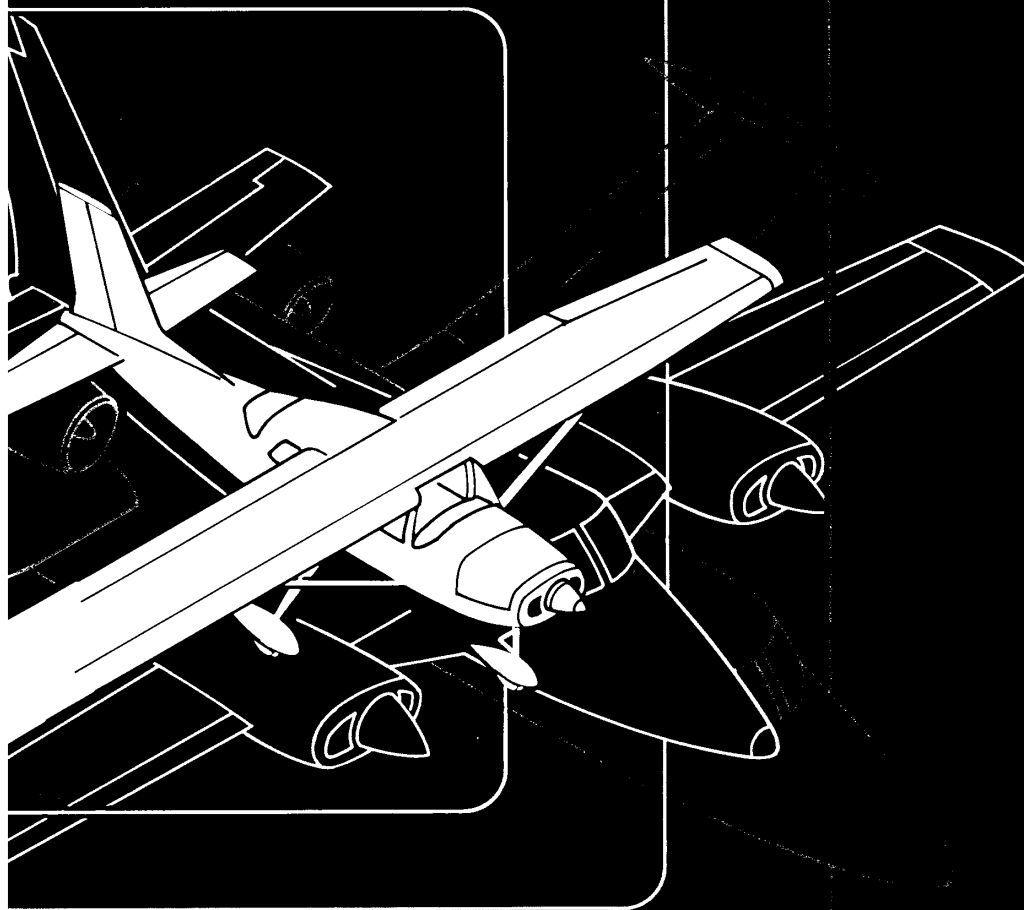


IEEE Guide for **AIRCRAFT ELECTRIC SYSTEMS**



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IEEE Guide for Aircraft Electric Systems

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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.

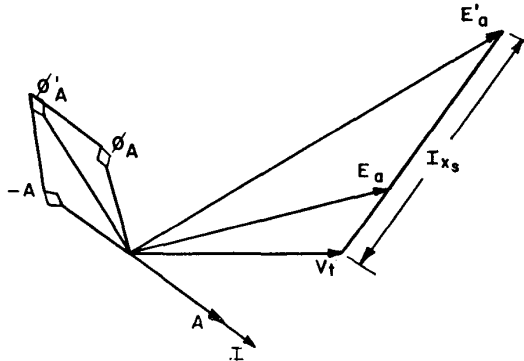


Figure I-2 Alternating-Current Generator Field Flux and Armature Voltage Vectors—Wound Rotor Machine with Load.

