



**NONRESIDENT  
TRAINING  
COURSE**



February 2002

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# **Aviation Electricity and Electronics—Power Generation and Distribution**

**NAVEDTRA 14323**

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**Although the words “he,” “him,” and “his” are used sparingly in this course to enhance communication, they are not intended to be gender driven or to affront or discriminate against anyone.**

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# PREFACE

By enrolling in this self-study course, you have demonstrated a desire to improve yourself and the Navy. Remember, however, this self-study course is only one part of the total Navy training program. Practical experience, schools, selected reading, and your desire to succeed are also necessary to successfully round out a fully meaningful training program.

**COURSE OVERVIEW:** Provides basic information on aircraft electrical power sources and circuit protection and distribution.

**THE COURSE:** This self-study course is organized into subject matter areas, each containing learning objectives to help you determine what you should learn along with text and illustrations to help you understand the information. The subject matter reflects day-to-day requirements and experiences of personnel in the rating or skill area. It also reflects guidance provided by Enlisted Community Managers (ECMs) and other senior personnel, technical references, instructions, etc., and either the occupational or naval standards, which are listed in the *Manual of Navy Enlisted Manpower Personnel Classifications and Occupational Standards*, NAVPERS 18068.

**THE QUESTIONS:** The questions that appear in this course are designed to help you understand the material in the text.

**VALUE:** In completing this course, you will improve your military and professional knowledge. Importantly, it can also help you study for the Navy-wide advancement in rate examination. If you are studying and discover a reference in the text to another publication for further information, look it up.

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"I am a United States Sailor.

I will support and defend the Constitution of the United States of America and I will obey the orders of those appointed over me.

I represent the fighting spirit of the Navy and those who have gone before me to defend freedom and democracy around the world.

I proudly serve my country's Navy combat team with honor, courage and commitment.

I am committed to excellence and the fair treatment of all."

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# INSTRUCTIONS FOR TAKING THE COURSE

## ASSIGNMENTS

The text pages that you are to study are listed at the beginning of each assignment. Study these pages carefully before attempting to answer the questions. Pay close attention to tables and illustrations and read the learning objectives. The learning objectives state what you should be able to do after studying the material. Answering the questions correctly helps you accomplish the objectives.

## SELECTING YOUR ANSWERS

Read each question carefully, then select the BEST answer. You may refer freely to the text. The answers must be the result of your own work and decisions. You are prohibited from referring to or copying the answers of others and from giving answers to anyone else taking the course.

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## Student Comments

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NETPDTC 1550/41 (Rev 4-00)



## CHAPTER 1

# AIRCRAFT ELECTRICAL POWER SOURCES

As a technician, operating and maintaining various electrical power systems of modern naval aircraft, you must be familiar with the operation of these systems. Electrical power requirements and electrical systems components vary widely according to the size and application of the aircraft on which they are used. Aircraft electrical power sources are divided into two categories: primary power sources and secondary power sources.

### AIRCRAFT PRIMARY AC POWER SOURCES

**LEARNING OBJECTIVES:** Identify types of primary alternating current (ac) power sources. Describe the construction of primary ac sources. Describe the characteristics of primary ac power sources.

Primary power sources include main generators, inverters, and transformers. You must have a basic understanding of the components of these electrical systems and power distribution systems in order to maintain them in proper operating condition.

### AC GENERATORS

Alternating current (ac) generators supply the electrical energy for operating aircraft avionics equipment. A generator is a machine that converts mechanical energy into electrical energy by electromagnetic induction.

Ac power systems result in better design and use of equipment than older electronic equipment powered by direct current (dc), which have inverters for ac power and dynamotors for supplying higher voltage dc power. These components are very heavy compared to their relative power outputs. They are not reliable and increase maintenance costs and time. In today's aircraft, the same ac-powered equipment obtains various ac voltages and dc power by using simple transformers and transformer-rectifiers. These components are lightweight, simple, and reliable.

Modern naval aircraft use the three-phase, 120-/208-volt, 400-hertz (Hz) ac power system. The number of magnetic poles and rotor revolutions per

minute (rpm) determine the voltage frequency of the generator. With a fixed number of poles, constant frequency requires constant rotor rpm.

An ac generator-rotating field has 12 poles with adjacent poles of opposite polarity. Each pair of poles produces one cycle per revolution; therefore, each revolution produces six cycles. The output frequency of the generator varies in direct proportion to the engine drive speed. A generator operating at 6,000 rpm is operating at 100 revolutions per second or at 600 Hz.

The 120-/208-volt, 400-Hz, three-phase ac power system has many advantages over the 28-volt dc system. It requires less current than the 28-volt dc system because of higher voltage and a ground neutral system. The current required is a fraction of that required for the same power in a 28-volt dc system. This permits the use of smaller aircraft wiring, saving weight. The ac generator and many of the system's control and protection components are lighter. Twelve kilowatts is the practical limit to the size of an aircraft dc generator. Aircraft now have ac generators with ratings up to 90 kilovolt-ampere (kVA).

### Types of Ac Generators

Aircraft ac generators range in size from the tachometer instrument generator up to the 90,000 volt-ampere generators. Generators are categorized as either brush-type or brushless. Regardless of weight, shape, or rating, practically all of these generators have the following common characteristics:

- The stator (stationary armature winding) provides the ac output.
- The ac generator field (rotor) is a rotating magnetic field with fixed polarity.
- Regulating the rpm of the rotating magnetic field controls the voltage frequency.
- Controlling the strength of the magnetic field regulates the voltage.

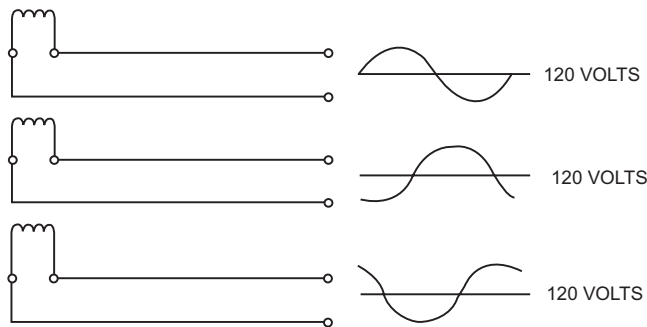
Present military specifications require that the basic aircraft ac power system produce voltage with a value of 120 and 208 volts. A three-phase generator is actually three separate power sources enclosed in one

housing (fig. 1-1(A)). To produce the required 120-/208-volt output, external connections form a wye (fig. 1-1(B)). Each output winding produces 120 volts as measured from n to a, b, or c (phase voltage). When measuring two separate phase voltages together (line voltage), such as a to b, a to c, or b to c, the voltage is 1.73 times the single-phase voltage, or 208 volts.

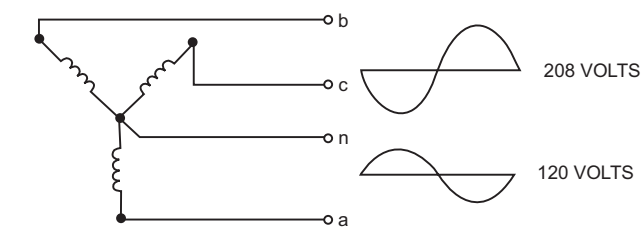
The line voltage found in a three-phase, wye-connected system is the vector sum of the voltages generated by two separate phase windings. Because a 120-degree phase difference exists between the voltages, they reach their peak amplitudes at different times. They add vectorially and not directly.

In the four-wire, grounded-neutral, wye-connected system, the neutral wire attaches to the frame of the aircraft (ground). The three-phase wires run to buses, which supply power to various loads. A bus is a primary power distribution point that is connected to the main power source. The connections for loads requiring 120 volts are between one of the buses and the aircraft frame. The load connections requiring 208 volts are between two of the buses (phases).

**BRUSH-TYPE.**—Figure 1-2 shows a brush-type ac generator. It consists of an ac generator and a smaller dc exciter generator as one unit. The output of the generator supplies ac to the load. The only purpose for the dc exciter generator is to supply the direct current required to maintain the ac generator field. Figure 1-3 is a simplified schematic of the generator.



(A)



(B)

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Figure 1-1.—Three-phase ac generator output.

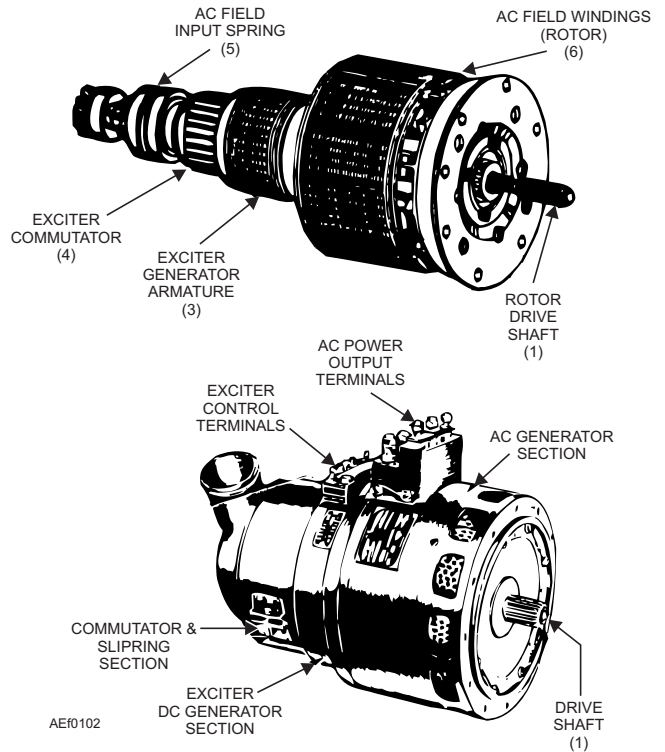
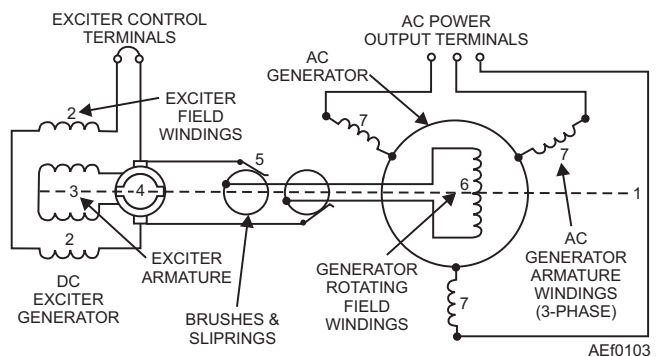


Figure 1-2.—Brush-type, three-phase ac generator.

Look at figures 1-2 and 1-3 as you read this section. The exciter is a dc, shunt-wound, self-excited generator. The exciter field (2) creates an area of intense magnetic flux between its poles. When the exciter armature (3) rotates in the exciter-field flux, voltage is induced in the exciter armature windings. The output from the exciter commutator (4) flows through brushes and slip rings (5) to the generator field. Being dc, already converted by the exciter commutator, the current always flows in one direction through the generator field (6). Thus, a fixed-polarity magnetic field is maintained in the generator field windings. When the field winding rotates, its magnetic flux passes through and across the generator armature windings (7). The ac in the ac generator armature windings flows through fixed terminals to the ac load.



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Figure 1-3.—Brush-type, three-phase ac generator schematic.

The stationary member of the generator consists of the ac armature and the dc exciter field. Both ac and exciter terminal boards are easily accessible. All brush rigging is on the generator and has a brush cover. The slotted-hole mounting provides for ease in attaching to the engine pad. The capacitors connected between the exciter armature terminals and ground suppress radio noise.

**BRUSHLESS-TYPE.**—Most naval aircraft are using brushless generators for voltage generation. The advantage of a brushless generator over a brush-type is its increased reliability and greater operating time between overhaul. Figure 1-4 is an expanded view of the main assembly of a brushless generator.

The brushless generator shown in figure 1-4 is a salient 8-pole, 6,000-rpm, ac generator. It has a 12-pole ac exciter and a three-phase, half-wave diode rectifier rotating with the exciter armature and main generator field assembly. The exciter rotor is a hollow frame assembly with the main ac field mounted on the inside and connected to a common drive shaft. A single-phase permanent magnet generator (PMG) furnishes control voltage and power for the voltage regulator. Three half-wave rectifiers are on the exciter rotor and connected to the exciter armature windings. A generator shaft shear section prevents possible damage to the engine or drive unit if the generator seizes. A fan at the drive end of the generator provides cooling airflow for the rotor and stator windings and the drive bearings. The end bell not only holds the generator

together, but also houses the PMG stator and the permanent magnetic rotor core. The generator to air duct adapter allows a vent tube to be attached to the generator so that built-up air and fumes created by the spinning generator can be vented to the outside of the aircraft.

Some aircraft have oil-cooled generators. The aircraft engine or gearbox oil enters the generator through an inlet port and leaves through an exit port in the mounting flange of the generator. As the oil passes through the generator, it absorbs the heat from the rotor and stator. At the same time, it cools the rotating seals, lubricates and cools the bearings, and is used for the constant speed drive operation.

As the generator shaft rotates, the PMG supplies single-phase, ac voltage to the voltage regulator and other protective circuits (fig. 1-5). PMG power is rectified and supplied to the exciter field. The electromagnetic field, built by the excitation current flowing in the exciter, induces current flow in the rotating three-phase exciter rotor. This current is half-wave rectified by rotating rectifiers. The resultant dc goes to the rotating field winding of the ac generator. The rotating electromagnetic field induces an ac voltage in the three-phase, wye-connected, output winding of the generator stator. Varying the strength of the exciter stationary field regulates voltage. Using an integral ac exciter eliminates the need for brushes within the generator, which minimizes radio noise in other avionics equipment.

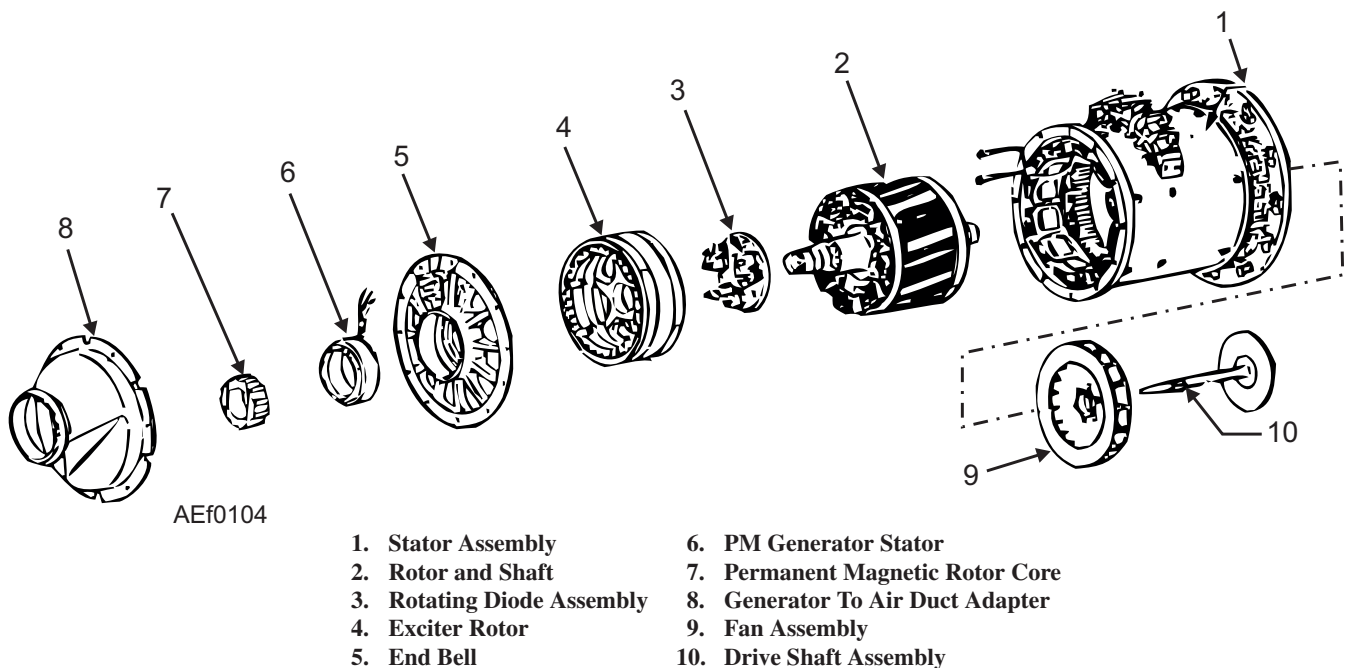


Figure 1-4.—Disassembled brushless ac generator.

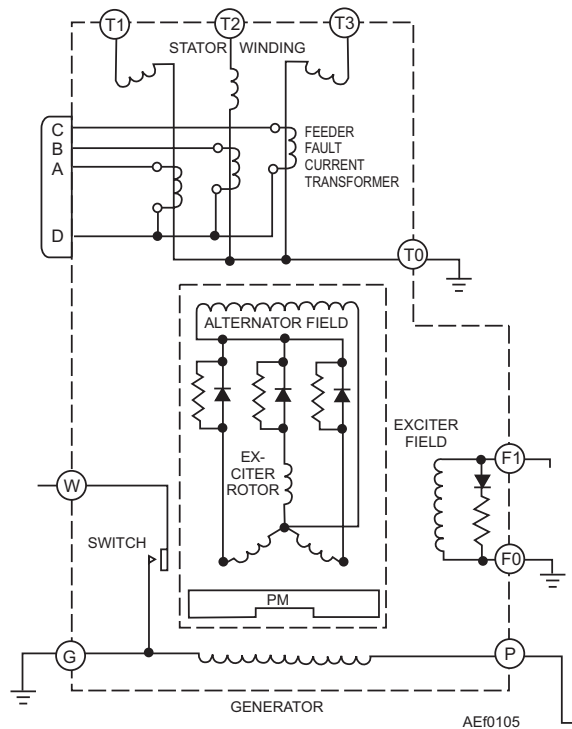


Figure 1-5.—Sectional schematic of a brushless ac generator.

Two three-phase differential transformers provide protection against shorts in the feeder lines between the generator and the bus (called feeder fault). One transformer is on the generator (fig. 1-5). Its coils sense the current flow through each of the legs that connect the ground side of the generator stator to ground. The other transformer is at the main bus and senses current flow through the three feeder lines. A short in the feeder line would cause the transformers sensing a difference in current to trip the generator off line.

A generator mechanical failure warning device is incorporated in the generator. It consists of a soft copper strip embedded in and insulated from the generator stator assembly. A bearing beginning to fail allows the rotor to rub against the copper strip, completing a warning light circuit to ground.

