconnect the automatic pilot or some portion thereof, thereby protecting the vehicle from being subjected to loads beyond its designed strength.

575.53 Wipe-off switches are sometimes used in conjunction with impact or deceleration switches to shut off flammable liquids and electric systems. Several of these wipe-off switches are mounted in the lowermost points of the fuselage and engine sections so if the aircraft lands with its wheels up these switches will be automatically operated with first contact of the vehicle and the ground. This switch is in effect a backup switch for the deceleration or impact switch mentioned above.

575.54 Mercury switches are considered undesirable on aircraft, because mercury in contact with aluminum causes serious structural weakening.

575.55 Pressure switches are employed in many varied applications to detect ram air pressure, air speed, engine fuel, hydraulic oil, and engine oil pressure. Such switches normally consist of a snap-acting basic switch coupled with a bellows or diaphragm and are packaged as a unitized assembly.

575.56 Many screw-jack actuators contain built-in snap-acting switches which are so coupled to the moving parts of the actuator that they provide automatic limits for the actuator travel. When switches are self-contained in such actuators they often simplify the aircraft designer's problems regarding the installation of limit switches for flaps, cowl flaps, air duct valve actuators, etc.

575.57 Precision switches are sometimes mounted in such a fashion that they detect relative movement

between the engine mount and the aircraft structure. This relative movement occurs when the engine is producing torque, and, by properly applying the switch, the aircraft designer can provide for torque indicating or automatic propeller feathering as signaled by the torque switch. This is applicable on both reciprocating and turbo-prop engines.

580 UTILIZATION EQUIPMENT— MISCELLANEOUS

581 Electronic Equipment

581.1 Types

Flight Vehicle and Group Control electronic equipment usually falls into one of the following categories:

- (a) Radio communication
- (b) Internal communication
- (c) Navigation systems
- (d) Radar and special military equipment
- (e) Control systems
- (f) Instrumentation

581.2 Electronic Equipment Circuit Features

The types of electronic equipment listed in Section 581.1 have many circuit features in common. Vacuum tubes, semiconductors or magnetic amplifiers are used in most of them to amplify signals, regulate current flow or generate signals of various frequencies and wave forms. Many have servo systems which require common synchronous excitation. Some have timing motors and time delay relays which require a relatively constant-frequency and/or voltage supply.

For the purpose of the designer of the flight vehicle electric power system a detailed knowledge of the circuitry of any of the electronic equipment is in most cases not necessary, as the load characteristics furnished by the equipment manufacturer give all the data needed. Manufacturers of electronic equipment are guided in their designs by electric power system standards of the vehicle manufacturers and by military specifications. They thus design their equipment to accept input power with these standard characteristics, and if there are internal circuits in the equipment which require better or different characteristics, then improvement or change must be accomplished as a part of the equipment. A simple and common example is the steady direct voltage required for the operation of a radio transmitter. A simple and common example is the various levels of low direct-current voltage required by most sophisticated electronic systems. These systems incorporate solid-state integrated circuits requiring various voltage levels of which the more common levels are 5, 10, 12 and/or 15 volts direct current at regulation levels of 1 to 3 percent. Input power to the equipment is normally 115/200 volts, 400 Hz, three phase with steady state and transient tolerances defined by MIL-STD-704.

The various levels of low voltage direct current are obtained from a multi-level, integrated power supply consisting of a tapped transformer(s) rectifiers, solid-state series or shunt regulators, and filters in each regulator output.

581.3 Power Types

The basic types of power furnished by flight vehicle electric power systems are primarily direct current, and narrow-frequency alternating current (380 to 420 Hz, with 395 to 405 Hz commonly achieved); other frequencies in use are variable-frequency alternating current (330 to 1200 Hz), wide-frequency alternating current (320 to 480 Hz) and fixed-frequency alternating current (400 to 0.1 Hz). Higher frequencies are being used, in some cases up to 3200 Hz. It has been proposed that 3200 Hz be adopted as standard frequency. However, a constant frequency in the range of 1200 to 2000 Hz appears more attractive for aircraft. In all cases, electronic equipment is designed to use the available power directly from the generators wherever possible. Alternating-current-operated equipment uses transformers to obtain the voltage levels required by the various internal circuits, with rectifiers and filters to obtain the smooth direct current required. Much of the standard equipment available today operates on 28 volts direct potential, and has a built-in converter to change the direct current supply to the voltage levels required.