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:

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

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

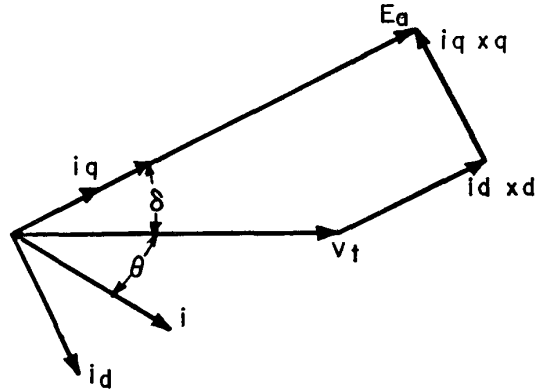


Figure I-3 Alternating-Current Voltage Vectors—Salient-Pole Machine with Load.

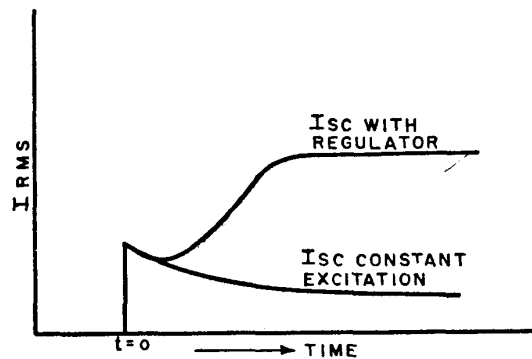


Figure I-4 Alternating-Current Generator Fault Currents with Constant and with Regulated Excitation.

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 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.

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

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.

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

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:

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

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 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 low-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 amortisseur 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) Se- quence 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.

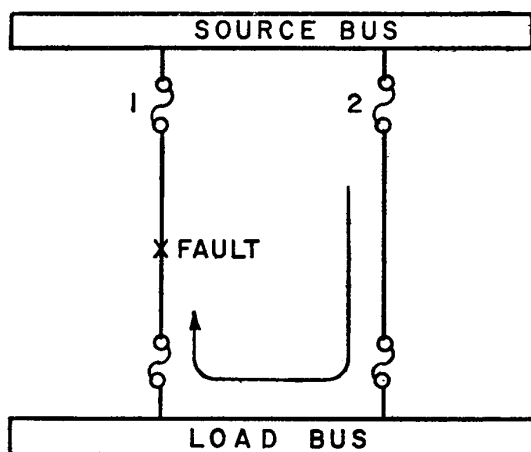


Figure II-1 Fuse Coordination with Fault on Dual Parallel Feeders.

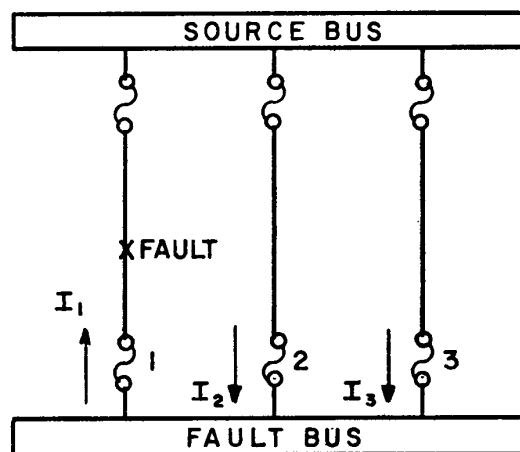


Figure II-2 Fuse Coordination with Fault on One of Three Parallel Feeders.

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.