### Prime Movers

A device, such as an aircraft engine, that provides the driving force for a generator, is a prime mover. Early attempts to control the rotor speed of ac generators using variable-pitch propellers or slipping clutches were unsuccessful, and ac generator power was of variable frequency. As power requirements grew, it became necessary to furnish ac power at a constant frequency, to save weight and improve performance. The constant frequency is obtained from constant speed drives such as hydromechanical constant-speed drive

(CSD) units, air or gas turbines, and the constant rpm turboprop engine.

The hydromechanical CSD unit converts variable engine speed to a constant speed output. It holds the frequency steady to within a few hertz of the desired 400 Hz. Load and fault transients limits are within a 380- to 420-Hz range. Air or gas turbine drives, which get the air supply by using bleed air from the jet engine compressor or from a separate compressor, are somewhat smoother in operation and hold steady-state frequencies to within  $\pm 10$  Hz. The constant rpm characteristic of the turboprop engine gives good frequency stability to the ac generator output. The propeller mechanical governor will hold the generator frequency to  $400 \pm 4$  Hz.

- Q1-1. What are the advantages of using transformers and transformer rectifiers vice inverters and dynamotors for supplying aircraft power?
- Q1-2. What power system requirements do modern naval aircraft have?
- Q1-3. What determines the voltage frequency of an ac generator?
- Q1-4. What are the two types of ac generators?
- Q1-5. What supplies the output ac power of a generator?
- Q1-6. How many phases is an ac generator?
- Q1-7. What are the advantages of a brushless generator over a brush-type generator?
- Q1-8. What is a prime mover?
- Q1-9. What is the purpose of a CSD?

### INVERTERS

Inverters are an emergency source of ac power when normal ac power fails. The backup system of the F/A-18 aircraft is an example of this type. The standby attitude indicator receives power from the right 115-volt ac bus. If the aircraft's generators fail to supply power to this bus, the standby attitude indicator receives power from an inverter. Because of a wide variety of inverters in use on aircraft, only one is discussed in this NRTC.

Inverters consist of a speed-governed dc motor, an armature and brush assembly, and a permanent magnet inductor-type ac generator in one unit. The armature and the permanent magnetic rotor mount on a common shaft.

The standard inverter is a 120-volt, three-phase, four-wire, 400-Hz ac system. The four-wire system is better than the three-wire system. It allows a greater choice of single-phase circuits, improves phase load balance, decreases vulnerability to power failure, and gives better frequency and voltage control.

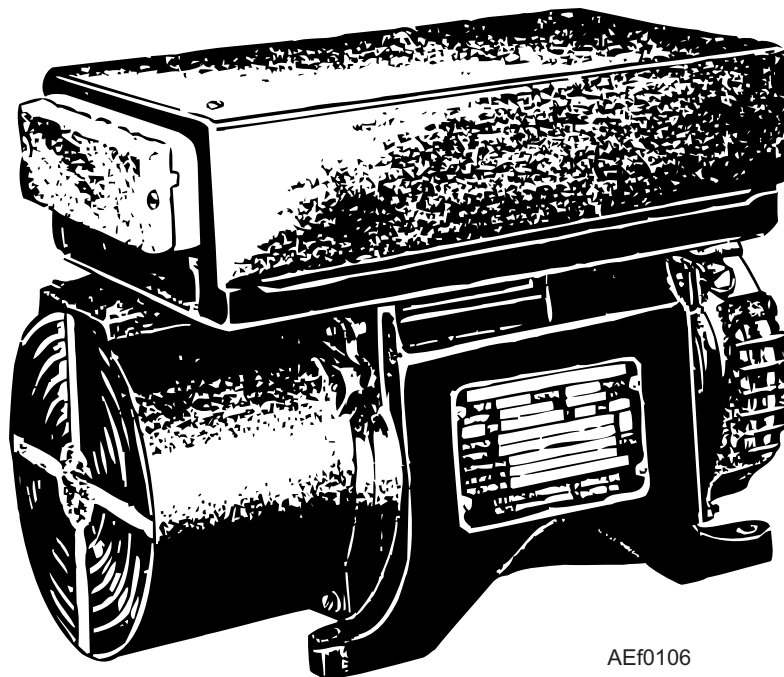
In most inverters, the dc armature and the ac generating field windings are on the same rotor shaft. The dc motor field and generator output (armature) windings are on the stator. A control box on the inverter contains the necessary devices to control the inverter's operation. These devices consist of the operating relays, voltage regulator and rectifier, filtering units, and smaller circuit components.

The dc motor of most aircraft inverters is essentially a shunt-wound motor. High starting current and a low rate of acceleration (due to low torque at starting) are characteristic of shunt-wound inverters. To avoid these undesirable effects, the larger inverters have a series-starting winding. When the inverter reaches its rated speed, relays disconnect the series-starting winding and connect the dc input to the dc motor armature and the shunt winding. The inverter then operates as a shunt-wound motor with constant-speed characteristics. Other inverters use small compensating and commutating pole windings in series with the motor armature. These windings have no effect on the shunt-motor action.

The dc motor converts electrical energy into mechanical energy to drive the generator. The dc load current drawn by the motor depends on the ac load on the generator. A speed governor, or pulsating dc current through the field windings, controls motor speed. A solid-state, on-off switching circuit provides the pulsating direct current. The speed of a dc motor is inversely proportional to the strength of the field, so, as the motor speeds up, more current flows in the shunt windings, reducing the speed. As the motor speed falls below its normal value, less current flows in the shunt-field windings, and the motor speeds up.

The generator ac voltage is proportional to the speed of the rotor and the strength of the generator rotor field flux. The controlled frequency of the ac output is usually 400 Hz. This frequency is a function of the number of poles in the generator field and the speed of the motor. The number of sets of generator stator windings determines the number of independent voltages, or phases, in the output. Some inverters supply both three-phase and single-phase outputs. Figure 1-6 shows a typical inverter.

The rating of aircraft inverters varies depending on the equipment that it supplies. For example, an aircraft may carry a number of inverters. One inverter may supply 120-volt, three-phase ac to an essential bus during emergencies. Another inverter supplies 120-volt, single-phase ac power, while another



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Figure 1-6.—Typical aircraft inverter.

furnishes 120-/208-volt, three-phase power to a specified bus or equipment. Figure 1-7 shows a cutaway view of an inverter.

Controlling the dc excitation current in the generator's rotating field maintains the inverter output voltage at a constant value. Demand variations on the inverter output determine the strength of the dc rotating field.

Inverters operate on the same electrical principles as dc motors and ac generators. For detailed information about a particular inverter, refer to the maintenance instruction manual (MIM) covering that inverter.

## TRANSFORMERS

A transformer, by itself, is not a true electrical power source. A true electrical power source can produce electrical energy from another type of energy, such as chemical or mechanical. Transformers take electrical energy in the form of an ac voltage and convert it to a different usable ac voltage.

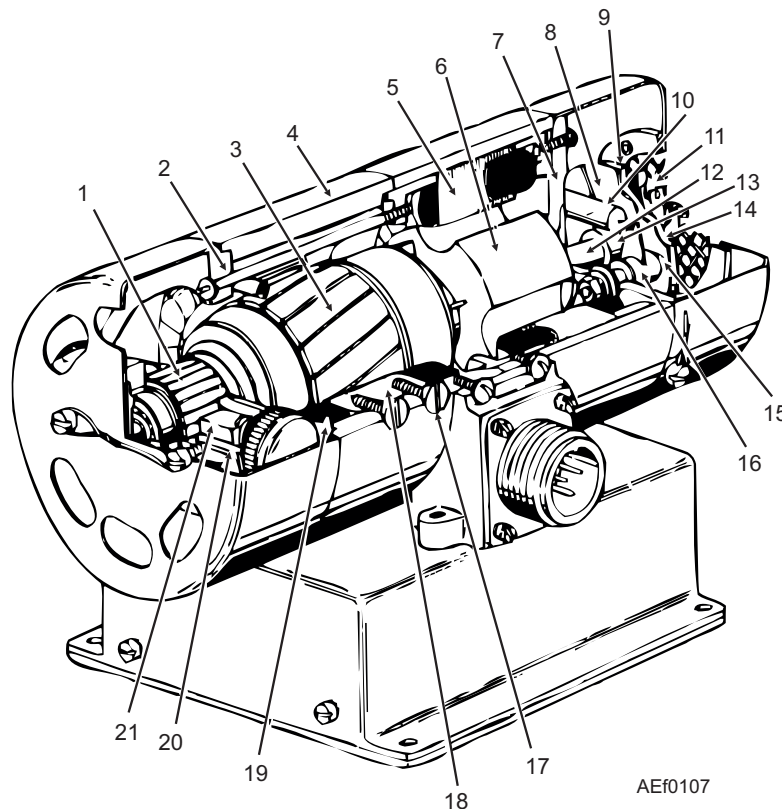
## Transformer-Rectifiers

Ac-powered equipment is more efficient than the larger, heavier dc-powered equipment. Therefore, ac generators now power naval aircraft; but dc power is needed for lighting and for controlling ac-powered equipment. The most common device now used to provide the necessary dc voltage is the transformer-rectifier (TR).

TRs have no moving parts other than a cooling fan. A separate voltage regulator is not necessary as long as the ac input voltage maintains reasonable limits. Dc current capability is high and is largely dependent on the cooling available.

Figure 1-8 shows an electrical schematic of a typical transformer-rectifier. You should refer to it as you read this section. It requires a 120-/208-volt, three-phase, four-wire input at 400 Hz. It has an output capability of 200 amperes at 25.5 to 29.5 volts.

The input ac voltage enters through pins B, F, and I and enters a radio frequency (RF) filter. The filter reduces noise interference to other avionics equipment



- |                    |                    |                    |                             |
|--------------------|--------------------|--------------------|-----------------------------|
| 1. Commutator      | 6. Rotor           | 11. Contacts       | 16. Brush Holder            |
| 2. Bearing Bracket | 7. Bearing Bracket | 12. Shaft          | 17. Screws                  |
| 3. Armature        | 8. Slip Rings      | 13. Bushing        | 18. Pole Shoe               |
| 4. Housing         | 9. Insulator Disk  | 14. Speed Governor | 19. Field Coil              |
| 5. Stator Core     | 10. Capacitor      | 15. Brushes        | 20. Commutator Brush Holder |
|                    |                    |                    | 21. Commutator Brush        |

Figure 1-7.—Cutaway view of an E1616-2 inverter.



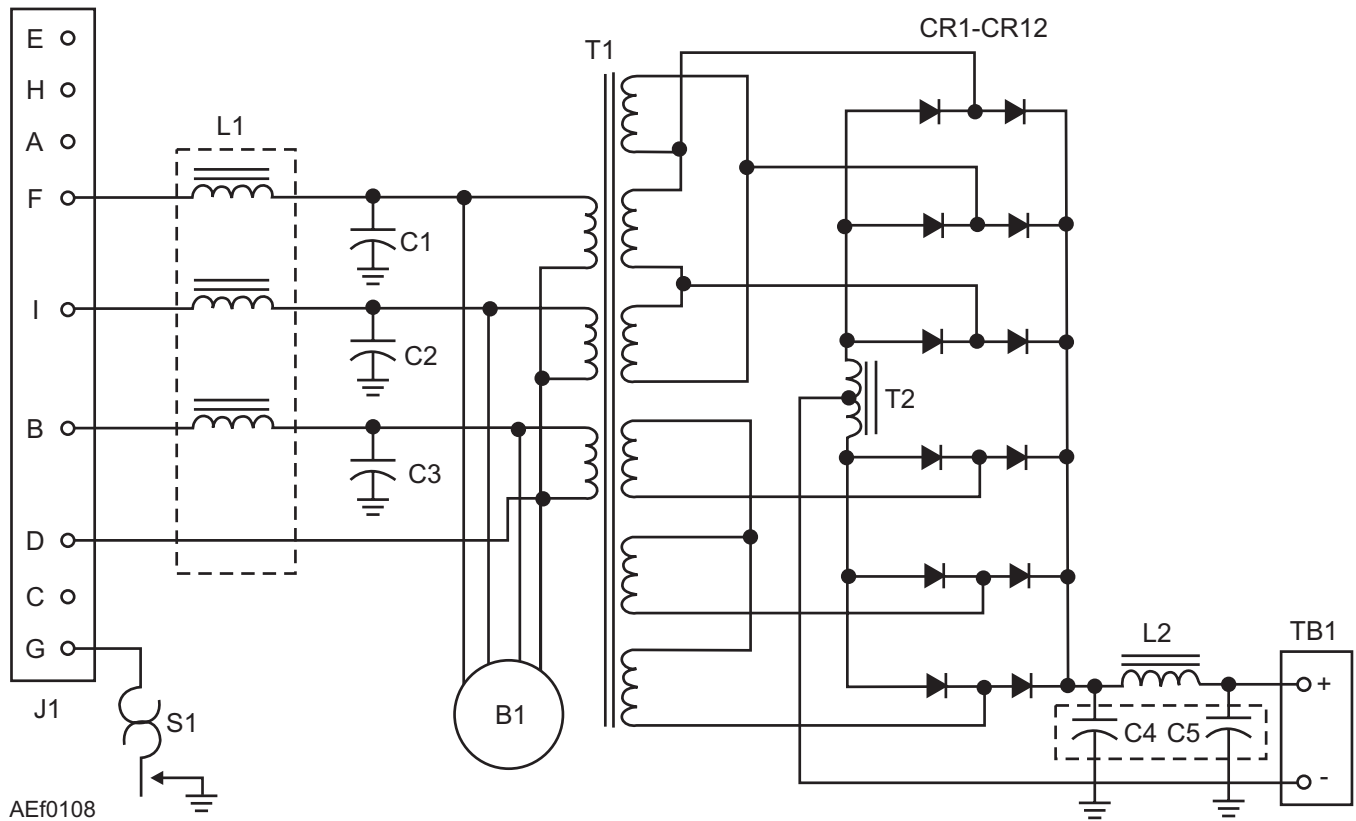


Figure 1-8.—Schematic diagram of a typical transformer-rectifier.

in the aircraft. Power then connects with the wye-connected primary of a step-down power transformer. The ac output of the wye, delta-connected secondary is rectified by diodes CR1 through CR12. The output goes through interphase transformer T2 and a filter network consisting of L2, C4, and C5 to the load. Interphase transformer T2 has an adjustable center tap to balance the two delta transformers for equal current output. The filter network reduces the 4,800-Hz ripple voltage to nearly straight-line dc voltage.

Fan motor B1 is connected in parallel with the power transformer primary. This fan motor is essential to proper operation and provides the only moving parts of the transformer-rectifier. Thermostat (S1) provides detection of excessively high temperatures and, in conjunction with external circuits, turns on an overheat warning light and automatically disconnects the input.

### Autotransformers

The autotransformer is like an ordinary transformer, except that it has one winding that is common to both primary and secondary windings. Within the limits of its application, autotransformers offer savings in both size and cost over conventional

units. These savings are greatest when the turn ratio is less than 2:1 (either step-up or step-down). Savings diminish to insignificance when the turn ratio increases beyond 8:10. There is no isolation between primary and secondary positions of the circuit, a feature that is sometimes objectionable.

Figure 1-9 shows a 2:1 step-down autotransformer circuit. The tap at point B divides the winding into two

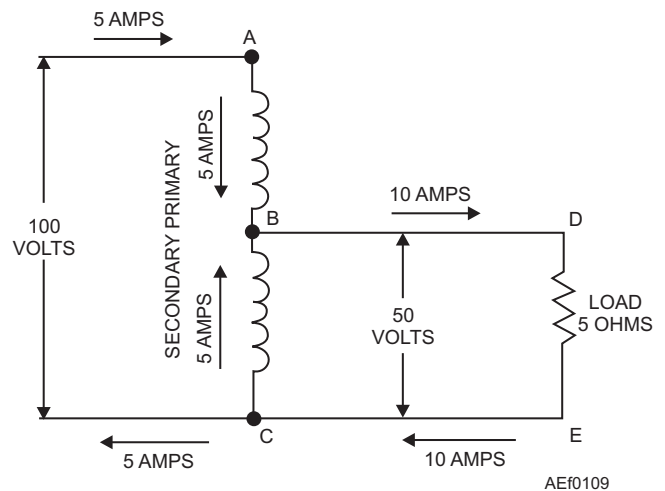


Figure 1-9.—A 2:1 ratio autotransformer.

equal parts. With a load of 5 ohms connected as shown, compute the load current where  $I$  is current,  $E$  is voltage,  $R$  is resistance, and  $P$  is power using the formula  $I = \frac{E}{R}$  or  $\frac{50}{5} = 10$  amperes. The power in the load equals  $EI$  ( $50 \times 10$ ) or 500 watts. Just like a regular transformer, this power comes from the primary by the magnetic field. Disregarding losses, the primary must take 500 watts from the line. Therefore, the primary current would be  $\frac{P}{E} \left( \frac{500}{100} \right)$  or 5 amperes. Only the difference between these two currents, 5 amperes, flows in the common portion C to B (shown by the arrow). When the turn ratio is 2:1, the current in both sections of the winding is the same. This saves the cost and weight of an entire winding.

The autotransformer in figure 1-10 has a turns ratio of 1.33:1. It connects to a load that draws 20 amperes. This represents a secondary power of  $EI = (90 \times 20)$  or 1,800 watts. The primary current equals  $\frac{P}{E} \left( \frac{1,800}{120} \right)$  or 15 amperes. The current in the winding from B to C common to both circuits is the difference between the primary and secondary line currents, or 5 amperes. The savings here are obvious. A conventional transformer with the same characteristics requires a 120-volt, 15-ampere primary and a separate 90-volt, 20-ampere secondary. Here, the requirement is a 30-volt, 15-ampere winding in series with a 90-volt, 5-ampere winding. Thus, a 0.45-kVA autotransformer supplies the 1.8-kVA load.

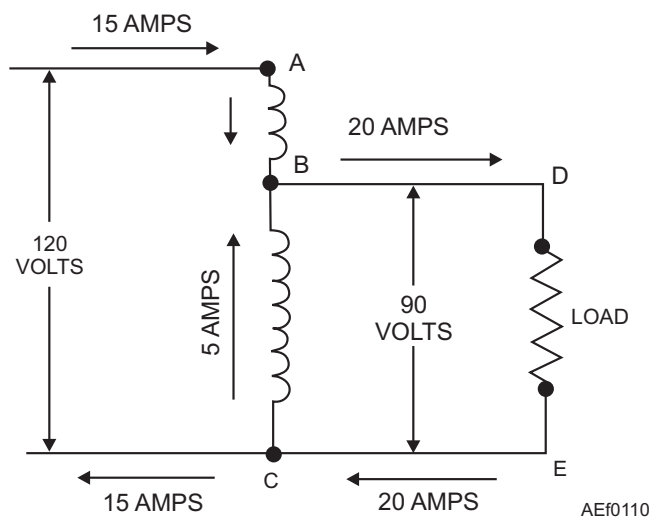


Figure 1-10.—A 1.33:1 ratio autotransformer.