581.4 Supply Variations

Variations in the voltage and frequency of the power supplied to electronic equipment terminals should be restricted, of course, to the excursions permitted by the flight vehicle specification, usually MIL-STD-704. Electronic equipment should be designed to function properly over these ranges by its own specification. In general, it can be said that increasing voltage above rated value will tend to decrease the life of electronic equipment, especially with regard to the filaments of vacuum tubes and increased semiconductor heat dissipation. Sustained reduction of the voltage below rated value will tend to reduce the power output of radio transmitters, reduce the sensitivity of radio receivers, reduce accuracy of some servo systems and in general reduce the performance of electronic equipment.

Short-time voltage surges, depending on the actual duration and amplitude, could cause drop-out of overload relays, fuse burn-outs, possible tube and transistor burn-outs and momentary instability.

Sustained frequency variations of the fixed-frequency supply could cause abnormal operation of timing relays and servo systems. The variable-frequency supply feeds, for the most part, power transformers and blower motors, and although these are designed to operate over a wide range of frequencies, the transformer voltage and heating may vary sufficiently with extreme changes to be objectionable. Blower motors, due to speed changes, may cool less effectively and possibly vibrate excessively.

581.5 Harmonic Content

A harmonic content of approximately five percent of the fundamental is usually permissible in alternating-current power systems. Electronic equipment should operate undisturbed with this degree of distortion. The lower the harmonic content of the supply the better, of course, and it should be observed that harmonics in the power wiring often cause interference with the operation of electronic equipment by mutual coupling between the power wiring and external wiring of the equipment. Both voltage and frequency modulations are normally present to some degree in alternating-current systems.

582 Electric Heaters

Electric heaters are resistive loads, substantially constant, designed to convert electric power directly into heat, and are used when heat from other sources is not readily available.

582.1 Space Heaters

Space heaters are often used to heat the air and walls of a compartment in an airplane by radiation and convection. Forced-air convection heaters have fans or blowers to assist in distributing the heat. The air flow from these heaters is often used in removing moisture (defogging) from chilled surfaces such as windows.

Care should be taken to see that heater elements are so designed and arranged that negligible magnetic fields will be produced near magnetic compasses.

Space heaters are often used to heat the air and walls of a compartment in an aircraft by radiation and resistance while operating. The initial current of a radiant heater may be 20 percent above the steady-state value with typical resistance materials.

582.2 Direct Thermal Transfer Heaters

Heaters with the element in direct physical contact with some equipment or material to be heated, rely on the thermal conductivity of the physical connection for heat transfer. Usually the element temperature remains near that of the item heated, so that the initial current is the steady-state current.

Direct-transfer heaters may take the form of a blanket or boot wrapped around a surface or part to be heated, or may be buried in a part like a casting. Resistance film heaters, such as Nesa, also fall in this category. Similarly, immersion heaters fall in this category, although fluid convection assists the heat transfer.

582.3 Other Heaters

Other types of heaters include incandescent lamp heaters and heaters of the space-heater type built into an item of equipment for localized heating, such as some galley equipment. (See Section 584 for incandescent lamps.)

583 Solenoid Actuators

A solenoid is a coil designed to perform work when energized, usually by pulling a movable member of the magnetic circuit into a position of reduced air

gap. Since coils are highly inductive, most solenoids are direct-current operated, although laminated and shaded-pole designs are occasionally used on alternating current. The inductive character of solenoids requires that special consideration be given to the switching mechanism, because a high-voltage switching transient is produced on opening the circuit.

Solenoids are used in relays and contactors (see Section 571), for the actuation of valves, and for performing other simple work operations requiring the movement of a lever or mechanism through a small predetermined travel. Usually a spring return is provided to complete the cycle. See Section 542 for information on motors also used for this purpose.

800 ELECTRIC SYSTEM DESIGN PROCEDURES

810 METHODS OF ANALYZING ELECTRIC LOADS

811 General

The accomplishment of a mission by a flight vehicle, be it military or commercial, is dependent on reliable performance of all components used during the flight program, and the electric power system, constituting a service upon which the operation of essential components is dependent, is particularly important to this achievement. In the design of an aircraft the selection of the electric power source equipment, and the capacity thereof, must be based on the loading on the electric system throughout a complete flight program in order to obtain maximum reliability, safety, and weight economy.

A systematic analysis of the loading consists of studies of the electric power requirements of the utilization components, both individually and collectively, during the various operating conditions of the aircraft.

812 Operating Conditions

The operating conditions can be segregated without difficulty into those which are readily associated with a requirement for the operation of utilization components peculiar to the operating condition, with variations in the operating characteristics of the prime mover insofar as they affect the output of the electric power generating equipment, or with abnormal environmental conditions. It must be borne in mind that, in general, all components designed for flight-vehicle use have a minimum factor of safety (marginal in some instances) and all factors which affect either the generating capacity or the power consumed must be given adequate consideration.