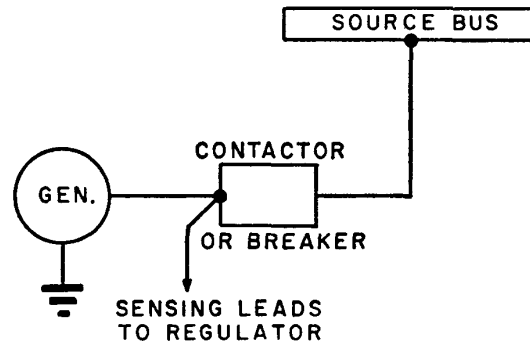


Figure II-3 Connection of Voltage Regulator Sensing Leads.

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 $\pm$ 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 co-ordination 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

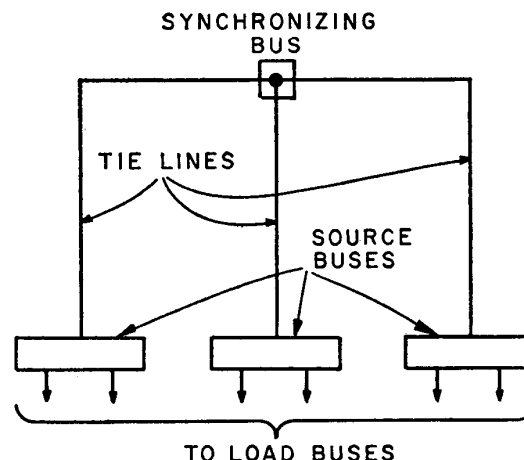


Figure II-4 Multi-Bus Arrangement with Synchronizing Bus.

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.

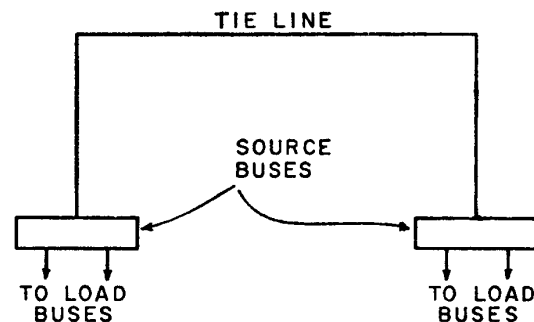


Figure II-5 Split-Bus System.

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.

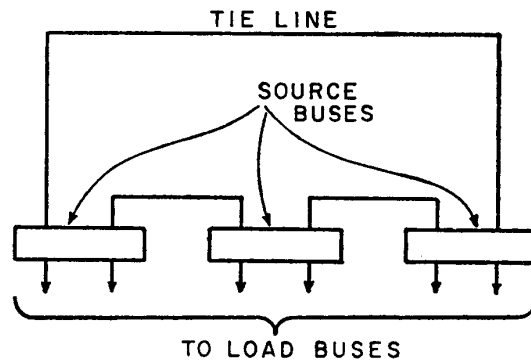


Figure II-6 Ring-Bus System.

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.

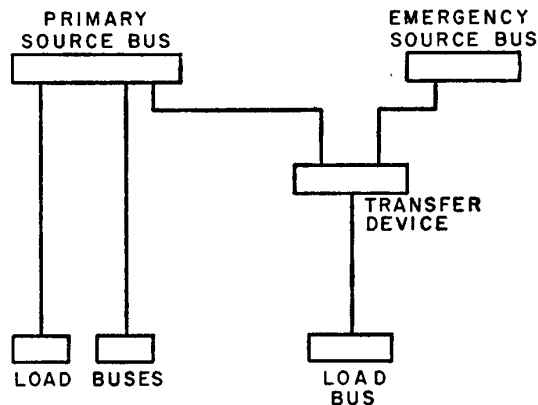


Figure II-7 Single Source-Bus System with Multiple Load Buses.

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.