There are many different uses for autotransformers. An autotransformer with a continuous variable tap, called a variac, is used where a continuous control from zero to full (or even above) line voltage is necessary. In this case, the core is in the form of a ring toroid. The winding is usually in the form of a single layer covering almost the entire surface. A control shaft carries an arm and a brush that makes contact with each turn of the winding as the shaft rotates. The setting of the shaft determines the turns ratio. One end of the winding goes to both line and load, and the other end goes to the line. The brush connects to the other side of the load. To obtain voltages higher than line voltage, the primary connects to a tap about 10% down from the end of the winding. (Voltages higher than line voltage compensate for abnormally low line voltage.) This provides secondary control from zero to full line voltage, even though the actual line voltage is as much as 10% below normal.

### Instrument Transformers

Usually, meters are not connected directly to high-voltage and high-current ac circuits. Instrument transformers connect meters to these circuits. These transformers are of two general types—the current and the potential. They permit the use of standard low-voltage meters for all high-voltage or high-current ac circuits. They also protect the operating personnel from the high-voltage circuits.

- Q1-10. What are inverters?
- Q1-11. In an inverter, what converts electrical energy to mechanical energy?
- Q1-12. On what does the rating of an aircraft inverter depend?
- Q1-13. What is the purpose of a transformer?
- Q1-14. What is the function of a transformer rectifier?
- Q1-15. What is the only moving part in a transformer rectifier?
- Q1-16. What is the difference between an autotransformer and an ordinary transformer?
- Q1-17. Autotransformers offer savings in both size and costs over conventional units. When are these savings greatest?
- Q1-18. What are the two general types of instrument transformers?

**Table 1-1.—Electrical Requirements for an Inertial Navigation System**

DC VOLTAGES	AC VOLTAGES
+45 V transistor bias	26 V, 400 Hz
-45 V transistor bias	140 V, 400 Hz, three phase
+28 V unfiltered and unregulated	90 V, 375 Hz, three phase
+28 V transistor bias	12.6 V, 400 Hz
+20 V transistor bias	6.3 V, 400 Hz
+10 V reference	
-10 V reference	

**Table 1-2.—Electrical Requirements for a Typical Transistorized Autopilot System**

Phase A	Phase B	Phase C	DC
120 Vac	120 Vac	120 Vac	28 V filtered
45 Vac	26 Vac	15 Vac	28 V unfiltered
26 Vac	15 Vac	10 Vac	
19 Vac			
15 Vac			

### AIRCRAFT SECONDARY POWER SOURCES

**LEARNING OBJECTIVES:** Identify types of secondary power sources. Describe the construction of secondary power sources. Describe the characteristics of secondary power sources. Describe the operating principles of secondary power sources.

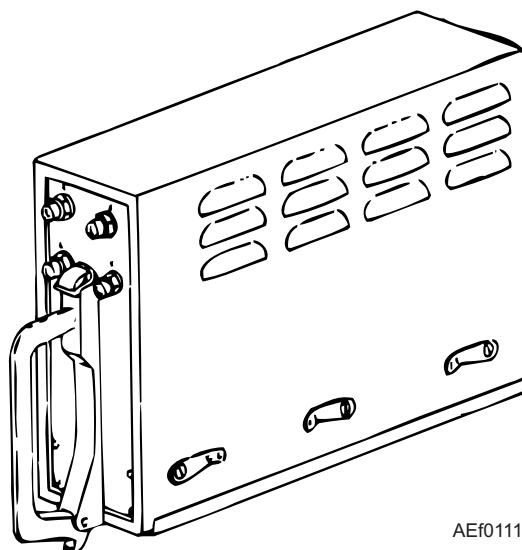
Secondary power sources include electronic power supplies, and emergency/backup power sources such as emergency generators, batteries, and external power supplies. Many of the electrical and electronic systems in naval aircraft require precise voltages to operate; therefore, each of these systems has its own power supply. These power supplies come in many different shapes, sizes, and designs, but all operate basically the same way. The power supply discussed in the next few paragraphs is typical of what is used on naval aircraft.

### ELECTRONIC POWER SUPPLIES

In high performance aircraft, avionics systems help the pilot communicate, navigate, or fire missiles. Other systems, such as radar and autopilot (AFCS), ease the pilot’s workload. Each of these systems requires precision voltage inputs for proper operation. For

example, an inertial navigation system may require the voltages shown in table 1-1. The voltages required by an AFCS in the same aircraft are shown in table 1-2. Obviously, one simple electrical power source will not provide all the needed power for 20 or 30 avionics systems.

Normally, each avionics system has its own power supply. Figure 1-11 shows the power supply for a typical autopilot system. The power supply require-



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**Figure 1-11.—Typical electronic power supply.**

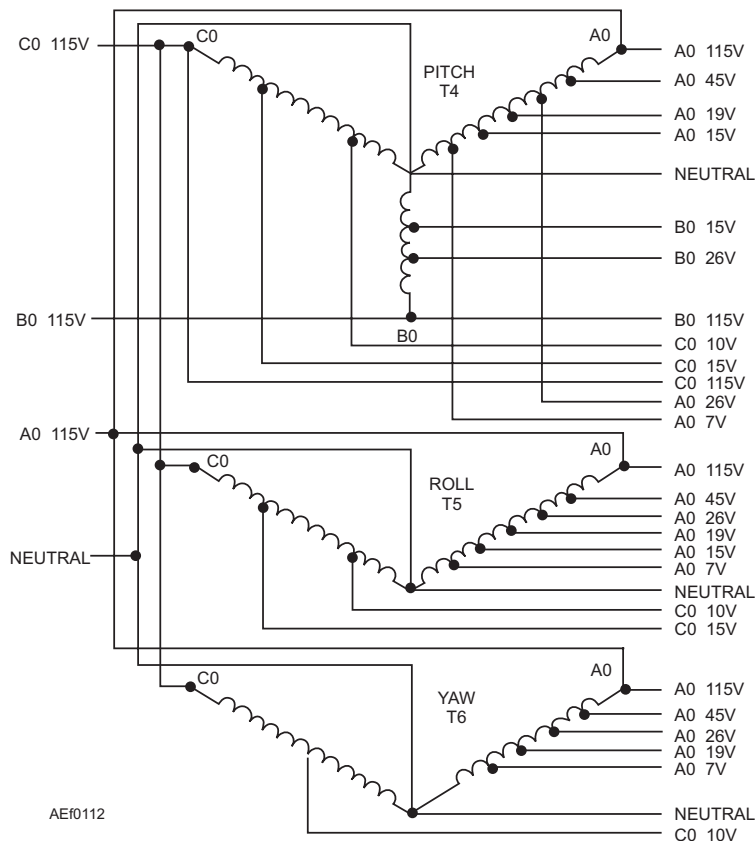


Figure 1-12.—Developing ac voltages for the autopilot.

ments (table 1-2) are for a 120-/208-volt, three-phase, four-wire, 400-Hz electrical power input. Look at the schematic shown in figure 1-12. Autotransformers T4, T5, and T6 produce the majority of the output voltages. The autotransformers have taps from each transformer winding at the proper position to produce the required voltage. Under fairly constant load conditions, no further voltage regulation is necessary.

Full-wave rectifiers (fig. 1-13) produce dc voltages. Each pair of rectifiers (either CR7 and CR10 or CR8 and CR9) conducts during alternate half cycles of the ac input from the secondary coil of step-down transformer T7. The unfiltered dc provides power to operate lights and relays for internal operation of the system and feeds a filter network. Also, filtered dc supplies transistor bias to the electronic amplifiers in the autopilot system.

The circuit shown in figure 1-14 develops precision dc voltages. Diode CR1 is a Zener diode that develops a constant dc voltage at the input of amplifier A1, regardless of input voltage fluctuations. If the dc input voltage at the top of R1 increases, CR1 will conduct harder; the excess voltage drops across R1. If the voltage decreases, CR1 conducts less; less voltage drops across R1. This maintains the voltage at the anode of CR1 at a constant, precision potential.

If no current flows through R2, the same potential present at the input of amplifier A1 and on the anode of CR1 is the same. Feedback voltage through resistors R3 and R4 control the gain of amplifier A1. If the combined resistance values of R3 and R4 are the same as the resistance of R2, the potential of the output voltage and the anode of CR1 are the same. Variable

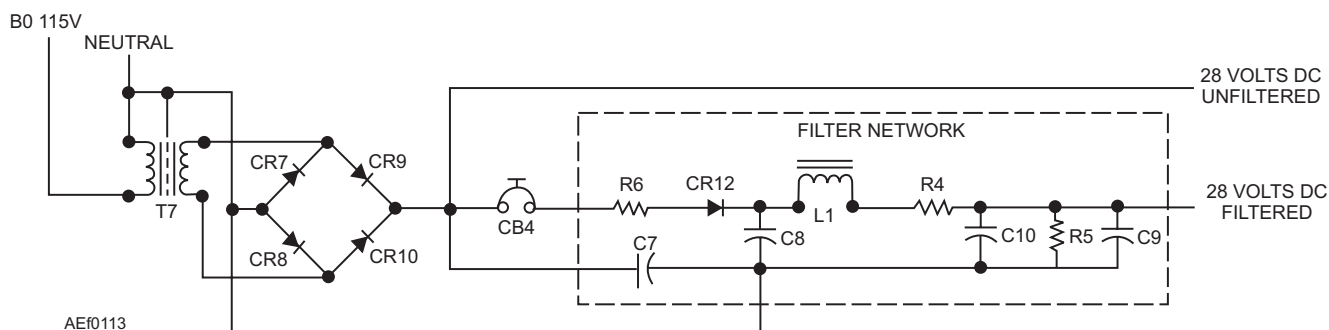


Figure 1-13.—Full-wave rectifier and filter network.

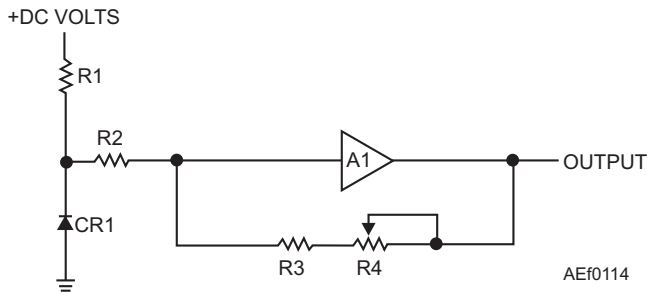


Figure 1-14.—Precision dc voltage developer.

resistor R4 provides fine-tuning of the output voltage to the desired level. Isolation amplifier A1 prevents changes in the load current from being felt at the Zener diode.

### EMERGENCY/BACKUP POWER SOURCES

Naval aircraft have backup (emergency) electrical power if primary sources of electrical power fail. The various ways of supplying this emergency power are aircraft storage batteries, auxiliary power units, and hydraulic motor driven generators.

*Q1-19. What are the ways in which emergency power is supplied to naval aircraft?*

### Batteries

Aircraft storage batteries provide an emergency source of electrical power for operating electrical systems of an aircraft. During normal aircraft operation, the ac generator and transformer-rectifier combination supply electrical energy and maintain the battery in a charged state. The battery supplies power to the aircraft only when the generating systems are unable to supply power. Figure 1-15 shows an aircraft storage battery with a quick disconnect.

The battery is the emergency power source for the aircraft, so it should be maintained in perfect condition at all times. Never use the battery for starting engines or servicing equipment if another power source is available; this shortens battery life. The service life of the aircraft battery depends upon the frequency and quality of care it receives.

The most common aircraft batteries used today are lead-acid and nickel-cadmium batteries. These batteries have a color-coded case for ease of identification, with red for lead-acid and blue for nickel-cadmium. The reference for batteries is *Naval Aircraft Storage Batteries*, NAVAIR 17-15BAD-1.

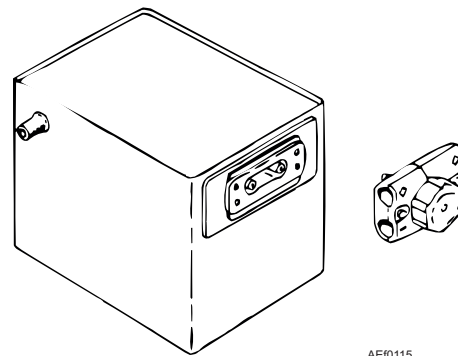


Figure 1-15.—Typical aircraft storage battery with quick disconnect.

Most wet-cell batteries emit some type of gas when being charged or discharged. This is especially true of lead-acid batteries and, to a lesser degree, the nickel-cadmium batteries. For this reason, a vent in the filler plug allows each cell to vent gas and moisture into the void of the battery. Allowing the moisture to stand in the battery void could cause shorting of the cells and corrosion, so openings at each end of the battery provide ventilation of the void area.

**VENTED LEAD-ACID BATTERY (VLAB).—**In a vent system (fig. 1-16), the void above the cells and

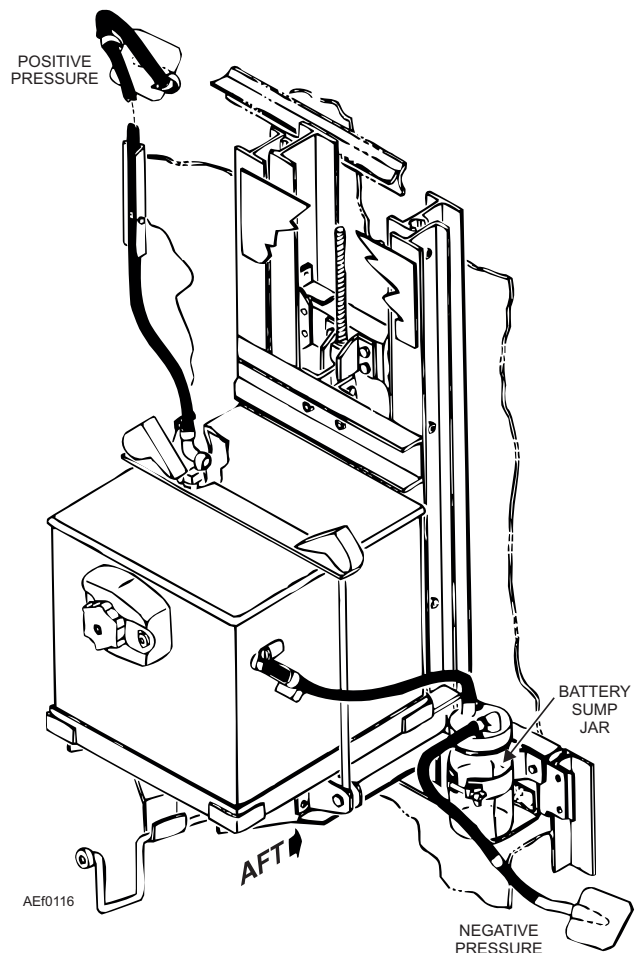


Figure 1-16.—Battery vent system.

beneath the sealed cover is subject to differential pressure through the vent nozzles. The higher of the two vent nozzles connects to a rising vent tube exposed to positive pressure on the aircraft surface. This provides definite pressure on the battery while in flight. It acts as a chimney for light hydrogen gas when the aircraft is at rest. The lower of the two vent nozzles connects to a tube exposed to negative pressure on the aircraft surface. This tube allows battery acid to escape without damage to the aircraft.

In the battery drain sump, the negative pressure tube from the battery connects to a jar sump and extends 1 inch into the jar. The exhaust tube from the sump jar is cut at a 30-degree angle. It extends into the sump jar for one-third its depth. The tube then runs to the aircraft surface. Normally, the sump jar contains a felt pad moistened with a concentrated solution of sodium bicarbonate for neutralizing gases and excess battery solution.

You should refer to the aircraft's MIM for specific directions concerning the maintenance of the battery systems for your aircraft.

#### **SEALED LEAD-ACID BATTERY (SLAB).—**

The electrochemical action in a SLAB is essentially the same as the flooded lead-acid battery. However, the oxygen permeable separator used in a SLAB allows oxygen generated at the positive plate to chemically combine with freshly formed lead sulfate and water. The oxygen recombination suppresses the generation of hydrogen at the negative plate. Overall, there is no water loss during controlled charging. A very small quantity of water can be lost as a result of self-charging reactions, although not enough to need replenishment.

The electrolyte used in a SLAB is a dilute mixture of sulfuric acid and water. SLABs often have immobilized rather than free-flowing electrolyte. The immobilization is done by a gel or by absorption of electrolyte into special glass mats that replace or supplement separators.

#### **NICKEL-CADMIUM (NICAD) BATTERY.—**

The fundamental unit of a NICAD battery is the cell. The sintered-plate NICAD cells used in the battery consist of two basic types: vented and sealed cells. Most naval aircraft NICAD batteries employ rectangular (prismatic) vented type cells.

The NICAD cell is generally assigned a nominal value of 1.26 volts. Unlike a lead-acid cell, the voltage of a NICAD cell has no relationship to its state of charge. While in lead-acid batteries, the electrolyte takes part in the reactions and its concentration changes significantly, the electrolyte changes very little during the discharge of NICAD batteries.

*Q1-20. What components maintain the aircraft (a/c) storage battery in a charged state?*

*Q1-21. What are the two most common types of a/c storage batteries in use today and what are the colors of each?*

*Q1-22. What manual is used for information on securing, storing, servicing, and handling a/c storage batteries?*

*Q1-23. On a VLAB, what is the purpose of the vent nozzles?*

*Q1-24. The sump jar of a VLAB system contains a felt pad moistened with what?*

*Q1-25. In a VLAB system, what is the purpose of the sump jar and the felt pad?*

*Q1-26. What type of electrolyte is used in a SLAB?*

*Q1-27. In a SLAB, how is electrolyte immobilization accomplished?*

*Q1-28. What is considered the fundamental unit of a NICAD battery?*

*Q1-29. What are the types of cells used in NICAD batteries?*

*Q1-30. What is the nominal value of a NICAD battery cell?*

#### **Ac/dc Hydraulic Motor-Driven Generators**

The ac/dc hydraulic motor-driven generators are emergency power sources (fig. 1-17). They consist of a hydraulically driven ac/dc generator, a motor-generator control unit, and a control solenoid. The motor-generator provides 115-/200-volt three-phase ac and 28-volt dc power to essential electrical circuits if normal power fails. The kVA rating of this emergency generator is much lower than the primary generator(s), so the emergency generator powers a limited number of circuits.