The fact that given sequences of operation of equipments during a flight are not generally predictable must be realized. Therefore, pessimistic assumptions must be made relative to simultaneous operation in order that flight safety and mission completion may be assured.

813 Power Requirements

813.1 Tabular Analysis

A thorough analysis demands the listing of each item of electric power consuming equipment and the power requirements thereof. These requirements may take the form of multiple values if variations occur during the operating phases of the equipments.

813.11 To arrive at an overall evaluation of electric power requirements for a given aircraft requires a tabulation of the requirements for each operating condition in order that maximum demand from the power source may be determined. For direct-current aircraft systems, the summation of individual component requirements may be made on a current or power basis. For alternating-current systems, the summation involves that of watts and vars for the separate phases to appraise the balancing of phase loading and determine the system power factor.

813.12 In addition to the steady-state power requirements, it is necessary to give adequate consideration to starting and other transient requirements which are of orders of magnitude or duration to impair system voltage and/or frequency stability, or to exceed short-time ratings of power sources. This is essential, since the ultimate use of an aircraft electric load analysis is for the proper selection of characteristics and capacity of power-source components and resulting assurance of satisfactory performance of equipments.

813.13 Generally accepted procedures for carrying out either alternating-current or direct-current load analyses are presented in Specifications MIL-E-7016 and MIL-E-7017, respectively. Although this section has been prepared as a guide for the evaluation of the loading on a flight-vehicle electric system, the purpose for which it is used, as indicated throughout the text, will aid in interpreting the reasons and necessity for approximating realistic loading conditions.

813.14 *Channel and System Capacities.* A minimum number of allowable inoperative channels in a multiple channel system design is important for safety and reliability considerations. A channel is a segment of a system that can operate independently of the system to provide a portion of system capacity. Table 8-1 illustrates recommended design channel capacity and minimum allowable channel inoperative conditions.

813.2 Additional Factors

Some additional factors pertinent to a thorough analysis are included for assistance where applicable.

813.21 Under emergency conditions caused by the loss of the primary generating equipment, it is sometimes necessary to rely on stored battery energy for safe return of the vehicle. Under these conditions, monitoring of the loads may be either automatic or manual. A condition of this nature should be investigated

Table 8-1—Recommended and Minimum Allowable Channel and System Design Capacities

Number of Engines	Number of Channels	Design Channel Capacity	Dispatch with One Channel Inoperative	Abort with One Channel Inoperative	Comments
4	4	0.25	No	No	Not Sufficient Margin for Commercial Aircraft
		0.333	Yes	No	Minimum Contingency Factor
		0.50	Yes	No	Adequate Margin for Most Emergencies
3	3	0.333	No	No	Second Failure Critical
		0.50	No	No	Second Failure Critical
		0.75	Yes	No	Unacceptable Contingency Factor
		0.67 Nominal 1.0 × E	Yes	No	Adequate Margin for Most Emergencies (Note Assumption that ½-Hour Emergency Capacity = 1.5 Normal)
2	2	0.50	No	No	Second Failure Critical
		0.67	No	No	Unacceptable Contingency Factor
		0.67 Nominal 1.0 × E	Yes (If APU Is Running and Has the Same Capacity as the Main Generator)	No	Acceptable with ½-Hour Emergency Rating of 1.5 (0.67) Adequate Margin Without Flight Engineer

N = Nominal Continuous Capacity
E = Suggested Emergency ½-Hour Rating = 1.5 N

thoroughly relative to necessary monitoring, operation of critical equipment, and adequacy of battery capacity.

813.22 Auxiliary power units are sometimes employed on larger vehicles. Ground operations dependent upon the output of these units and emergency flight requirements must be given the same consideration, insofar as load demands are concerned, as the primary generators and batteries.

813.23 Ground operations during engine starting, etc., are usually facilitated by the use of external power supplies which may be in the form of batteries, rectified power, or generators, and the loading requirements must be appropriately analyzed.

813.24 Utilization equipments are designed to operate from power having certain nominal voltage and frequency characteristics, as applicable, and departures from these may result in faulty operation, damage, or failure of the equipment. Thus, it is necessary to give special consideration to these factors relative to each item of utilization equipment when formulating the electric power requirements for the various operation conditions.

813.3 Load Analysis Value

The time spent on the determination of realistic electric load evaluation for a flight vehicle can be well justified by weight saving and assurance of safe operating conditions. Best of all, the analytical method used will result in all parties proceeding from a common base. There will be no lack of understanding.

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