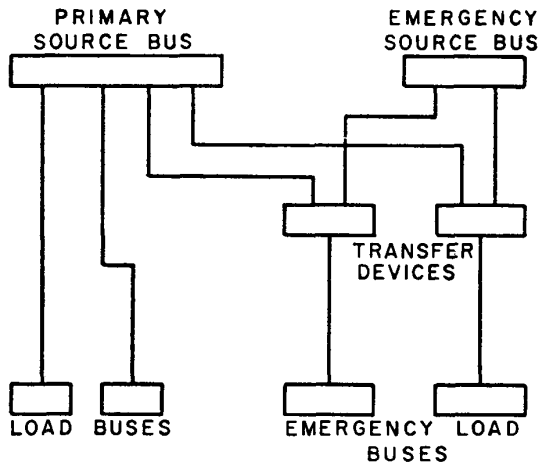


Figure II-8 Single Source-Bus with Multiple Emergency Buses.

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.

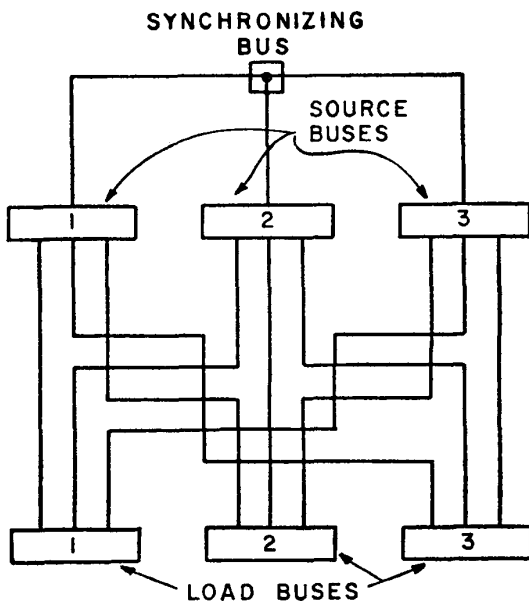


Figure II-9 Interconnected Transmission System.

- (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.

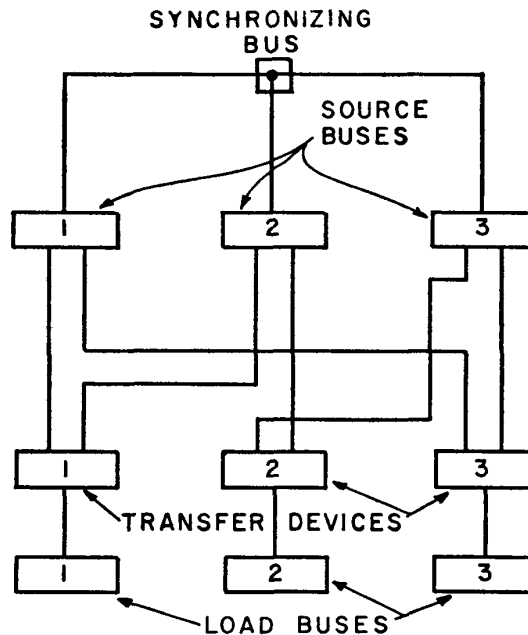


Figure II-10 Load Transfer System.

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.

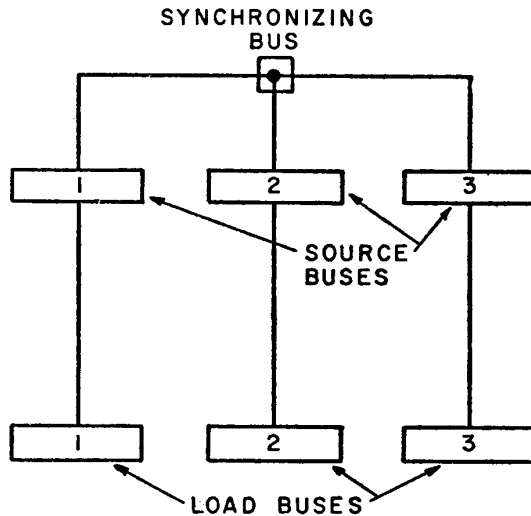


Figure II-11 Single-Feed Transmission System.

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.

