

Report on
**AIRCRAFT and MISSILES
ELECTRIC SYSTEMS GUIDE**

Appendices I, II, and III

*One of several parts
(See Preface)*

(Published for trial use)



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PREFACE

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 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 pamphlet is one of a series comprising the Report on Aircraft and Missiles Electric Systems Guide, and has been so printed in order to allow for more convenient revision and addition of Sections as available without necessitating a reprint of the entire Guide.

As of the time of printing this pamphlet the available Sections are:

No. 750.1—Sections 000 — Introduction
100 — Criteria for the Electric System
200 — Principal Subdivisions of Electric System
300 — Selection of the System

No. 750.4—Section 400 — Installation Practices

No. 750.5—Sections 500 — Equipment Characteristics
800 — Electric System Design Procedures

No. 750.11—Appendices I — Characteristics of Alternating-Current Generators
Affecting Their Application
II — Distribution System Design
III — Symmetrical Components

Acknowledgment

This Guide was prepared by the Flight Vehicle Electric Systems Integration Subcommittee of the AIEE Aero-Space Transportation Committee. The personnel of the Subcommittee was:

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Aircraft and Missiles Electric Systems Guide

APPENDIX I

CHARACTERISTICS OF ALTERNATING-CURRENT GENERATORS AFFECTING THEIR APPLICATION

Other material in the Guide has discussed the design of alternating-current generators, their voltage regulators and various types of excitation systems. 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 appendix 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. 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 round 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.

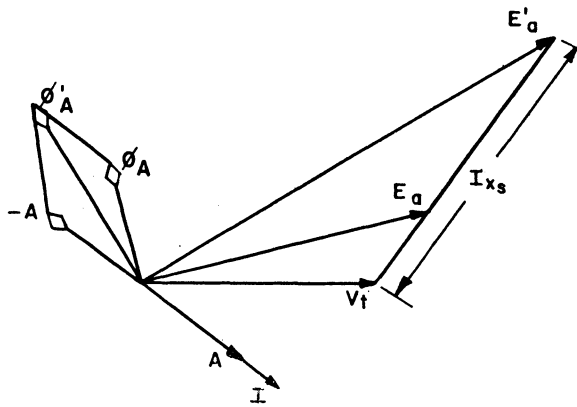


Figure I-2 Alternating-Current Generator Field Flux and Armature Voltage Vectors—Wound Rotor Machine with Load.

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:

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

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

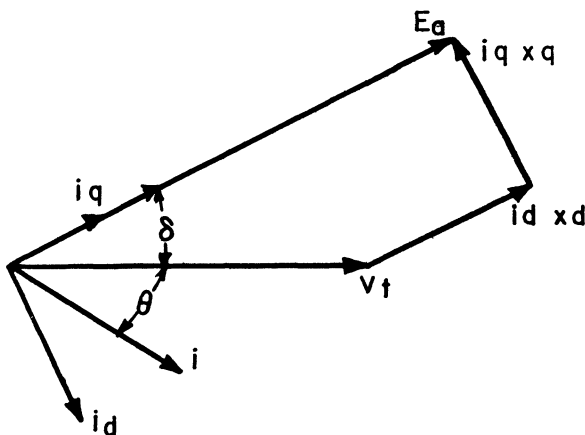


Figure I-3 Alternating-Current Voltage Vectors—Salient-Pole Machine with Load.

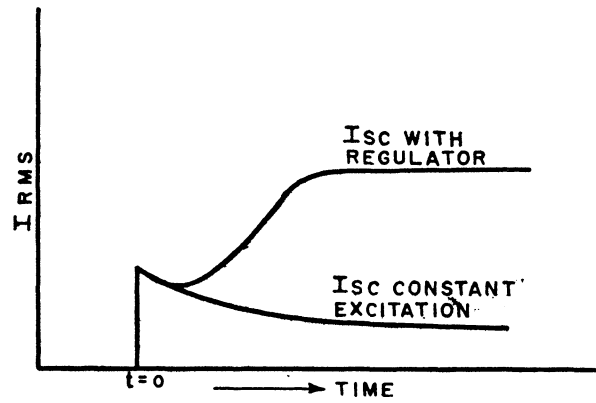


Figure I-4 Alternating-Current Generator Fault Currents with Constant and with Regulated Excitation.