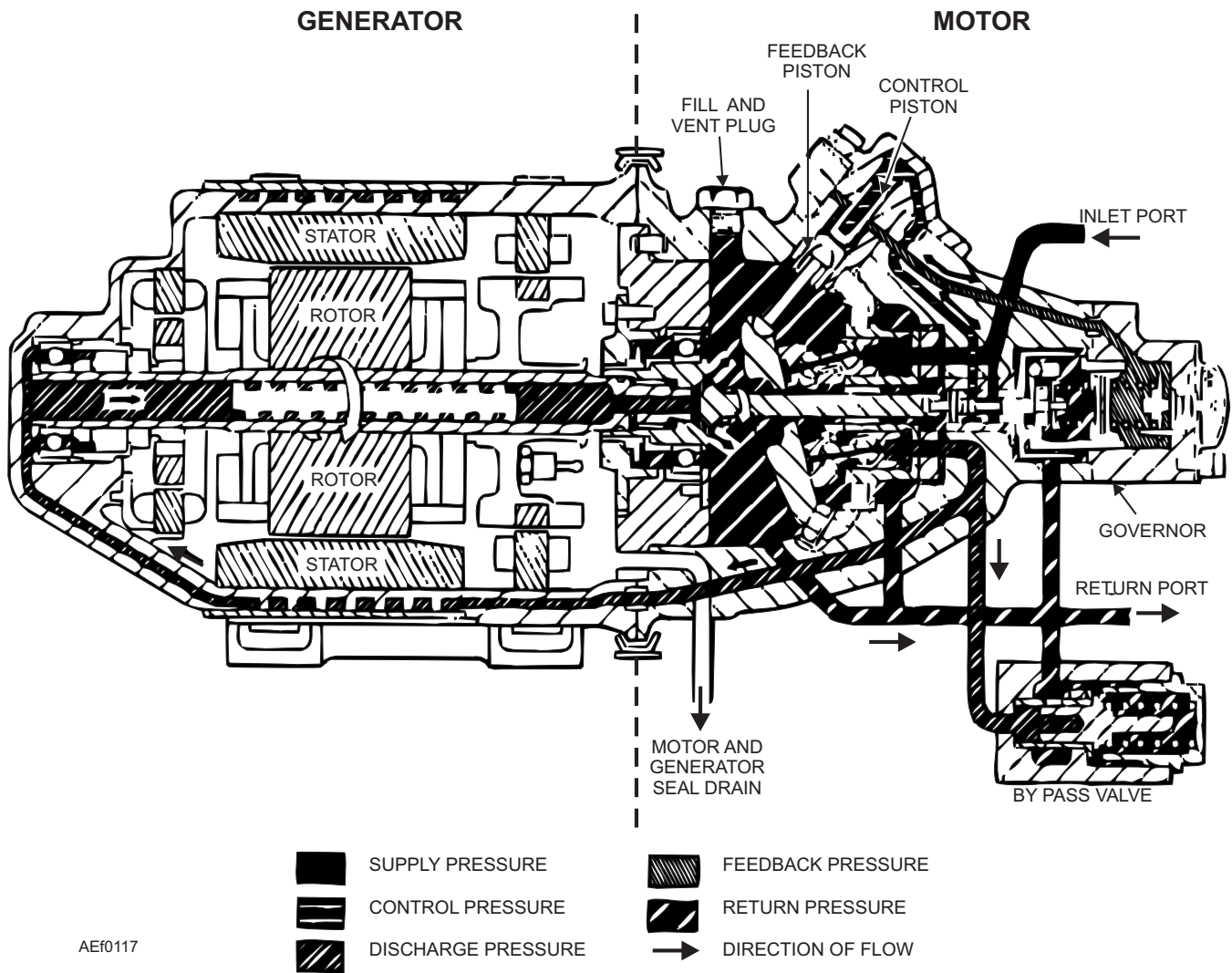


Figure 1-17.—Motor-generator.

**AC/DC GENERATOR.**—As the rotor turns (hydraulic motor running), the permanent magnet induces power into the PMG. This power energizes the control and regulation circuits and the four essential power transfer relays. Regulated and rectified PMG output power goes to a stationary control field within the motor-generator. The motion of the rotor assembly induces PMG power into the windings of the exciter alternator. This power is rectified and, in turn, induced into the output ac winding and the dc winding. The motor-generator control unit monitors ac output. This unit adjusts the regulation to maintain the ac output at 115 volts per phase  $\pm 1.5\%$  when operating under full hydraulic system pressure. The dc output from the stationary rectifier goes to the dc transfer relay contacts for distribution to the essential dc buses.

The hydraulic motor converts 3,000 pounds per square inch of hydraulic pressure to constant-speed

rotation, maintaining generator output frequency at 400 Hz. The motor-generator is cooled by hydraulic fluid from the same source that drives the hydraulic motor.

**MOTOR-GENERATOR CONTROL.**—The motor-generator control provides voltage regulation for, and fault detection of, motor-generator output. When the motor-generator is operating, PMG power flows to the rectifier, where the three-phase ac is rectified to a dc signal. The dc signal is for control panel and relay control power. The signal then flows to the voltage regulator section of the motor-generator control unit. The voltage regulator supplies field excitation to the motor-generator and monitors the output voltage. Monitoring protective circuits in the motor-generator control prevents out-of-tolerance power from being connected to the essential bus system.

**MOTOR-GENERATOR SOLENOID CONTROL VALVE.**—The motor-generator solenoid

control valve (fig. 1-18) controls the operation of the emergency electrical power system. The valve drives electrically to the closed position when primary electrical power is available. When primary electrical power fails, the valve de-energizes and opens, routing hydraulic pressure to the hydraulic motor, driving the generator. The entire operation is completely automatic upon primary electrical power failure.

- Q1-31. Why can the hydraulic driven emergency generator only power a small number of circuits?*
- Q1-32. What causes the rotor in the generator to turn?*
- Q1-33. What helps to maintain generator output frequency?*
- Q1-34. How is the generator cooled?*
- Q1-35. What is the purpose of the motor-generator control?*
- Q1-36. What is the function of the solenoid control valve?*

**Auxiliary Power Unit (APU)**

Some aircraft have auxiliary power units, which furnish electrical power when engine-driven generators are not operating, external power is not available, or the engine-driven generator fails. APUs are used for ground maintenance as well as emergency in-flight power loss.

Using the pneumatic starting system, the gas-turbine APU provides compressed air to start

engines and for air conditioning. The aircraft is made independent of the need for ground power units to carry out its mission. There are many types and configurations of gas-turbine units. Because of their similarity in construction and operation, only one is described in the following paragraphs.

**GTCP-95 UNIT.**—The GTCP-95 (fig. 1-19) is a gas-turbine power plant unit (referred to as an APU). It is capable of furnishing electricity, starting air, and air conditioning while on the ground by supplying air for the air-cycle cooling systems. The gas-turbine engine of the APU requires only the aircraft battery and fuel for starting. Shaft power at the main output drive pad powers the generator. Pneumatic power is available as clean, compressed air at the output end of the engine bleed load control and air shutoff valve. The engine is composed of two main sections and four main systems. The two main sections include an accessory assembly and a compressor and turbine assembly. The four main systems consist of an electrical system, a fuel control system, a bleed-air system, and a lubrication system.

The engine develops power by compressing ambient air with a two-stage centrifugal compressor. Compressed air, mixed with fuel and ignited, drives a radial, inward-flow turbine wheel. The rotating shaft of the turbine wheel drives the compressor, the accessories, and the output shaft for the ac generator.

**GAS-TURBINE ENGINE ELECTRICAL SYSTEM.**—The gas-turbine electrical system (fig. 1-20) provides automatic actuation (in proper sequence) of the various circuits that control fuel, ignition, engine starting, acceleration, and monitoring. The electrical system consists of the following

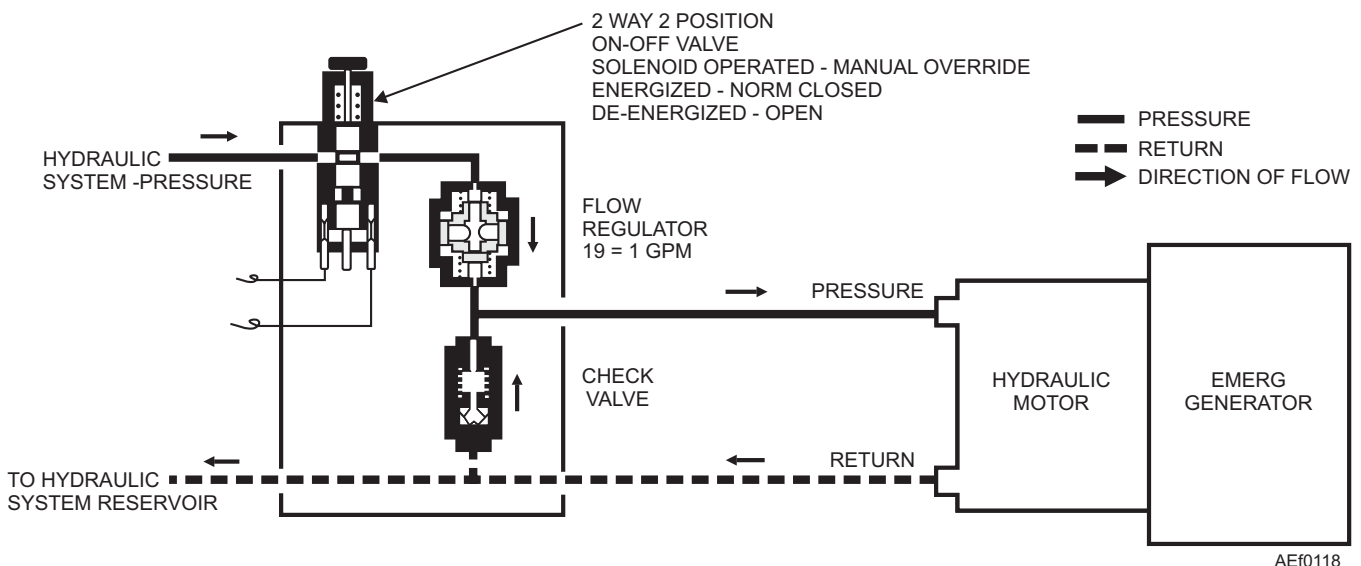
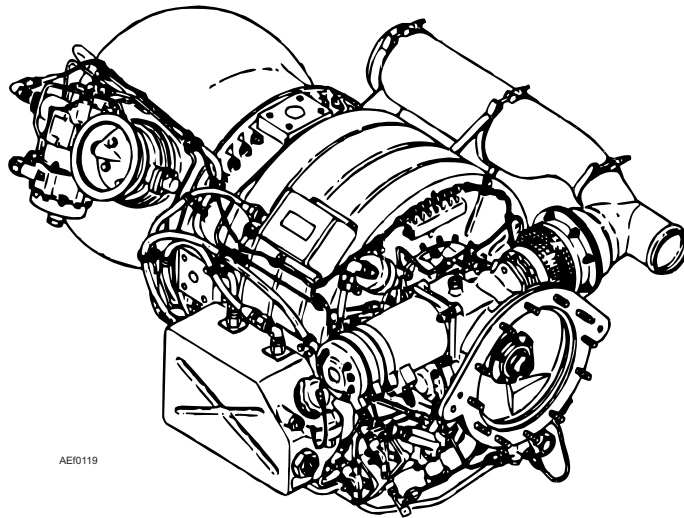


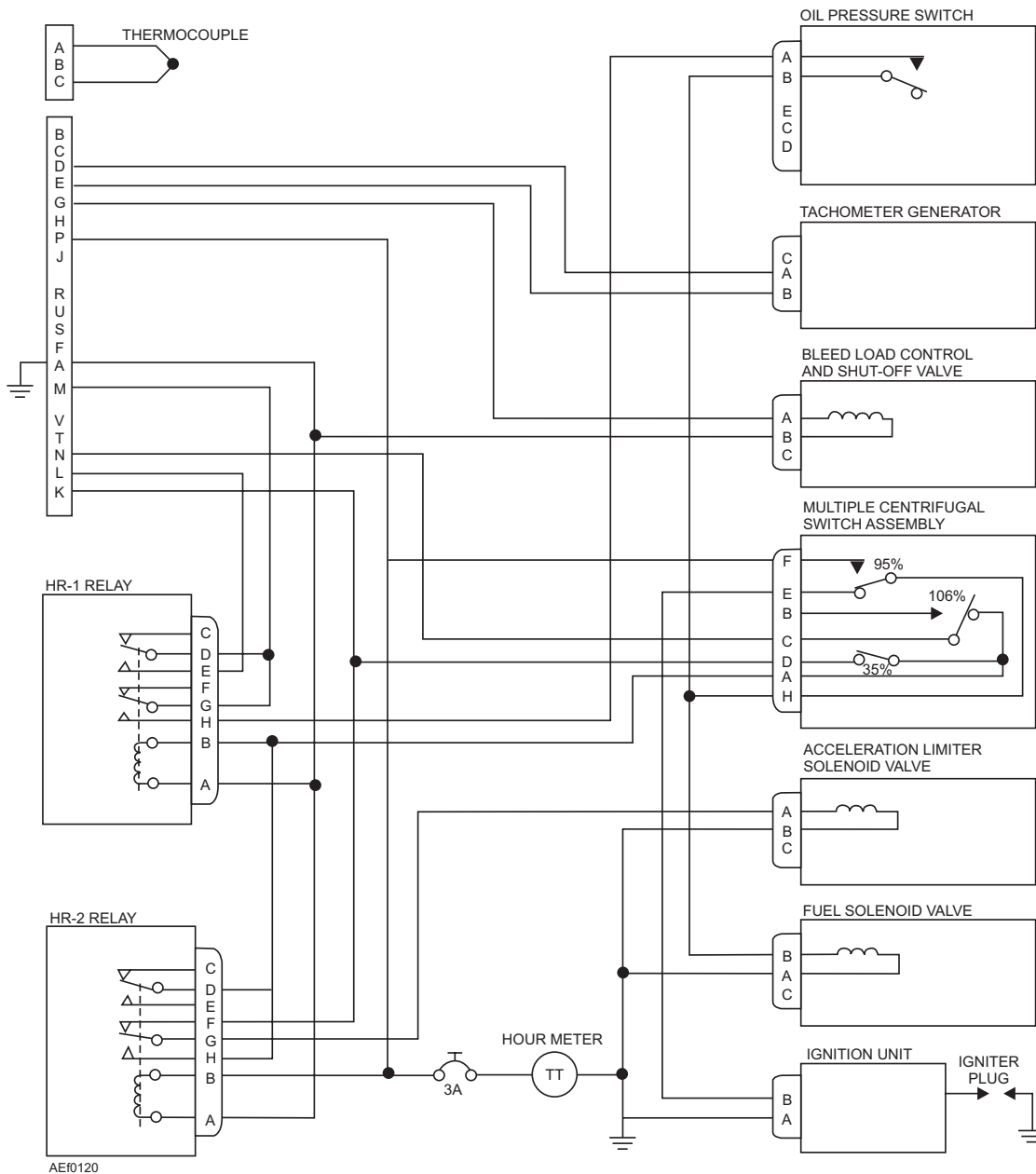
Figure 1-18.—Motor-generator solenoid control valve.





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Figure 1-19.—Gas-turbine power plant unit (GTCP-95).



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Figure 1-20.—GTCP-95 gas-turbine engine electrical schematic.

components: holding relays, oil pressure switch, centrifugal switch assembly, hour meter, and harness assembly. The ignition portion consists of an exciter and ignition plug controlled by the multiple centrifugal switch. Ignition is only required during starting and automatically cuts out at 95% engine rpm.

**CENTRIFUGAL SPEED SEQUENCE SWITCH.**—This component (fig. 1-21) controls the sequence of operation of various electrical components. The input drive shaft turns a knife-edged fulcrum (flyweight support) and a pair of flyweights pivots on the knife edges. Each flyweight has a toe that lies under the outer race of a ball bearing on the actuating shaft. As the centrifugal switch turns, centrifugal force causes the flyweights to pivot, moving the actuating shaft to the right against the lever arm. The three electrical switches actuate at 35%, 95%, and 106% of turbine speed. These switches are fine adjusted by applying spring tension to the lever arm with the three adjustment screws shown in figure 1-21. The functions of the switches are as follows:

- 35%—turns off starter motor
- 95%—arms load control circuits, starts hour meter, turns off ignition
- 106%—stops unit (overspeed protection)

As the drive shaft rotates, the flyweights move outward. This action forces the actuating shaft to move the lever arm, actuating the switches. The lowest percent speed adjustment spring acts on the lever arm during the actuating of all switches. Changing its setting affects the setting of the 95% and 106% switches. A drift in setting of the 106% switch affects only the 106% switch.

Checking an overspeed switch in a gas turbine requires that the unit operate above its governed speed. The centrifugal switch assembly on the engine incorporates a lever that can be manually positioned to operate the three switches. The lever is spring loaded so it does not interfere during normal operation. When the lever is manually actuated, it rotates on a pivot, making

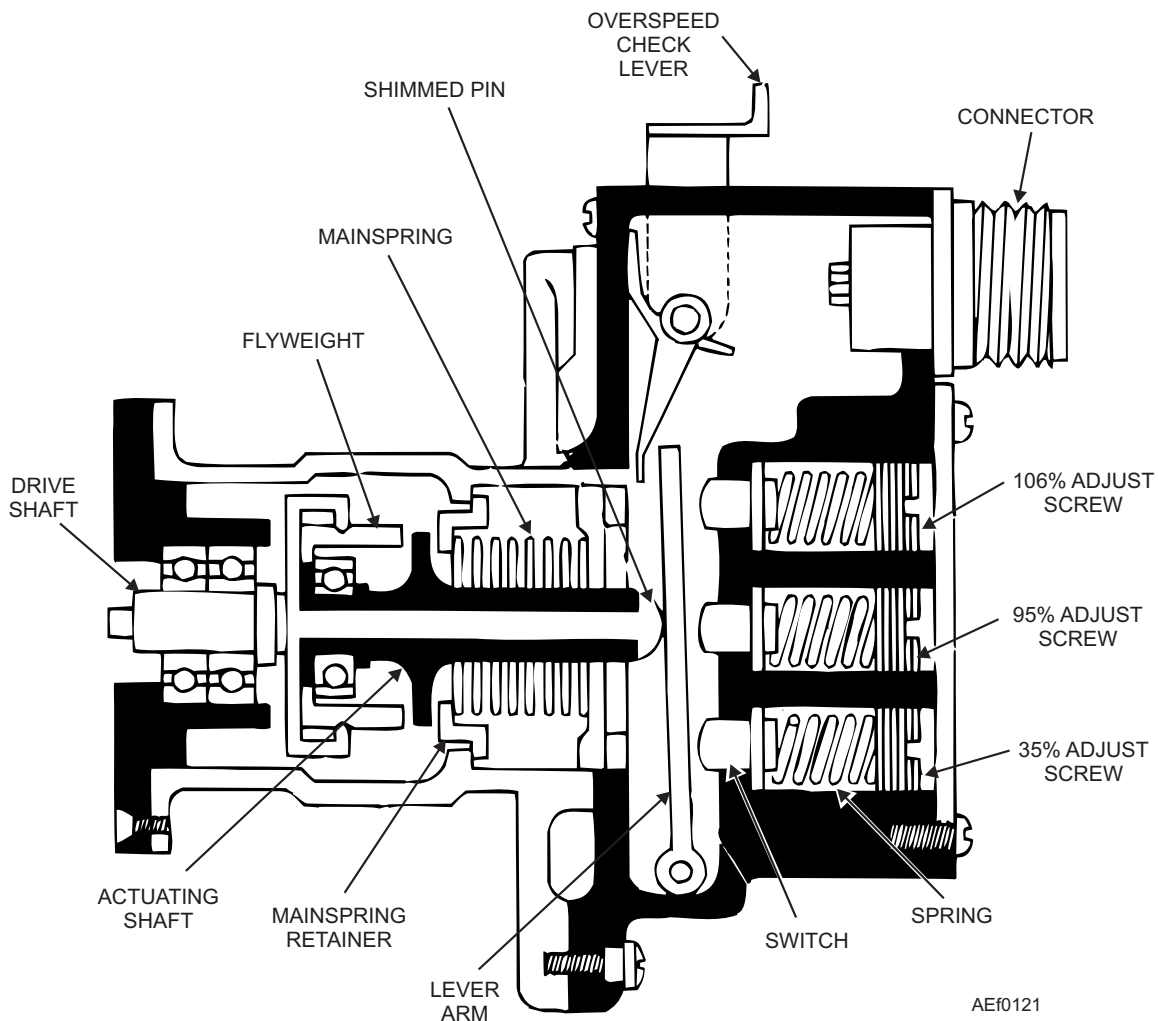


Figure 1-21.—Centrifugal switch assembly.

the centrifugal switch lever arm actuate the switches. This check may be performed with the unit operating or stopped. Actuation of the switch cuts off the fuel flow to the combustion chamber and stops the unit.