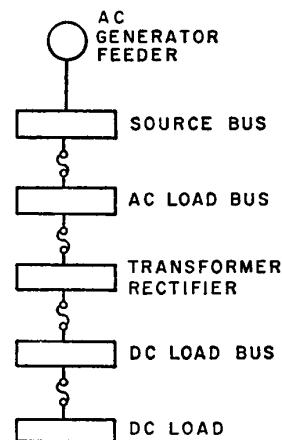


Figure II-12 Complex Coordination Problem.

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

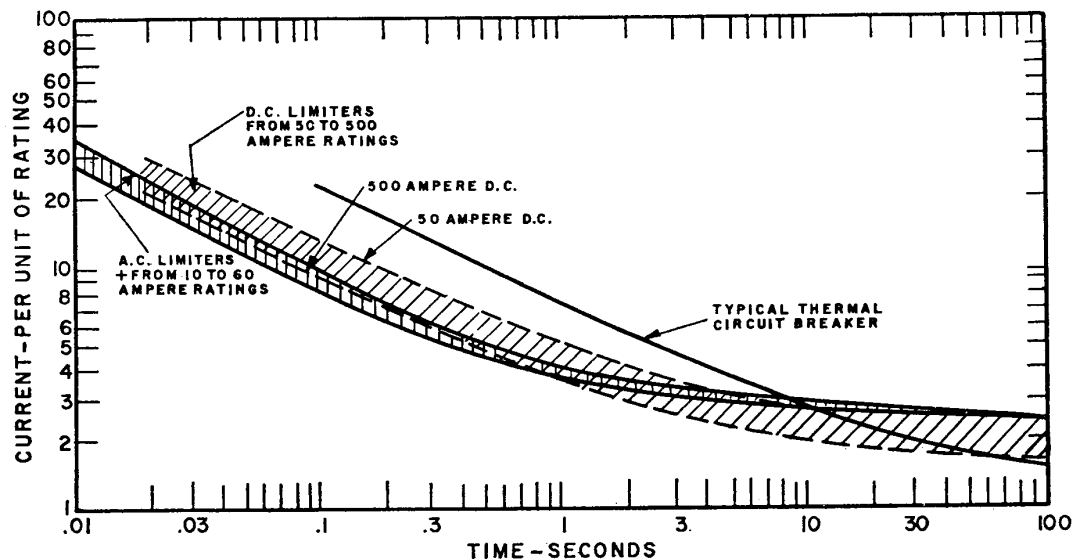


Figure II-13 Typical Aircraft Circuit Breaker and Current Limiter Characteristics.

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

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

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

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.

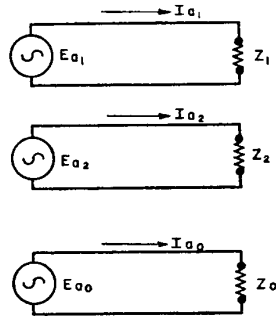


Figure III-1 Positive, Negative and Zero-Sequence Circuit Diagrams.

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

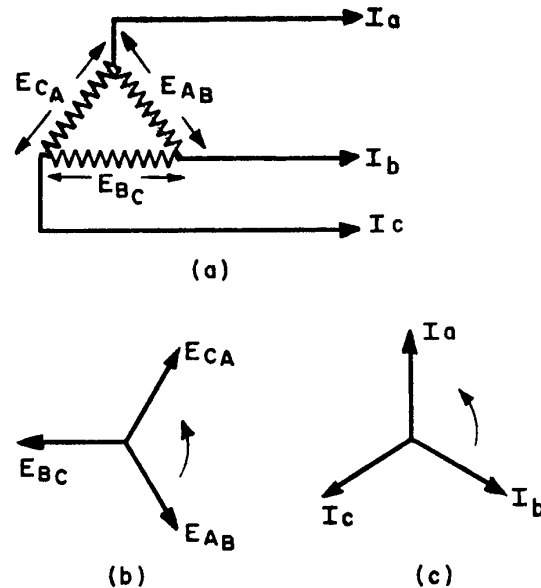


Figure III-2 Three-Phase, Three-Wire System Voltage and Current Vectors.