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-

$$\text{chine, results in the equation } I_a = \frac{3E}{Z_1 + Z_2 + Z_0 + 3Z_F}$$

where I_a is the fault current and E is the machine open-circuit voltage prior to the fault. See Appendix III 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.

$$\text{It is } i_{ac} = (i''_d - i'_d)e^{-\frac{t}{T''_d}} + (i'_d - i_d)e^{-\frac{t}{T'_d + i_d}}$$

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:

$$\begin{aligned} i''_d &= \frac{V_{\text{rated}}}{x''_d} \\ i'_d &= \frac{V_{\text{rated}}}{x'_d} \\ \text{and } i_d &= \frac{V_{\text{rated}}}{x_d} \end{aligned}$$

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.

$$e_a = (e_x - e_o) \left(1 - \frac{t}{T'_{do}}\right) + e_o$$

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:

$$\begin{aligned} i''_d &= \frac{e_o}{x''_d} \\ i'_d &= (e_x - e_o) \frac{1}{(1 - e^{-\frac{t}{T'_{do}}})} + e_o \\ i_d &= \frac{e_x}{x_d} \end{aligned}$$

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 that 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-6099A 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 resorted to, 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 present 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 airplane. 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.

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 which will attempt to hold the average voltage of the two remaining phases equal to the normal three-phase average.

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.

Aircraft and Missiles Electric Systems Guide

APPENDIX II

DISTRIBUTION SYSTEM DESIGN

INTRODUCTION

This appendix 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 the 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 smoking. 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 airplane so that a fault on one line does not involve the other paralleled lines. In three-phase alternating-current systems, multiple lines per

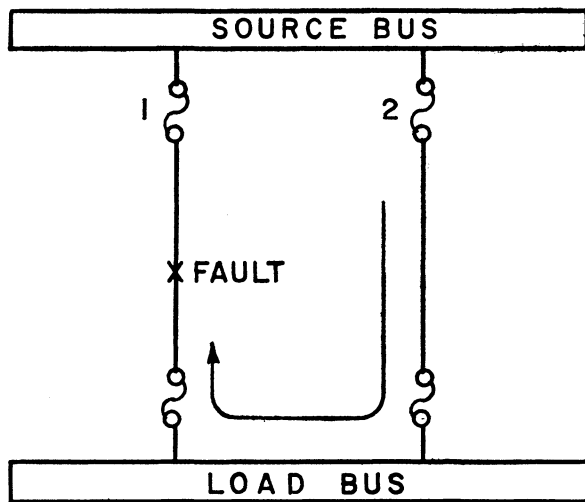


Figure II-1 Fuse Coordination with Fault on Dual Parallel Feeders.

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 are just as likely to clear as the limiter in the faulted line. An exception exists if any of the loads is itself 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.

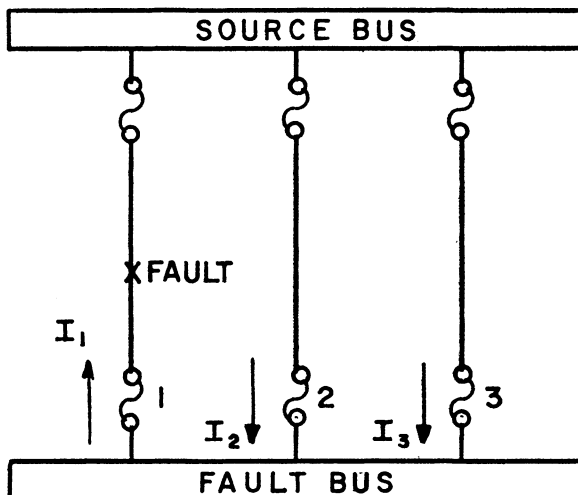


Figure II-2 Fuse Coordination with Fault on One of Three Parallel Feeders.

- (2) In three-phase alternating-current systems, wye-delta connected transformers and three-phase wye-connected induction motors are capable of acting as sizeable 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