**STARTER MOTOR.**—The starter provides initial power for rotating the components of the gas turbine to self-sustaining speeds. It rotates the compressor to a speed high enough for correct airflow for combustion. Also, the starter assists acceleration after light-off, preventing excessive turbine temperature at low speeds.

The starter motor rating is 1.5 horsepower at 14 volts at 5,000 rpm. The starter has a duty cycle of 1 minute on and 4 minutes off. The starter motor armature shaft is splined and pinned to the clutch assembly. The starter clutch assembly performs two functions:

- As a friction clutch, it prevents excessive torque between the starter and accessory drive gears to protect both.
- As an overrunning clutch, it provides the means of automatically engaging the starter with the gear train for starting. The clutch automatically releases it when the unit has reached a condition allowing it to accelerate and run without assistance.

The friction clutch section provides overtorque protection. The assembly will slip at 135 to 145 inch-pounds of torque. Due to the inertia the engine offers when the starter motor pawls first engage with the gearbox ratchet, the overrunning clutch flange and splined clutch plates remain stationary. When in this state, the motor, clutch housing, and keyed clutch plates rotate. Slippage occurs until engine and starter speeds have increased enough to develop less than the specified torque value.

The starter normally is de-energized by the centrifugal switch at 35%. If the switch does not cut out at this speed, the starter may fail from overheating or it may fail mechanically from overspeed. If the overrunning clutch does not release properly, mechanical overspeed failure of the starter will result.

*Q1-37. What is the function of an APU?*

*Q1-38. What is needed for APU starting?*

*Q1-39. On a GTCP-95, what drives the generator?*

*Q1-40. What are the two main sections of an APU?*

*Q1-41. The electrical system of an APU consists of what components?*

*Q1-42. APU ignition cuts out at what rpm?*

*Q1-43. What is the purpose of the centrifugal speed switch assembly?*

*Q1-44. How many sub-switches make up the centrifugal speed switch assembly?*

*Q1-45. How are the centrifugal speed switches adjusted?*

*Q1-46. What are the functions of each switch?*

*Q1-47. Changing the setting of the 35% switch also affects what?*

*Q1-48. How does the 106% switch shut down the APU?*

*Q1-49. At what rpm is the starter disengaged?*

*Q1-50. What could happen to the starter if the dropout relay fails?*

## **External Power Sources**

Naval aircraft accept electrical power from external sources, providing ground crews with electrical power for servicing, fueling, and performing maintenance actions. Aside from fuel costs and engine wear, it is unsafe and impractical to routinely turn up aircraft engines on the flight line or in the hangar bay to provide electrical power to perform these tasks.

Aircraft design features make it impossible to have both aircraft generator power and external power applied to the buses simultaneously. To protect the aircraft, monitoring circuits ensure voltage, frequency, and phasing of external power are correct before the aircraft accepts power from an external source. These monitoring circuits are an integral part of the electrical system of the aircraft. In principle, they operate as a supervisory panel (discussed in chapter 2 of this NRTC).

*Q1-51. Why do we use external electrical power on aircraft?*

## CHAPTER 1

# ANSWERS TO REVIEW QUESTIONS

- A1-1. Lightweight, more reliable, and simple to maintain*
- A1-2. 120-/208-volt ac, 3 phase and 400 Hz*
- A1-3. The number of magnetic poles and the rotor rpm*
- A1-4. The stator*
- A1-5. Three*
- A1-6. Brush and brushless*
- A1-7. Increased reliability and greater operating time between overhaul*
- A1-8. A device that provides the driving force for a generator*
- A1-9. Convert variable engine speed to a constant speed output*
- A1-10. An emergency source of ac power when normal ac power fails*
- A1-11. The dc motor*
- A1-12. The equipment that it will supply*
- A1-13. To convert an input ac voltage into a usable ac output voltage by either stepping up or stepping down that voltage*
- A1-14. To convert ac input voltage to a dc output voltage*
- A1-15. The cooling fan*
- A1-16. An autotransformer has one winding that is common to both primary and secondary windings.*
- A1-17. When the turns ratio is less than 2:1*
- A1-18. Current and potential*
- A1-19. Aircraft storage batteries, auxiliary power units, and hydraulic motor driven generator*
- A1-20. Ac generator and transformer rectifier*
- A1-21. Lead-acid which have a red case and nickel-cadmium which have a blue case*
- A1-22. NAVAIR 17-15BAD-1*
- A1-23. The upper nozzle is connected to a tube that supplies definite pressure on the battery while in flight. The lower nozzle is connected to a negative pressure tube, allowing battery acid to drain without damaging the aircraft*
- A1-24. Sodium bicarbonate*
- A1-25. To neutralize the gases and excess battery solution*
- A1-26. A mixture of sulfuric acid and water*
- A1-27. By using a gel or special mats to absorb electrolyte*
- A1-28. The cell*
- A1-29. Vented and sealed*

- A1-30. 1.26 volts dc*
- A1-31. The kVA rating is too low*
- A1-32. The hydraulic motor*
- A1-33. The motor converts 3000 pounds per square inch of fluid to a constant speed rotation*
- A1-34. By the hydraulic fluid*
- A1-35. It provides voltage regulation and fault detection of the generator output*
- A1-36. It is de-energized when primary electrical power is lost and allows hydraulic fluid to be routed to the hydraulic motor to drive the generator*
- A1-37. To supply pneumatic power for starting engines and operating air conditioning systems, electrical power for in-flight emergencies, and ground maintenance*
- A1-38. Aircraft battery and fuel*
- A1-39. Shaft power at the main output drive pad*
- A1-40. Accessory assembly and compressor/turbine assembly*
- A1-41. Holding relays, oil pressure switch, centrifugal switch assembly, hour meter, and wiring harness*
- A1-42. 95%*
- A1-43. It controls the sequence of operation of various electrical components*
- A1-44. Three*
- A1-45. By using an adjustment screw to apply spring tension to the lever arm*
- A1-46. 35%—shuts the starter down; 95%—arms load control circuit, starts hour meter, and shuts off ignition; 106%—overspeed protection (shuts down the APU during an overspeed condition)*
- A1-47. The settings of the 95% and 106% switches*
- A1-48. When the switch is actuated it cuts off fuel flow, causing the APU to shut down*
- A1-49. 35%*
- A1-50. The starter may fail internally due to an overheat or overspeed condition*
- A1-51. It provides ground crews with electrical power for servicing, fueling, and performing maintenance actions*



## CHAPTER 2

# CIRCUIT PROTECTION AND DISTRIBUTION

The first chapter of this module dealt with the various devices used to provide electrical power in naval aircraft. This chapter discusses the different methods used to regulate the output voltages and frequencies of ac generators, through controls, circuit protection, and distribution systems.

### CONTROLS AND REGULATION

**LEARNING OBJECTIVES:** Identify alternating current (ac) generator controls. Describe ac generator voltage regulation. Describe ac generator frequency control.

Methods of voltage regulation include varying the current to the generator exciter windings and maintaining a constant load on the generator. This is accomplished by using a voltage regulator.

Generator output frequency is regulated by keeping the generator rotating at a required speed. This is done by mounting the generator on a constant speed drive (CSD) unit.

The most common method of voltage control in power generating systems is varying the current to the generator exciter winding (sometimes called field winding). This, in turn, changes the size of the magnetic field, which changes the voltage output of the generator.

The second method of voltage regulation is to maintain a constant load on the generator. This method uses a permanent magnet on the generator rotor in place of exciter windings, which simplifies generator construction. This type of regulation must be used with systems that supply constant loads and have a limited capacity. For example, an inverter or an electronic power supply uses this type of voltage regulation. The regulator varies the resistance of a parallel resistor, so total resistance remains constant regardless of the load resistance. This type regulator is for use with both ac and direct current (dc) power sources.

### AC GENERATOR VOLTAGE CONTROL

When magnetic fields of alternating polarity pass across the armature windings, ac voltage induction

occurs. Control of the voltage induced into the ac generator windings depends on three things:

- The number of turns of conductor per winding
- The speed of the magnetic field passing across the winding (generator revolutions per minute [rpm])
- The magnetic field strength

The number of turns per winding and the number of windings are set during generator manufacture. The frequency of the output voltage depends on the speed of the generator. The strength of the magnetic field controls the level of output voltage. In some cases, as in tachometer generators, a permanent magnet field maintains the load at a constant value.

In today's aircraft, electrical and electronic equipment operate at exact frequencies and voltages. Systems exposed to extreme overvoltages or off-frequencies not only destroy themselves, but may start a fire during an emergency. Ac generator control systems must contain circuits to protect against undervoltage and overvoltage, underfrequency and overfrequency, and improper phase sequence.

The generators shown in figure 2-1(A) and 2-1(B) use an electromagnetic field rather than a permanent magnet-type field.

**NOTE:** Some brushless generators use permanent magnets in the exciter circuits.

The current flowing through the field controls electromagnetic field strength. To control the field strength, you vary the voltage applied across the field. By varying the dc output voltage from the exciter armature, you control the ac generator field strength. The value of the generated ac voltage depends directly on the size of the exciter input. This relationship allows a small dc voltage to control a much larger ac voltage. On the brushless generator, the rotating three-phase rectifiers change the ac output of the exciter to dc. Dc then feeds the main ac generator rotating field, eliminating the use of brushes.

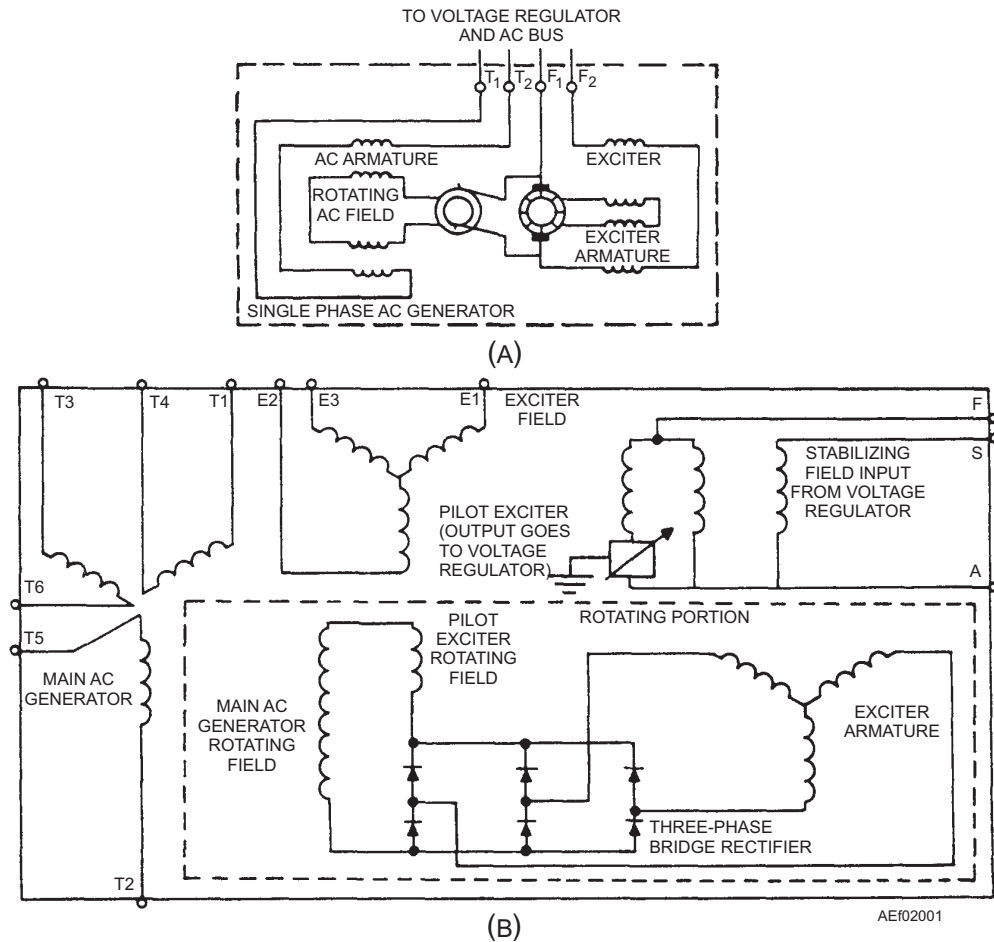


Figure 2-1.—Ac generators. (A) brush type; (B) brushless type.

## AC GENERATOR VOLTAGE REGULATION

As you have already learned, controlling the strength of the magnetic field controls the generated voltage. A voltage regulator controls the magnetic field strength. Current generating the magnetic field is known as *excitation current*. The auxiliary dc generator (called the exciter) or a rotating three-phase rectified ac exciter generator supplies this current. The exciter is on the same shaft as the ac generator to make it an integral part of the generator.

The military specification for aircraft ac generators states that they should be self-supporting. To meet this requirement, dc exciter units are integrated into the ac generators. The chief advantage of exciter units is that each generator has its own independent source of excitation. No external source of electric power is necessary for generator operation. In a multi-generator installation, failure of one generator exciter does not make the complete system inoperative. This would happen if a generator system had a common external excitation system. Internal excitation makes it

unnecessary to transmit excitation power, which reduces the chances of losing excitation from an open or short-circuited wire. In contrast to dc generators, the magnetic field coils in most aircraft ac generators rotate. This induces the ac voltage into the stationary windings.

## Reference Voltage Regulator

One type of voltage regulator that has no mechanical moving parts (except the exciter control relay) is the solid-state regulator.

The ac generator output flows to the voltage regulator, which compares it to a reference voltage. The difference supplies the control amplifier section of the regulator (fig. 2-2). If the output is too low, regulator circuitry increases the field strength of the ac exciter. If the output is too high, it reduces the field strength.

The power supply for the bridge circuit is CR1. CR1 provides full-wave rectification of the three-phase output from transformer T1. The dc output voltages of CR1 are proportional to the average phase voltages.



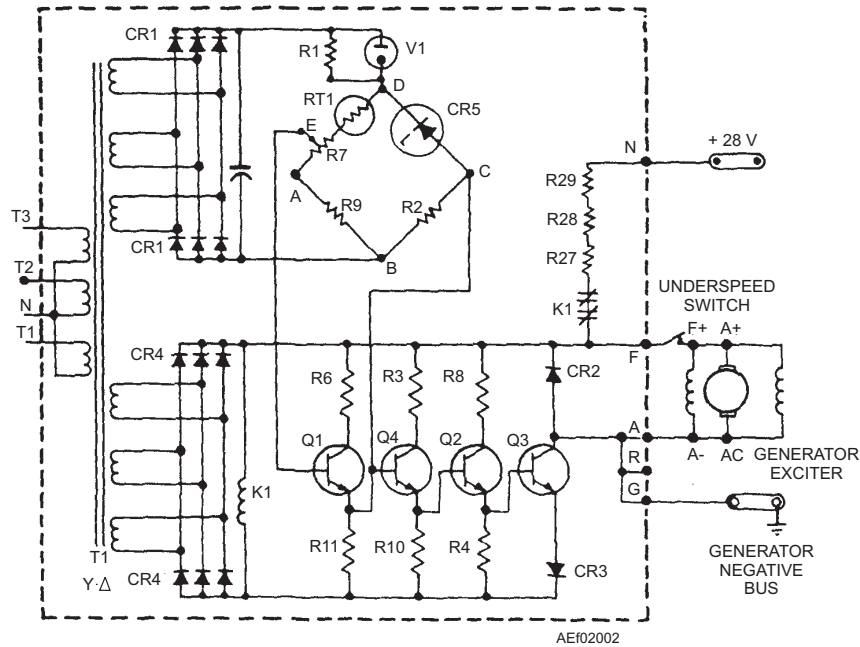


Figure 2-2.—Solid-state voltage regulator.

The negative anode of CR1 supplies power through point B, R2, point C, Zener diode CR1, point D, and to parallel-connected V1 and R1. Takeoff point C of the bridge is located between resistor R2 and the Zener diode. The other leg of the reference bridge (resistors R9, R7, and temperature compensating resistor RT1) connects in series with V1 and R1 through points B, A, and D. The output of this leg of the bridge is at point E.

As voltage changes occur, voltage across R1 and V1 (once V1 starts conducting) remains constant, leaving the total voltage change occurring across the bridge. Since voltage across the Zener diode remains constant (once it starts conducting), the total voltage change occurring in that leg of the bridge is across resistor R2. In the other leg of the bridge, the voltage change across the resistors is proportional to their resistance values.

For this reason, the voltage change across R2 is greater than the voltage change at point E. If the generator output voltage drops, point C is negative with respect to point E. Conversely, if the generator output increases, the voltage between the two points reverses polarity.