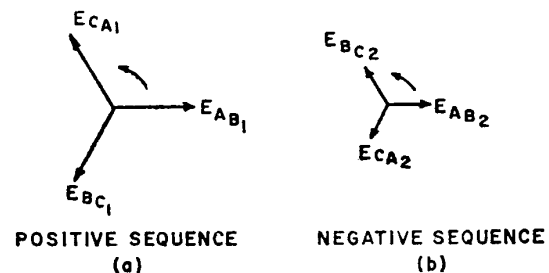


Figure III-3 Positive and Negative-Sequence Voltage Vectors and Their Resultant.

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.

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

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:

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

Then

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

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 $I_{co} = I_{bo} = I_{co}$ and $E_{ao} = E_{bo} = E_{co}$. Thus, $I_{\text{neutral}} = 3I_{ao} = 3I_{bo} = 3I_{co}$. Furthermore there is no "rotation" as such, there is no phase sequence, since $I_{ao} = I_{bo} = I_{co}$ in all respects.

Let us now assume the existence of three sets of current vectors, positive, negative and zero, and with $E_{a1} = 1.0 \angle 0^\circ$, $E_{a2} = 1.0 \angle 0^\circ$, $E_{ao} = 1.0 \angle 0^\circ$. 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

$$\begin{aligned}
I_{a1} &= 1.0 \angle 0^\circ = 1.000 + j 0.000 \\
I_{b1} &= 1.0 \angle -120^\circ = -0.500 - j 0.866 \\
I_{c1} &= 1.0 \angle +120^\circ = -0.500 + j 0.866 \\
I_{a2} &= 1.0 \angle 0^\circ = 1.000 + j 0.000 \\
I_{b2} &= 1.0 \angle 120^\circ = -0.500 + j 0.866 \\
I_{c2} &= 1.0 \angle -120^\circ = -0.500 - j 0.866 \\
I_{ao} &= 1.0 \angle 0^\circ = 1.000 + j 0.000 \\
I_{bo} &= 1.0 \angle 0^\circ = 1.000 + j 0.000 \\
I_{co} &= 1.0 \angle 0^\circ = 1.000 + j 0.000
\end{aligned}$$

Referring to Formula (4)

$$\begin{aligned}
I_a &= I_{ao} + I_{a1} + I_{a2} \\
&= (1.000 + j 0.000) + (1.000 + j 0.000) \\
&\quad + (1.000 + j 0.000) \\
&= 3.000 + j 0.000 \\
&= 3.000 \angle 0^\circ \\
I_b &= I_{bo} + I_{b1} + I_{b2} \\
&= (1.000 + j 0.000) + (-0.500 - j 0.866) \\
&\quad + (-0.500 + j 0.866) \\
&= 0 \\
I_c &= I_{co} + I_{c1} + I_{c2} \\
&= (1.000 + j 0.000) + (-0.500 - j 0.866) \\
&\quad + (-0.500 + j 0.866) \\
&= 0
\end{aligned}$$