The bridge output taken between points C and E connects between the emitter and the base of transistor Q1. With the generator output voltage low, the voltage from the bridge is negative to the emitter and positive to the base. This is a forward bias signal to the transistor, and the emitter to collector current increases. With the

increase of current, the voltage across emitter resistor R11 increases. This increase, in turn, applies a positive signal to the base of transistor Q4, which increases emitter to collector current and increases the voltage drop across emitter resistor R10. This gives a positive bias on the base of Q2, which increases its emitter to collector current and increases the voltage drop across its emitter resistor, R4. This positive signal controls output transistor Q3. The positive signal on the base of Q3 increases the emitter to collector current.

The control field of the exciter generator is in the collector circuit. Increasing the output of the exciter generator increases the field strength of the ac generator, which increases the generator output.

An underspeed switch located near the F+ terminal prevents generator excitation when the frequency is at a low value. When the generator reaches a suitable operating frequency, the switch closes and allows the generator excitation.

Resistors R27, R28, and R29 connect in series with the normally closed contacts of relay K1. The coil of relay K1 connects across the power supply (CR4) for the transistor amplifier. When the generator starts turning, electricity from the 28-volt dc bus goes to the exciter generator field to flash the field for initial excitation. When the field of the exciter generator energizes and the ac generator output voltage increases, relay K1 energizes, opening the field flash circuit.

## Sensing Voltage Regulator

Another type of solid-state voltage regulator (fig. 2-3) operates by sensing the voltage existing on the lines. It amplifies the changes in this signal, and varies the average current supplied to the field winding of the integral exciter. The voltage regulator consists of a sensing circuit with input rectifiers, a temperature compensated Zener diode, reference and error-detecting bridge, and a three-stage transistor amplifier. The output of the bridge circuit is a voltage inversely proportional to the difference between generator voltage and regulator set voltage. This output is referred to as the error signal.

Transformer T1 in the regulator supplies three-phase, ac generator output. It provides isolation from the generator and delivers correct utilization voltages. The transformer output passes through the full-wave bridge rectifier (CR1) to obtain a dc voltage to supply the comparison circuit. The rectifier output is proportional to the average of the three line voltages. The voltage reference and error-detecting bridge uses this voltage for comparison with the constant voltage across the Zener diode (CR5), which tells whether the generator output is too high or too low. Potentiometer

R7 permits adjustment to the desired voltage. The glow tube (V1) serves to increase the sensitivity of the voltage reference and error-detecting bridge. Thermistor RT1 provides temperature compensation in the comparison circuit. It offsets the effects of changes in other elements of the circuit that result from temperature variations to maintain a nearly constant voltage.

The error-detecting bridge output voltage sawtooth wave shape is due to the ripple resulting from the semi-filtered, three-phase rectifier supply. This sawtooth voltage goes to the input of the first stage of the three-stage transistor amplifier. Overdriving the second and third stages obtains an essentially square wave output. The effect of the error detecting bridge output is to modulate the width of the pulses passing through the amplifier.

Refer to figure 2-3 as you read this paragraph. The power for operating the three-stage transistor amplifier comes through the full-wave bridge rectifier (CR4) from transformer T1. Obtaining amplifier power this way requires special consideration. There are conditions that require excitation when no voltage is available to supply the amplifier. Such conditions exist

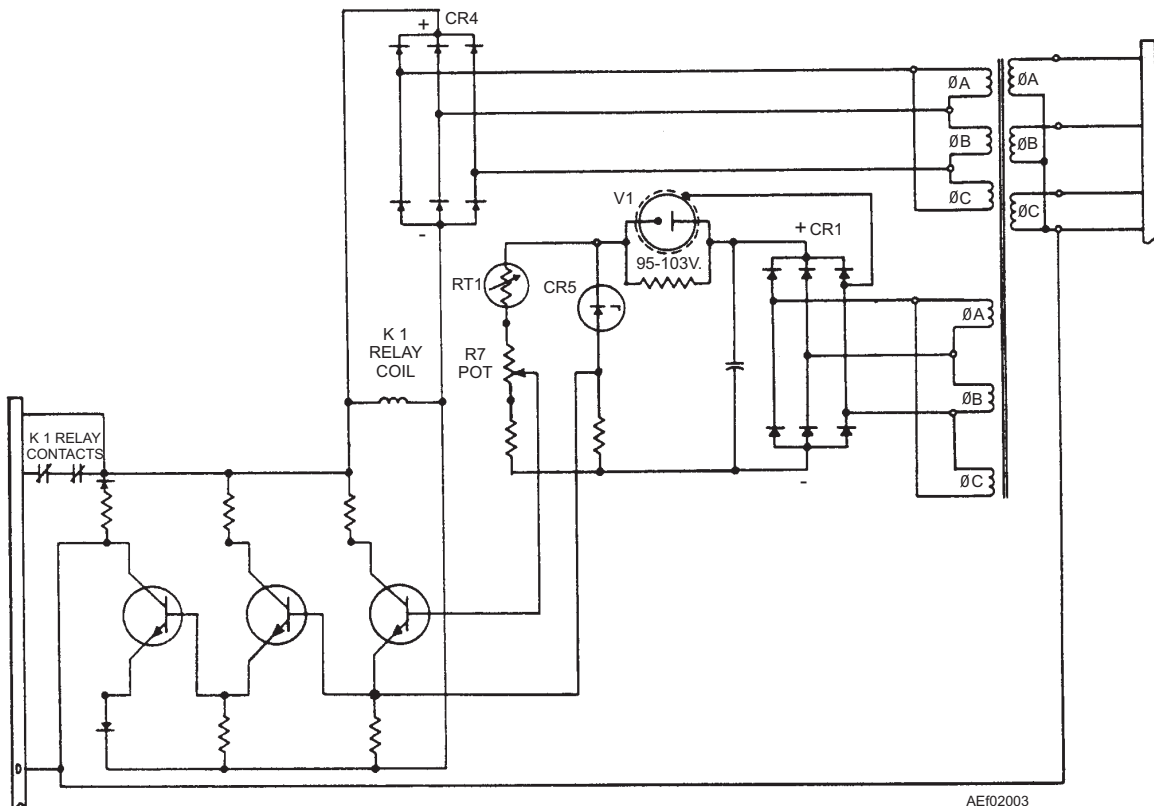


Figure 2-3.—Solid-state voltage regulator schematic.

during initial buildup of system voltage and during three-phase short circuit on the generator. Control relay (K1) connects across the full-wave bridge rectifier (CR4), overcoming these obstacles. When the relay is de-energized, its contacts provide permanent magnet generator (PMG) voltage to the exciter field. When generator voltage is 90 volts line to line, voltage across CR4 energizes control relay (K1), removing the self-excited field circuit. The voltage regulator then supplies the exciter field. The absence of phase shift and fast response characteristics of transistor-type amplifiers eliminates feedback networks and stabilizing transformers in this voltage regulator. Varying the output current to the exciter field varies the width of the square wave impulses.

Figure 2-4 shows a pulse width modulation diagram. As the voltage rises (shown by the dotted back-to-back sawtooth), the square wave pulse to the exciter field is off longer than it is on. This causes the output of the ac generator to decrease. The decrease in voltage causes the back-to-back sawtooth to drop to its normal value (shown by the solid waveform). This causes the on and off times of the square wave pulse to the exciter field to be about equal. Varying the on and off excitation to the exciter field controls the ac generator output.

## AC GENERATOR FREQUENCY CONTROL

Because of the fixed number of poles, the only means of fine-tuning the output frequency is controlling rotor rpm, often done by using CSDs. CSDs receive drive power from hydraulic power, pneumatic power, or the accessory drive section of an engine. It is for this reason that on most aircraft a CSD unit is located between the aircraft engine and the ac generator. On helicopters, the main generators are mounted on an accessory gearbox that is driven by the main transmission.

The purpose of the CSD is to transfer and convert aircraft engine variable-speed rotation to a constant-speed rotation, which drives the generator. The CSD consists of a variable-displacement hydraulic pump, constant-displacement hydraulic motor, and a governing system. The governing system controls the rate of flow from the pump, thereby controlling the speed of the motor. There are several other components in the CSD that are necessary for self-regulating constant-speed operation. Among these components are three output-driven gear pumps: the charge pump, replenishing pump, and scavenge pump. A gear on the CSD output shaft drives these pumps, the limit governor, and basic governor.

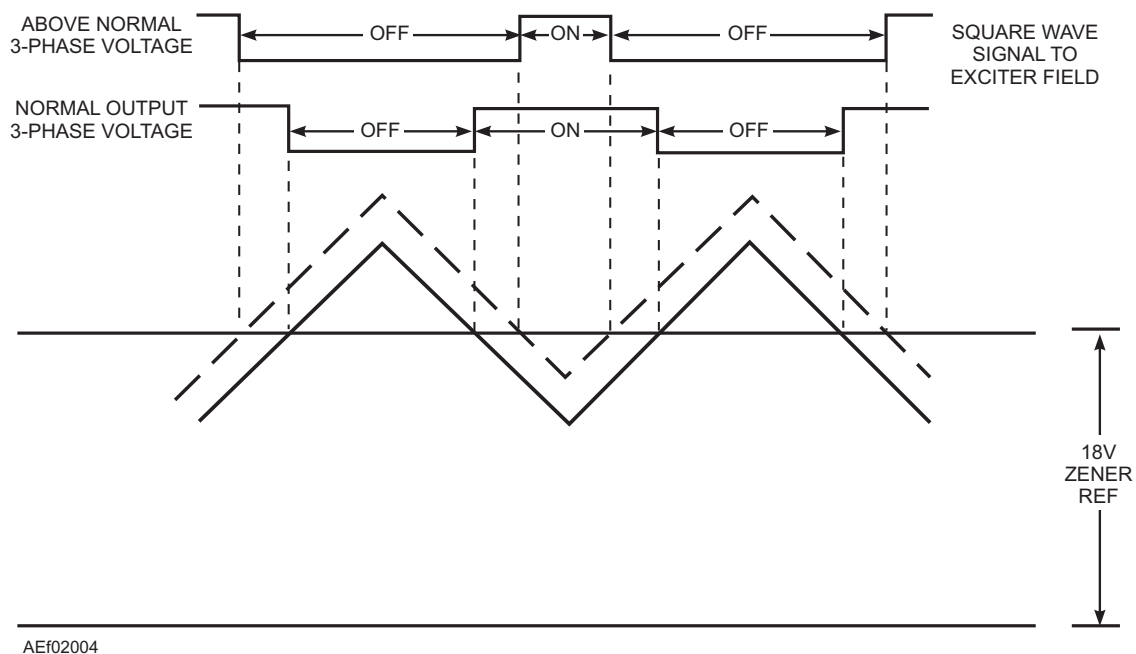


Figure 2-4.—Pulse width modulation diagram.

The pump wobbler and the pump section of the cylinder block assembly form the variable displacement pump in the CSD. Figure 2-5 shows a simplified CSD functional diagram. The pump wobbler consists of an outer stationary shell and an inner race. The inner race is separated from the wobbler shell by bearing rollers. It is free to turn with the pump pistons, which are always in contact with the race during operation. Two control pistons in the CSD housing move the wobbler sideways to vary the output of the pump.

The CSD functions in three different phases of operation: overdrive phase, straight-through phase, and underdrive phase.

When the engine input rpm is less than the rpm required for the generator, the CSD makes up the difference in rpm. The CSD does this by causing the pump wobbler system to respond to governor signals. This response causes the pump to supply more oil to the motor. The difference between the input and output rpm depends on the quantity of oil pumped by regulating the wobbler pump. Anytime the motor wobbler (output) is rotating faster than the cylinder block assembly (input) the CSD is in overdrive.

When the input rpm equals the required output rpm, the rotary motion transmits through the CSD without hydraulic action. The pump wobbler would, theoretically, be positioned through the action of the governor to be concentric with the cylinder block assembly. In this condition, the pump neither sends oil to the motor nor accepts oil from the motor. The motor pistons lock in position against the motor wobbler, forcing the wobbler to rotate at the same speed as the cylinder block assembly. Since the drive starts in underdrive and operates normally in overdrive, this straight-through condition is only temporary.

When engine input rpm exceeds the output rpm requirements for the generator, the CSD acts to subtract from the input rotation. The wobbler pump accomplishes this in response to the governor signal. The pump-motor action for underdrive is the reverse of the action required for overdrive. In the underdrive phase, the pump performs in a negative pumping

action. The generator load opposes the driving force of the CSD, so it always tries to slow the wobbler. The cylinder block assembly then rotates faster than the motor wobbler. Excess input torque is dissipated in the reverse pumping action to the charged oil system. Whenever the motor wobbler is rotating more slowly than the cylinder block assembly, the CSD is in underdrive. When the engine overspeeds or if the basic governor fails, the CSD goes into underdrive to protect the generator from overspeed.

The underspeed pressure switch in the governor oil line functions to break the electrical circuit of the ac control system. The system is protected during an underspeed condition.

In some CSDs, aircraft engine oil from the engine lubricating system is the hydraulic medium. In this case, the CSD also functions as a pump for supplying the generator with engine oil for cooling. Due to cooling capabilities, oil-cooled generators are of smaller construction than air-cooled generators having a similar rating.

- Q2-1. What is the most common method of voltage regulation for ac generators?*
- Q2-2. Why would we use a permanent magnet on the generator rotor in place of exciter windings?*
- Q2-3. What happens when magnetic fields of alternating polarity pass across the armature windings?*
- Q2-4. What controls the voltage induced into the armature windings?*
- Q2-5. What must ac generator control systems protect against?*
- Q2-6. What is the purpose of the rotating three-phase rectifier in a brushless generator?*
- Q2-7. What is the chief advantage of having dc exciter units integrated into ac generators?*
- Q2-8. What is the only moving mechanical part in a solid state voltage regulator?*

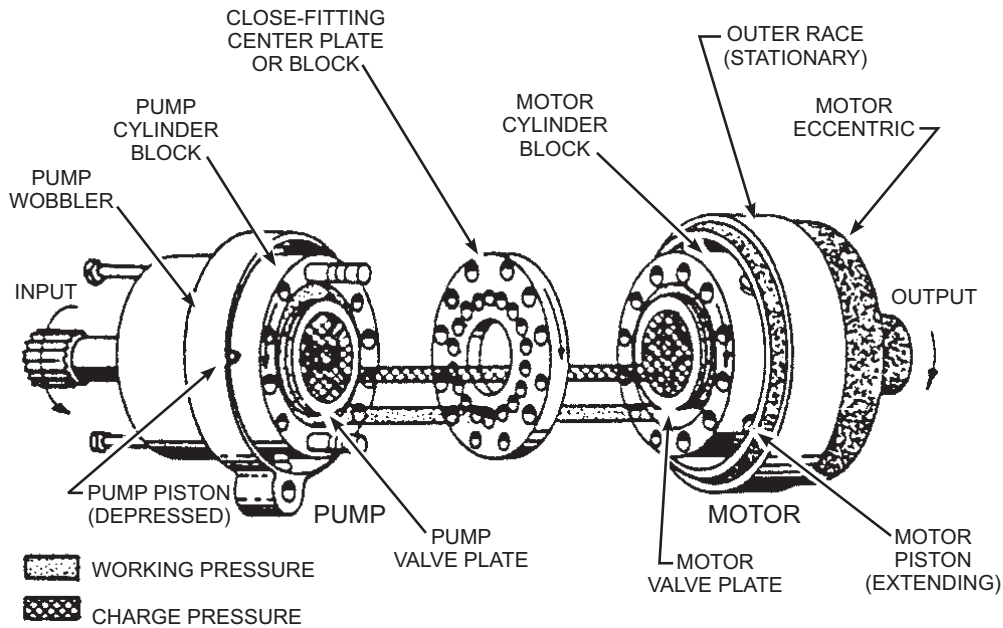


Figure 2-5.—Simplified CSD functional diagram.

- Q2-9. What happens if the output of the control amplifier section of a voltage regulator is too low?
- Q2-10. In a solid-state voltage regulator, what component supplies the power to the bridge circuit?
- Q2-11. What prevents the generator from receiving excitation voltages when the frequency is too low?
- Q2-12. Why is controlling the rotor rpm the only means of fine-tuning the output frequency of a generator?
- Q2-13. What two components are joined by the CSD?
- Q2-14. List the components of the CSD.
- Q2-15. When the input engine rpm is too low, what happens to the CSD hydraulic pump?
- Q2-16. How is the CSD/generator system protected during underspeed conditions?

## CIRCUIT PROTECTION

**LEARNING OBJECTIVES:** recognize ac circuit protection. Describe underfrequency and overfrequency control. Describe over-voltage and undervoltage control. Describe the feeder fault system.

The generator and equipment and systems the generator powers need protection if a malfunction occurs. Circuits designed to sense malfunctions and energize relays provide protection by either warning the pilot of the malfunction or disconnecting the generator. The circuit protection needed and the methods used to control the malfunctions depend on aircraft and equipment design. For example, in a single-pilot aircraft, all malfunction detection and correction might be automatic. In a multi-piloted aircraft, the generating system may only warn the flight crew of a problem. This leaves corrective action to the discretion of the pilot in command.

A supervisory panel (fig. 2-6) provides regulation and circuit protection for both the operating generator and equipment it powers in newer generating systems. This single component provides the same functions as several components in older power generating systems.

The supervisory panel provides voltage regulation at 120/208 volts ac, while some types of CSDs provide frequency control at 400 hertz (Hz). The supervisory panel further has relays and other associated circuitry to disconnect the generator from the load if any of the following conditions occur:

- Underfrequency
- Overfrequency
- Undervoltage
- Overvoltage
- Feeder fault (A condition where the current leaving the generator does not pass through the load. System design has cut out the need for feeder fault protection in systems where it is not likely to occur.)

## **UNDERFREQUENCY AND OVERFREQUENCY CONTROL**

You should refer to figure 2-6 as you read this section. The PMG output is 39 volts at 600 Hz when the generator is on speed. The voltage reference bridge and the frequency sensitive bridge sample output voltage and frequency. The band-pass filter is tuned to 600 Hz (called its resonant frequency). Its minimum resistance and maximum current flow occur at 600 Hz. At this frequency, the output of the bridge networks are equal and opposite. The underfrequency/overfrequency sensor senses an on-frequency condition energizing the underfrequency/overfrequency relay (K1). Current flows through contacts 4 and 6 of energized relay K1. This allows generator control relay (K2) to energize if the frequency remains within tolerance for at least 3 seconds.

If the PMG frequency changes from the desired 600 Hz, the band-pass resistance increases, and output of the circuits is unbalanced. The underfrequency/overfrequency sensor senses the unbalance and causes K1 to de-energize and immediately cuts off SCR-1. K2 de-energizes and disconnects any input to the exciter stator coils and reduces the generator output voltage to zero.