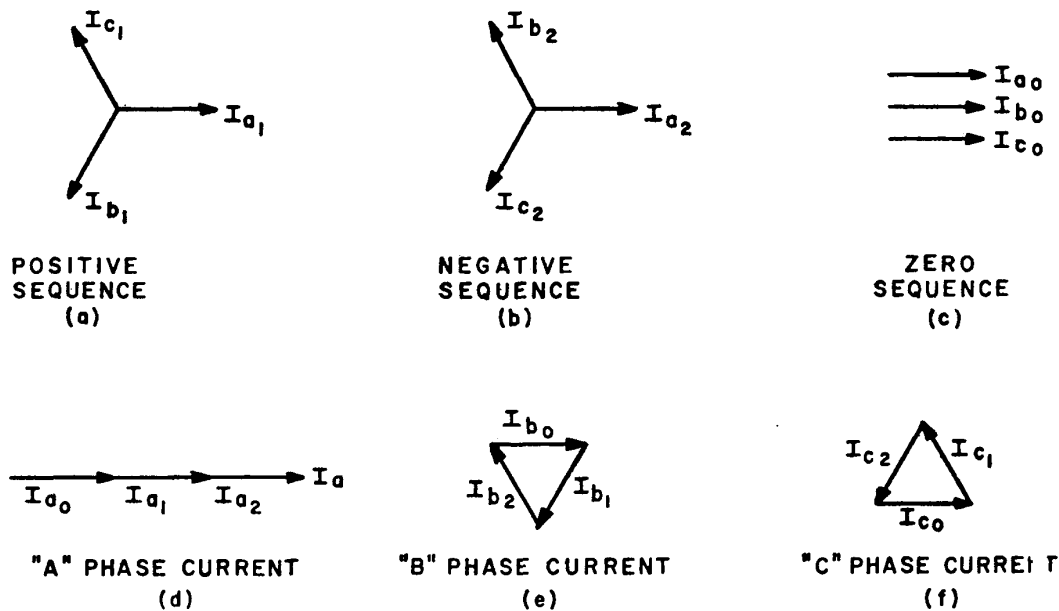


Figure III-4 Addition of Positive, Negative and Zero-Sequence Current Vectors and Their Resultant.

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

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

$$\begin{aligned} E_{AB1} &= \frac{1}{3} (E_{AB} + a E_{BC} + a^2 E_{CA}) \\ E_{AB2} &= \frac{1}{3} (E_{AB} + a^2 E_{BC} + a E_{CA}) \end{aligned} \quad (11)$$

$$\begin{aligned} E_{a0} &= \frac{1}{3} (E_{an} + E_{bn} + E_{cn}) \\ E_{a1} &= \frac{1}{3} (E_{an} + a E_{bn} + a^2 E_{cn}) \\ E_{a2} &= \frac{1}{3} (E_{an} + a^2 E_{bn} + a E_{cn}) \end{aligned} \quad (12)$$

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

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

$$\begin{aligned} E_{a2} &= \frac{E_{AB2}}{1.73} \angle 90^\circ \\ E_{AB1} &= 1.73 E_{a1} \angle 90^\circ \\ E_{AB2} &= 1.73 E_{a2} \angle -90^\circ \end{aligned} \quad (14)$$

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

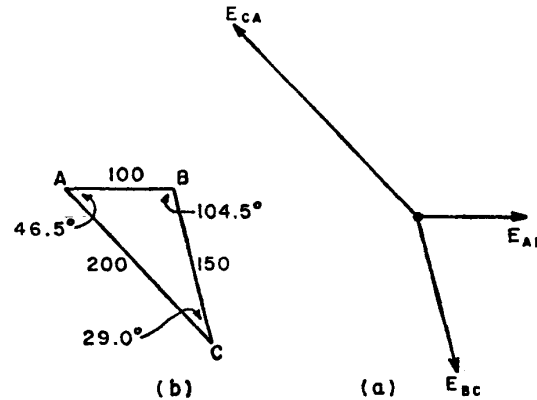
EXAMPLES IN THE USE OF SYMMETRICAL COMPONENTS

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.



$$\begin{aligned} \cos \angle A &= \frac{AB^2 + AC^2 - BC^2}{2 \times AB \times AC} \\ \cos \angle B &= \frac{BC^2 + AB^2 - AC^2}{2 \times BC \times AB} \\ \cos \angle C &= \frac{BC^2 + AC^2 - AB^2}{2 \times BC \times AC} \end{aligned}$$