Contacts 1 and 2 of K1 change frequency tolerance from 600 Hz  $\pm$  42 to 600 Hz  $\pm$  53 by adding resistance to the voltage reference bridge circuit when K1

energizes. This prevents the relay from chattering when the generator is operating at or very near its tolerance limit.

## **VOLTAGE CONTROL**

A voltage regulating circuit changes PMG ac voltage to dc voltage and controls its amplitude. The voltage regulator senses all three phases of the generator output. If the average of these voltages is low, dc voltage to the exciter stator coils increases until output voltage is at the desired level. If output voltage is high, the voltage regulator decreases its output to the exciter stator coils until voltage is within tolerance.

The generator system maintains three-phase output voltage to 120 volts  $\pm$  2 through a wide range of loads from 1 to 120 kilovolt amperes (kVA). One phase load may be one-third more than the other two phase loads, and voltage will not vary more than 5 volts between phases. It takes 1.7 amperes of current through the exciter stator coils to produce the desired magnetic field to generate a 120-/208-volt, 60-kVA load.

### **Undervoltage**

Refer to figure 2-6 as you read this section. The undervoltage sensing and control circuit allows generator output to power the distribution system when voltage rises to 105 volts during initial generator buildup. However, it does not de-energize the generator output until one or more phases falls below 90 volts. The undervoltage sensor monitors generator output. In conjunction with K1, it also energizes auxiliary control relay (K3), connecting generator output to the power distribution system.

When K3 energizes, its contacts arm a timing circuit that acts automatically when one or more phases are 90 volts or less. The timing cycle duration is electronically divided into a 3-second period and a 1-second period: these two periods are additive. The total time involved before an undervoltage trip occurs is about 4 seconds. The delay circuitry allows time for corrective measures (circuit breakers or current limiters to open) to remove the cause of the undervoltage.

If the cause of the undervoltage is removed and voltage rises to 105 volts before the initial time delay lapses, the generator stays on line. This cancels the lapsed increment and the full 4-second delay is reinstated. However, after a 4-second delay, differential protection latch-out relay (K6) energizes, energizing lockout relay (K4), and removes power from K3 and K2.

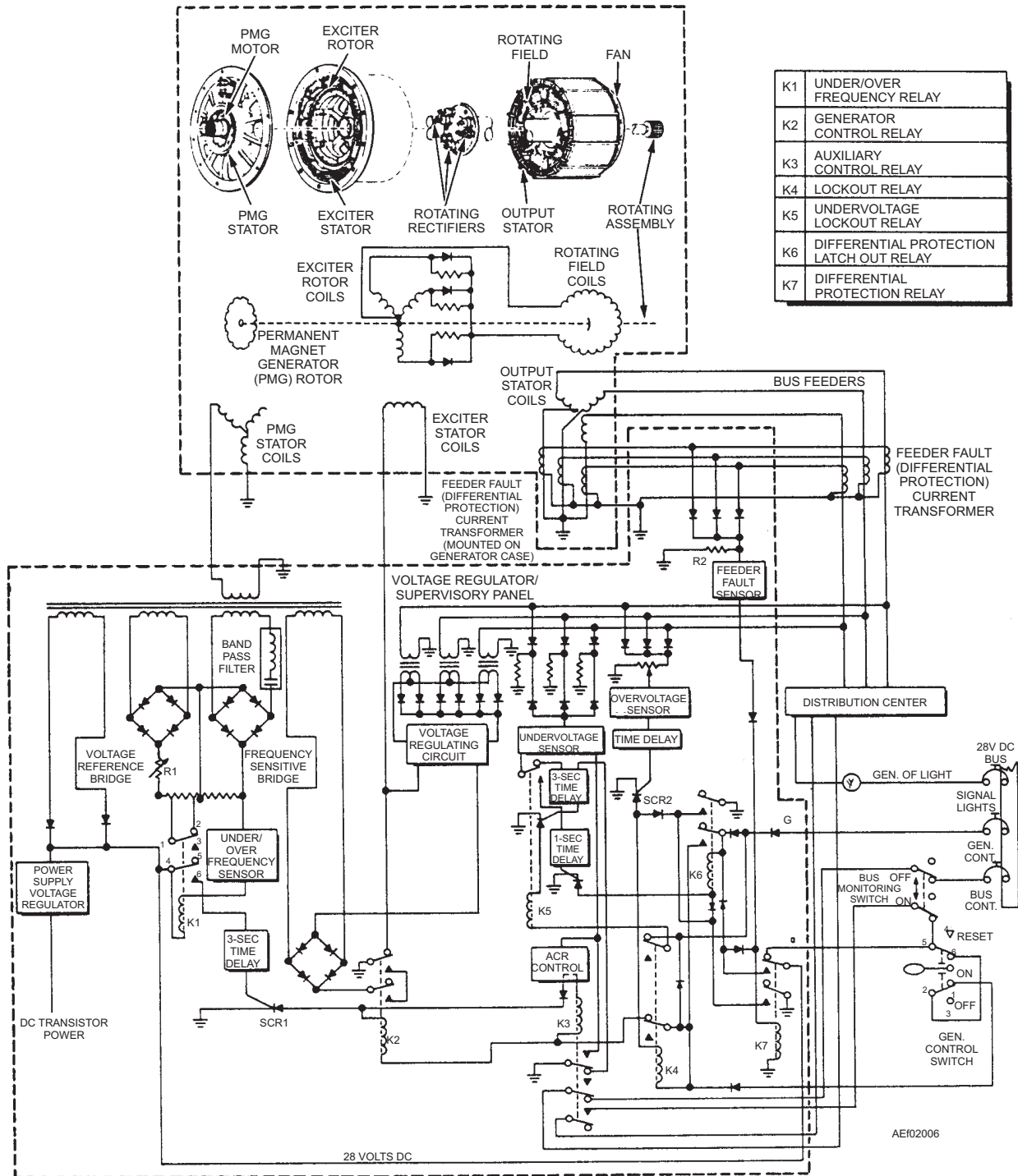


Figure 2-6.—Generator control system voltage regulator/supervisory panel.

An excessive load on the generator can cause an undervoltage (a short circuit in a system that has a defective circuit breaker or fuse). This condition, if allowed to continue, could cause a fire or destroy the generator. Therefore, both K6 and K4 have holding circuits to keep them energized even when the undervoltage condition is corrected. To check for correction of the undervoltage, use the following procedure:

1. Place the GEN CONTROL SWITCH to the OFF position.
2. Pull and reset the GEN CONT circuit breaker.
3. Return the GEN CONTROL SWITCH to ON.

### Overvoltage

As you read this section, refer to figure 2-6. An overvoltage sensor senses line voltage above 129 volts and starts a time delay. When started, the delay times out for a time inversely proportional to the overvoltage. A voltage of 130 volts on a single phase may have a delay of 3 to 4 seconds. A large overvoltage on all three phases may have a delay of a few milliseconds. When the delay completes timing, it triggers SCR2 into conduction and allows K4 to energize.

An overvoltage occurs if a voltage regulator malfunctions or if a large load (several loads) is removed from the generator at once. The voltage regulator is not fast enough to react when the generator loses several loads quickly. That is, it is possible for an overvoltage to occur during normal operation of the generating system. K4, supplying its own holding circuit, prevents the generator from powering the load again. If you place the GEN CONTROL SWITCH to either the RESET or the OFF position and back to ON, the generator stays on line. This prevents a generating system with a malfunctioning voltage regulator from cycling on and off.

### FEEDER FAULT SYSTEM

A short occurring between the generator and distribution system could cause a fire because there are not any protective devices (such as circuit breakers and fuses). A feeder fault circuit (fig. 2-6) protects against this possibility.

The generator armature winding (output) has current transformers on each side of each winding. One set of current transformers (on the grounded side) is as close to the armature windings as possible. The other set is as close to the distribution system (and its

protective devices) as possible. The transformer's connections are then made so the voltages produced cancel each other out. The input to the feeder fault sensor would then be nearly zero. A short to ground or phase to phase would place a voltage across R2, causing the feeder fault sensor to energize differential protection relay (K7). K7 then acts to energize K6, K6 energizes K4, and K4 de-energizes K2 and K3. Since K7 remains energized by its own contacts using PMG voltage, the system cannot be reset until removal of PMG voltage by stopping the generator.

- Q2-17. *What component provides circuit protection for an ac generator?*
- Q2-18. *A supervisory panel will disconnect the generator from the load under what conditions?*
- Q2-19. *What is the required output frequency of the PMG?*
- Q2-20. *How many amperes are required through the exciter coil to generate a 120-/208-volt, 60-kilovolt ampere (kVA) load?*
- Q2-21. *During an undervoltage condition, at what voltage will the generator be dropped off line?*
- Q2-22. *At what voltage will the generator be dropped off line during an overvoltage condition?*
- Q2-23. *What is feeder fault?*

## AIRCRAFT POWER DISTRIBUTION

**LEARNING OBJECTIVES:** Identify the uses of electrical buses. Describe the purpose of power transfer contactors. Recognize aircraft power sources. Recognize ac and dc

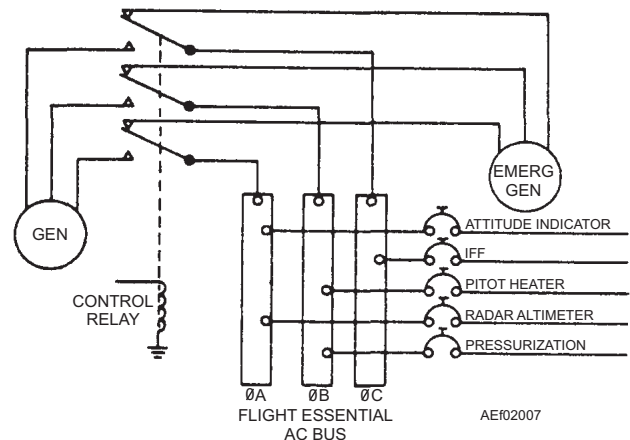


Figure 2-7.—Three-phase ac bus.



power distribution. Explain the operation of external power applied to an aircraft. Explain the operation of main generators applied to an aircraft. Recognize the component failures of ac/dc power distribution. Explain the operation of the emergency generator system. Identify grounded and ungrounded systems. Identify single-phase and polyphase systems.

You have learned that various sources are used to provide electrical power to operate aircraft electrical equipment and systems. In this section, the system that connects the electrical power source to the equipment is discussed. Each manufacturer develops a system that meets the needs of their particular aircraft design. A system of priorities ensures certain critical equipment is operable if there is a malfunction. For example, if a power lead used to start an engine shorted out during flight, it is inappropriate to sacrifice all electrical power, especially power to lighting, navigation equipment, flight instruments, and other essential

equipment. Therefore, systems of like priority are on a common line called a *bus*.

## ELECTRICAL BUSES

Each type of aircraft has a group of buses identified by the priority of the equipment it powers. For example, a flight-essential bus may power emergency lighting, critical flight and engine instruments, and/or an emergency radio. Less important critical equipment receives power from an essential bus. Normal systems used to complete the assigned mission or provide crew comfort are on the main bus. The input to a bus may be either dc or ac. The output from the bus has a protective device such as a circuit breaker, fuse, or current limiter. A three-phase ac bus has three separate common lines, one for each phase (fig. 2-7). Sometimes, schematics show three phases drawn as one line.

The P-3C aircraft is an example of versatility and flexibility in electric systems. Figure 2-8 shows a portion of the P-3C power distribution system.

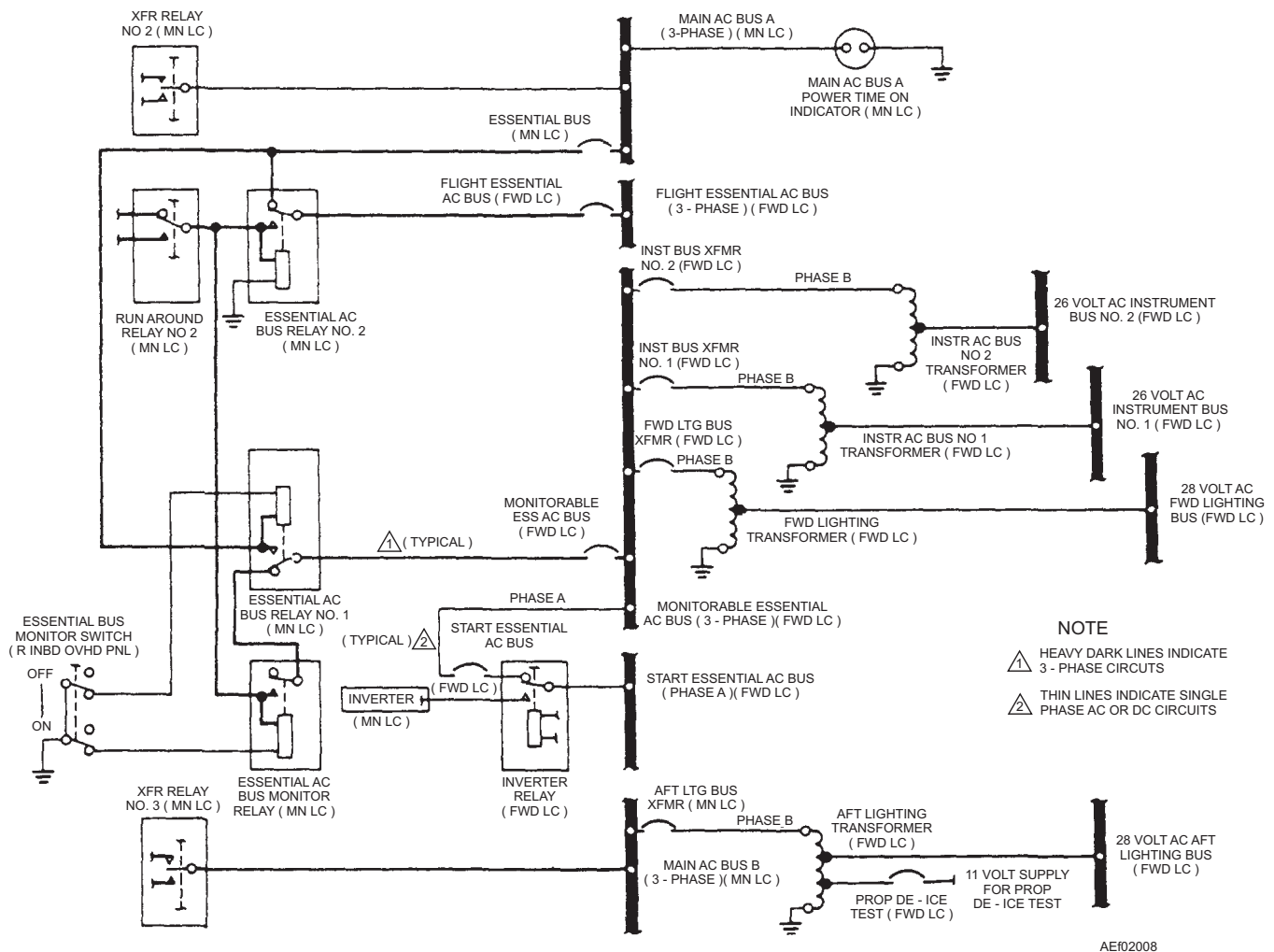


Figure 2-8.—Simplified P-3C electrical power distribution.

**Table 2-1.—F-14 Ac Bus Distribution**

**AC ESSENTIAL NO. 1 BUS—115 V AC**

APX-72 AC—(PH B)  
 RED FLOOD LT—(PH C)  
 AWG-15 PH A NO. 1  
 AWG-15 PH B NO. 1  
 AWG-15 PH C NO. 1  
 AWG-15 PH A NO. 2  
 AWG-15 PH B NO. 2  
 AWG-15 PH C NO. 2  
 UHF COMM PH A  
 UHF COMM PH B  
 UHF COMM PH C  
 STBY ATTD IND PH A  
 STBY ATTD IND PH B  
 RADAR ALTM—(PH B)  
 INST BUS FDR

**AC ESSENTIAL NO. 2 BUS—115 V AC**

ROLL CMPTR AC—(PH A)  
 PITCH CMPTR AC—(PH A)  
 R AICS—(PH A)  
 L AICS—(PH C)  
 AUTO PITCH DRIVE TRIM—(PH A)  
 FLT CONTR AUTH AC—(PH C)  
 MACH TRIM AC—(PH C)  
 L FUEL CONTR/MACH LVR—(PH C)  
 R FUEL CONTR/MACH LVR—(PH B)  
 ICE DET—(PH C)  
 GLOVE VANE CONTR—(PH C)  
 WING SWEEP DRIVE NO.—(PH C)  
 WG SWP DR NO. 2/MANUV FLAP—(PH C)  
 YAW SAS A PWR SUP—(PH A)  
 YAW SAS B PWR SUP—(PH A)  
 YAW SAS M PWR SUP—(PH A)  
 CHAN 1 CADC PH A  
 CHAN 1 CADC PH B  
 CHAN 1 CADC PH C  
 CHAN 2 CADC—(PH B)  
 26 VAC BUS FDR—(PH A)  
 AC ESS BUS NO. 2 FDR PH A  
 RUDDER TRIM PH A  
 L PH A TEST/P-ROLL TRIM  
 AN/ARA-50—(PH A)  
 TACAN ARN-84—(PH A)  
 HUD PH A  
 AHRS PH A  
 CSDC PH A  
 VDI PH A  
 ILS ARA-63 PH A  
 ILS ARA-63 PH B  
 ILS ARA-63 PH C  
 L PH B TEST/P-ROLL TRIM  
 L PH C TEST/P-ROLL TRIM  
 RUDDER TRIM PH B  
 RUDDER TRIM PH C  
 HUD PH B  
 HUG PH C  
 AHRS PH B  
 AHRS PH C  
 CSDC H B  
 ALPHA HTR (PH C) <sup>5</sup>  
 CSDC PH C  
 VDI PH B  
 VDI PH C  
 AC ESS BUS NO. 2 FDR PH B  
 AC ESS BUS NO. 2 FDR PH C  
 L PITOT STATIC HTR—(PH B)  
 R PITOT STATIC HTR—(PH B) <sup>13</sup>  
 INST BUS FDR—(PH B)  
 PROBELT—(PH B)  
 UTILITY LT—(PH C)  
 TEMP CONT AC—(PH C)

**AC ESSENTIAL NO. 2  
 BUS—115 V AC—CONTINUED**

INTRF BLANKER—(PH B)  
 BLEED DUCT AC—(PH C)  
 ANL ATTK TOTAL TEMP HTR—(PH C)