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}

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

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

$$\begin{aligned} aE_{CA} &= 100 \angle 133.5^\circ \times 1.0 \angle 120^\circ \\ &= 200 \angle -106.5^\circ \\ &= 56.8 - j 191.8 \end{aligned}$$

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

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

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

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

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

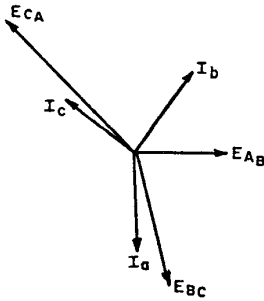


Figure III-6 Line-to-Line Voltage and Line-Current Vectors.

$$\begin{aligned} \text{Let } Z_{g1} + Z_{L1} &= Z_1 \\ Z_{g2} + Z_{L2} &= Z_2 \\ Z_{g0} + Z_{L0} &= Z_0 \end{aligned}$$

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

$$\begin{aligned} Z_{g0} &= 0.025 + j0.050 \\ Z_{g1} &= 0.025 + j1.500 \\ Z_{g2} &= 0.050 + j0.150 \\ Z_{L0} &= 0.021 + j0.177 \\ Z_{L1} &= 0.016 + j0.020 \\ Z_{L2} &= 0.016 + j0.020 \\ Z_f &= 1.000 + j0.000 \\ &= 1.000 / 0^\circ \end{aligned}$$

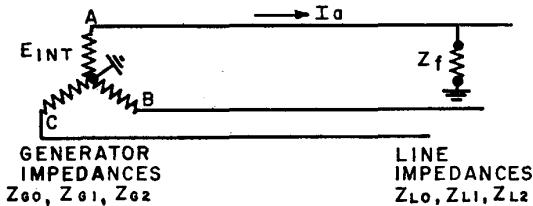


Figure III-7 Single-Phase Load Connected to End of Transmission Line.

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 $115 / 0^\circ$ volts, I_a is 115 amperes and Z_f is $1.0 / 0^\circ$.

Then:

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

From the formula (15)

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

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 $I_{a0} = I_{a2} = I_{a1} = I_a/3 = 38.3 / 0^\circ$.

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

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

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

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

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

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

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

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

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

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

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.

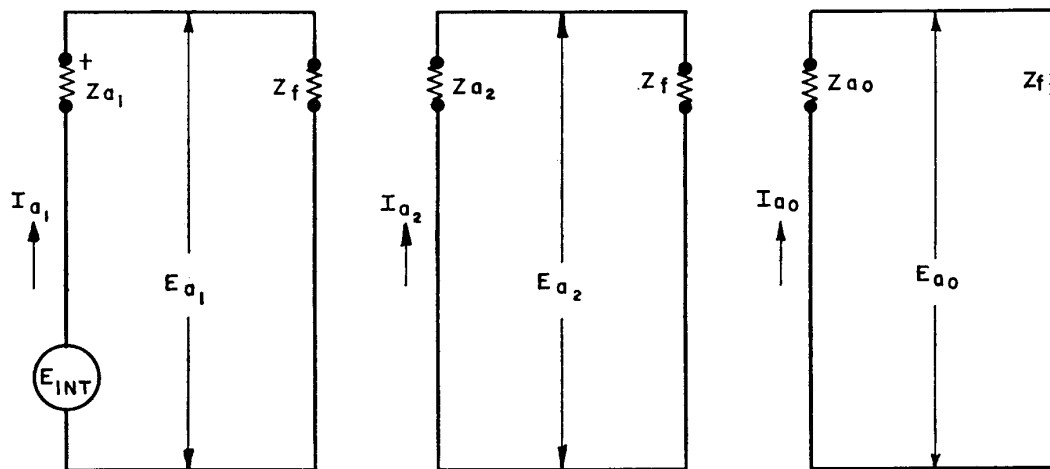


Figure III-8 Sequence Impedance Connections for Three-Phase Symmetrical Fault.