**AC LEFT MAIN BUS—115 V AC**

NAV IMU PH A  
 NAV IMU PH B  
 NAV IMU PH C  
 NAV PWR SUP PH A  
 NAV PWR SUP PH B  
 NAV PWR SUP PH C  
 IR/TV PH A  
 IR/TV PH B  
 IR/TV PH C  
 SOL PWR SUP PH A  
 SOL PWR SUP PH B  
 SOL PWR SUP PH C  
 MSL AUX PH A  
 MSL AUX PH B  
 MSL AUX PH C  
 CONTR/DISPLAY PH A  
 CONTR/DISPLAY PH B  
 CONTR/DISPLAY PH C  
 ANT SVO HYD PH A  
 ANT SVO HYD PH B  
 ANT SVO HYD PH C  
 STA 1/8 AIM-7 PH A  
 STA 1/8 AIM-7 PH B  
 STA 1/8 AIM-7 PH C  
 SEMI REG PWR SUP PH A  
 SEMI REG PWR SUP PH B  
 SEMI REG PWR SUP PH C  
 STA 3/6 AIM-7/AIM-54 PUMP PH A  
 STA 3/6 AIM-7/AIM-54 PUMP PH B  
 STA 3/6 AIM-7/AIM-54 PUMP PH C  
 AN/AWG-9 CMPTR PH A  
 AN/AWG-9 CMPTR PH B  
 AN/AWG-9 CMPTR PH C  
 STA 4/5 AIM-7 PH A  
 STA 4/5 AIM-7 PH B  
 STA 4/5 AIM-7 PH C  
 MSL HTR PH A  
 MSL HTR PH B  
 MSL HTR PH C  
 AN/AWW-4 PH A  
 AN/AWW-4 PH B  
 AN/AWW-4 PH C  
 HSD/ECMD PH A  
 HSD/ECMD PH B  
 HSD/ECMD PH C  
 28 VDC PWR SUP PH A  
 28 VDC PWR SUP PH B  
 28 VDC PWR SUP PH C  
 HV PWR SUP PH A  
 HV PWR SUP PH B  
 HV PWR SUP PH C  
 L MAIN XFMR/RECT  
 DDI AC—(PH B)  
 IFF A/A AC—(PH C)  
 AUTO THROT AC—(PH A)  
 AN/ALR-45 (PH B)  
 ASW-27 (PH B)  
 INTEG TRIM AC (PH A)  
 HUD CAMERA (PH A) } <sup>17</sup>  
 HUD CAMERA (PH B)  
 HUD CAMERA (PH C)

**26 V AC ENGINE INSTRUMENT BUS**

L ENG OIL PRESS/NOZ IND—(PH A)  
 R ENG OIL PRESS/NOZ IND—(PH A)

**26 V AC NAVIGATION BUS**

AS/ARA-48 ANT—(PH A)  
 TACAN/BDHI INST PWR (PH A)  
 INS SYNC/ACM PNL LT—(PH A)

**115 V AC INSTRUMENT BUS**

A/S IND/BARO ALTM AC (PH B) <sup>3</sup>  
 BARO ALTM AC (PH B) <sup>4</sup>  
 FLT HYD PRESS IND—(PH B)  
 COMB HYD PRESS IND—(PH B)  
 ANGLE OF ATTK IND AC—(PH B)  
 WING POS IND AC—(PH B)  
 L ENG N<sub>2</sub> TACH—(PH B)  
 R ENG N<sub>2</sub> TACH—(PH B)  
 L TIT IND—(PH B)  
 R TIT IND—(PH B)  
 OXY QTY IND—(PH B)  
 FUEL QTY IND AC—(PH B)  
 TAIL/RUDDER/FLAP IND—(PH B)  
 ENG FUEL FLOW/L IND OVSP—(PH B)  
 R ENG FUEL FLOW IND—(PH B)

**AC RIGHT MAIN BUS—115 V AC**

FLT HYD BACKUP PH A  
 FLT HYD BACKUP PH B  
 FLT HYD BACKUP PH C  
 OUTBD SPOILER PUMP PH A  
 OUTBD SPOILER PUMP PH B  
 OUTBD SPOILER PUMP PH C  
 R MAIN XFMR RECT  
 ALQ-100 PH A } <sup>16</sup>  
 ALQ-100 PH B  
 ALQ-100 PH C  
 AN/AWG-9 PUMP PH A  
 AN/AWG-9 PUMP PH B  
 AN/AWG-9 PUMP PH C  
 R PH A TEST/GAS TEMP LIM  
 R PH B TEST/GAS TEMP LIM  
 R PH C TEST/GAS TEMP LIM  
 STA 1A AIM-9 PWR PH B  
 STA 1B AIM-9 PWR PH C  
 STA 8A AIM-9 PWR PH B  
 STA 8B AIM-9 PWR PH C  
 TAXI/FORM LT—(PH A)  
 GUN CONTR PWR AC—(PH B)  
 WHITE FLOOD LT—(PH B)  
 LIQUID COOLING CONTR AC—(PH C)  
 ANTI COLL/SUPP POS/POS LTS—(PH A)  
 ACM LT/SEAT ADJ/STEADY POS  
 LT—(PH B)  
 L AICS HTR—(PH B)  
 R AICS HTR—(PH C)  
 INST LT—(PH B)  
 PILOT CONSOLE LT—(PH A)  
 NFO CONSOLE LT—(PH A)  
 RECON GCS CONT AC  
 RECON HTR PWR PH A } <sup>20</sup>  
 RECON HTR PWR PH B  
 RECON HTR PWR PH C

AEI02001

Operation of the P-3C electrical power distribution system during normal flight conditions is entirely automatic. The crew only monitors the control panels for any indication of a malfunction. Control of the system is also automatic during ground operation, except switching to and from external power.

Tables 2-1 and 2-2 list systems receiving power from the F-14 aircraft power distribution system. Many of these systems are not applicable to other naval aircraft. Often, systems vary with the model number of the same type of aircraft, and it isn't appropriate to have the same bus system in all aircraft types or models.

## **POWER TRANSFER CONTACTORS/RELAYS**

Naval aircraft power requirements have grown with technology, resulting in numerous power resources, which use transfer relays for distribution. There are basically two types of power transfer contactors: single coil and double coil.

A single coil contactor consists of auxiliary contacts and two sets of three main contacts with a paralleled common output. The auxiliary contacts normally control identification lights on the power control panel. The two sets of three main contacts are arranged so that only one set of contacts can be closed at a time.

A double coil relay is a two-section mechanically interlocking device having two energizing coils. Each section has three main contacts in addition to a common output. The mechanical interlock prevents simultaneous actuation of the two relay sections. The auxiliary contacts normally control identification lights on the power control panel.

## **POWER SOURCES**

This section contains a discussion of a representative power distribution system used in F-14 aircraft. Electrical power is provided to the buses from four sources:

- Left main generator
- Right main generator
- External power
- Emergency power

Two engine-driven generator transmissions supply ac. Each one is coupled to a 115-/208-volt ac, 400-Hz, three-phase brushless ac generator. These generators supply electrical power to the main, essential, and

monitor ac buses. Either of the two generators can supply the entire electrical demand of the aircraft in the event one generator fails. Two transformer-rectifiers (TR) supply dc power. Each TR unit receives power from its respective main ac bus. The TR units convert 115 Vac to 28 Vdc for distribution to the secondary bus system. Either of the TRs is capable of supplying the entire dc requirements of the aircraft.

A hydraulically driven, 5-kVA/50-amp generator provides ac and dc emergency power for essential equipment only. The emergency generator automatically actuates upon multiple generator or multiple TR unit failure. Emergency generator operation terminates upon reactivation of either main generator. The aircraft receives external power through an external ac power contactor. Discussion of each of these power sources, as well as contactor control logic, is contained in the following paragraphs.

## **AC BUS DISTRIBUTION SYSTEM**

The distribution system consists of five three-phase ac buses, which are listed below:

- Left main ac bus
- Right main ac bus
- Monitor ac bus
- Ac essential number one bus
- Ac essential number two bus

The left and right main ac buses provide power to nonessential equipment throughout the aircraft. The monitor ac bus currently has no load attached to it. When used, it provides power to nonessential equipment only. With both generators operating, ac essential buses number one and number two and the 115-volt ac instrument bus power safety-of-flight equipment. The main generators normally supply power to these two buses, but they also tie in to the emergency generator when it is in operation. A step-down transformer supplies 26 Vac for instruments and navigation systems. The output of the transformer also provides power to safety-of-flight equipment.

## **DC BUS DISTRIBUTION SYSTEM**

The main sources of dc power are the left and right TR units. These units receive power from the left and right main ac, three-phase buses, respectively. The left and right main dc buses provide power to nonessential dc systems. When both generators are operating, the

Table 2-2.—F-14 Dc Bus Distribution

DC ESSENTIAL NO. 1 BUS—28 V AC

L AICS RAMPS STOW  
R AICS RAMP STOW  
AWG-15 DC  
ALT LOW WARN  
DC ESS NO. 1 FDR  
MASTER ARM  
ARC-159 NO. 1  
EMERG FLT HYD AUTO  
EMERG FLT HYD MAN  
STA 1 REL PWR A  
STA 1 REL PWR B  
L FIRE EXT }  $\triangle$ <sub>9</sub>  
R FIRE EXT }  
ECM DEST  $\triangle$ <sub>16</sub>  
STA 2, 3 & 4 REL PWR A  
STA 2, 3 & 4 REL PWR B  
ACM PNL PWR  
STA 1 AIM-9 REL PWR  
STA 8 AIM-9 REL PWR  
ARC-159 NO. 2  
STA 5, 6 & 7 REL PWR A  
STA 5, 6 & 7 REL PWR B  
STA 8 REL PWR A  
STA 8 REL PWR B  
JETT 1  
JETT 2  
APX-72 DC  
UHF CONTR  
MLG SAFETY RLY NO. 1  
MLG SAFETY RLY NO. 2  
ICS PILOT  
ICS NFO  $\triangle$ <sub>1</sub>  
R MID CPRSN BYPASS }  $\triangle$ <sub>12</sub>  $\triangle$ <sub>14</sub>  
L MID CPRSN BYPASS }  
ENG STALL TONE  $\triangle$ <sub>6</sub>  
A/S INB/BARO ALTM DC }  $\triangle$ <sub>4</sub>  
BARO ALTM DC }  $\triangle$ <sub>12</sub>  $\triangle$ <sub>14</sub>  
L FIRE DET/LT }  
R FIRE DET/LT }

INTERRUPTION FREE DC  
BUS—28 V DC

AUTO THROT DC  
INTEG TRIM DC

DC ESSENTIAL NO. 2  
BUS—28 V DC

ENG/PROBE/ANTI-ICE  
FLT CONTR AUTH DC  
FLAP/SLAT CONTR SHUT-OFF  
MACH TRIM DC  
AIR SOURCE CONTR  
NOSE WHEEL STEER/AFCS  
SPD BK P-ROLL TRIM ENABLE  
FUEL P/MOTIVE FLOW ISOL V  
ENG START  
FUEL FEED/DUMP  
FUEL MGT PNL  
ENG ANTI-ICE VALVES  
NLG STRUT LCH RAR ADVSY  
DC ESS NO. 2 BUS FDR  
CABIN PRESS  
DISPLAY PWR  
AFCS BUS FDR  $\triangle$ <sub>8</sub>  
UHF NO. 2  $\triangle$ <sub>8</sub>  
ALPHA COMP/PEDAL SHAKER  $\triangle$ <sub>9</sub>  
ILS ARA 63 DC  
CAN/LAD CAUTION/EJECT CMD IND  
RAIN RPL/ANTI-ICE CONTR/HK CONTROL

DC ESSENTIAL NO. 2  
BUS—28 V DC—CONTINUED

ANN PANEL PWR  
JULIET-28  
AN/ARA 50/ARA-69  $\triangle$ <sub>11</sub>  
AN/ARA-50  $\triangle$ <sub>10</sub>  
CSDC  
ECS TEMP CONTR DC  
FUEL QTY IND DC  
OVSP CAUTION R OIL HOT  
END OIL COOL  
TACAN/BDHI  
APN 154  
HYD PRESS IND  
HYD VALVE CONTR  
FUEL TRANS ORIDE  
ANGLE OF ATTK IND DC  
EMERG GEN TEST/L AICS LKUP PWR  
ANTI SKID/R AICS LKUP PWR  
HYD PUMP SPOILER CONTR  
FUEL VENT VALVE  
STARTER CONTR VALVE  $\triangle$ <sub>7</sub>  
FUEL LOW CAUTION  
OXY/BINGO CAUTION  
L GEN CAUTION  
R GEN CAUTION  
TR-ADVSY/PLT ANN PNL AUX PWR  
BLEED AIR/L OIL HOT  
FUEL PRESS ADVSY  
EXT L CONTR  
INBD SPOILER CONTR  
MACH LEVER SHIFT  
L DC TEST/RUDDER TRIM  
WHEELS POS IND  
MLG HANDLE RLY NO. 1  
MLG HANDLE RLY NO. 2  
AUX FLAP/FLAP CONTR  
WING POS IND DC  
GND ROLL BRAKING/SPOILING POS IND

AFCS BUS—28 V DC

YAW SAS A  
YAW SAS B  
YAW SAS M  
PITCH CMPTR DC  
ROLL CMPTR DC

DC LEFT MAIN BUS—28 V DC

INTRPT FREE DC BUS FDR NO. 1  
EMERG GEN CONTR  
GYRO PWR  
MOTOR FIRE B  
MOTOR FIRE A  
APX-72 TEST SET  
MECH FUZING STA 5/6  
MECH FUZING STA 3/4  
MECH FUZING STA 1/8  
ELEC COOLING  
MASTER TEST  
AN/AWW 4  
ARMCS ENABLE  
ANT LOCK EXCIT  
R AIM-7 BATT ARM  
L AIM-7 BATT ARM  
DDI DC  
ASW-27  
GND PWR/COOLING INTERLK  
AN/ALR-50  
IFFA/ADA  
BRAKE ACCUM SOV  $\triangle$ <sub>18</sub>  
HUD CAMERA DC  $\triangle$ <sub>19</sub>

DC LEFT MAIN  
BUS—28 V DC—CONTINUED

RECON ECS CONT DC  
RECON POD CONT  
RECON POD DC PWR NO. 1  
RECON POD DC PWR NO. 2 }  $\triangle$ <sub>20</sub>

DC RIGHT MAIN BUS—28 V DC

STA 8 AIM-9 COOL PWR  
STA 8B AIM-9 PWR  
STA 8A AIM-9 PWR  
STA 1 AIM-9 COOL PWR  
STA 1B AIM-9 PWR  
STA 1A AIM-9 PWR  
DYHR UNIT  
R DC TEST/ACM BIT  
COUNTING ACCEL  
MONITOR BUS CONTR  
GND TEST/MARCH LV BIT  
MID CPRSN BYPASS PWR  
DDI/ANN PNL DIM CONTR  
GUN ARMED POWER  
OUTBD SPOILER CONTR  
INTRPT FREE DC BUSS FDR NO. 2  
WSHLD DEFOG CONTR  
GUN CLR/GUN CONTR PWR DC  
LIQUID COOLING CONTR DC  
ALE-39 SEQ 1 & 2 SQUIBS  
ALE-39 CHAFF/FLARE DISP

monitor bus provides power to nonessential equipment only. The automatic flight control system (AFCS) bus and essential buses numbers one and two provide power to safety-of-flight equipment. The TR units normally supply these three buses, but they receive power directly from the emergency generator when it is in operation.

Either external electrical power or both generators can supply the entire ac and dc bus system. If only one generator is operating, the entire ac and dc bus systems (except the monitor ac and dc buses) have power. If only one TR unit is in operation, the entire dc bus system (except the monitor bus) has power.

The emergency generator powers only the ac-essential bus, 115-volt ac instrument bus, 26-volt ac instrument bus, dc essential bus, and AFCS buses. If a complete propulsion system fails, the hydraulic pressure developed by the windmilling of the engines is sufficient to drive the emergency generator. In this configuration, only the essential ac number one bus and the dc essential number one bus have power.

Tables 2-1 and 2-2 list the elements of the various ac and dc buses and the applicable systems attached to each particular bus.

- Q2-24. In an electrical system, what is a “bus?”
- Q2-25. How are buses identified?
- Q2-26. What are the types of output protection devices used by buses?
- Q2-27. What are the two basic types of power contactors?

- Q2-28. What are the four power sources available to the F-14 aircraft?
- Q2-29. List the three-phase buses of the F-14 aircraft.
- Q2-30. What dc bus will **NOT** be powered in the event of one TR failure in the F-14 aircraft?

## AC/DC POWER DISTRIBUTION OPERATION

As you have already learned, the two main generators and two TR units of an external ac power source provide electrical power. If engines are operating and hydraulic pressure is available, the emergency generator is available as a source of power. Switching between power supply systems is automatic without pilot action. However, the pilot can selectively isolate power sources and the distribution system in emergency situations.

When operating normally, the buses receive power through a series of contacts and logic situations, depending on the power source(s) in use. Normal power sources include external power and the left and right generators. Grounded and ungrounded, single-phase and polyphase systems also are discussed.

### External Power

The external electrical power system (fig. 2-9) permits application of three-phase, ac power to the aircraft electrical power distribution system. External power goes to the ground power monitor (GPM) and de-energized contacts of the external power contactor.

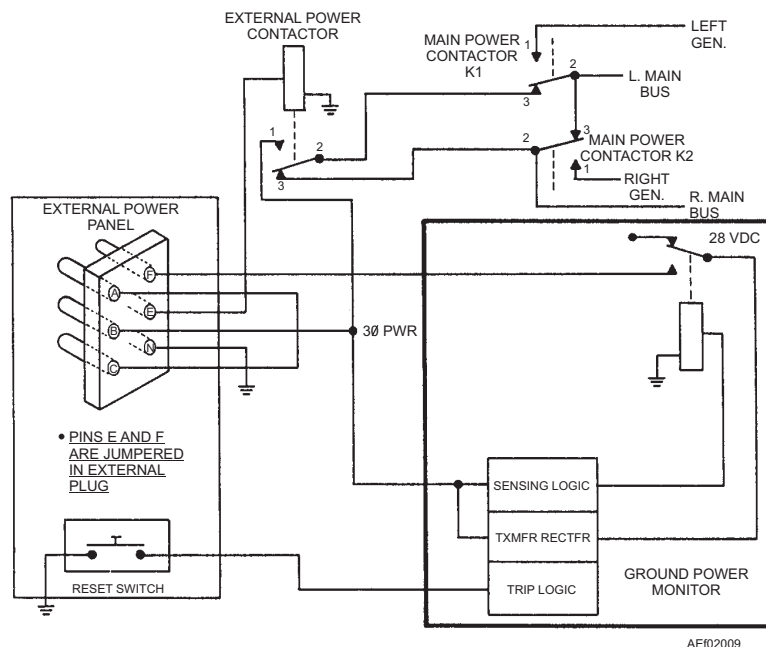


Figure 2-9.—External ac power functional block diagram.

The GPM prevents application of external power not within tolerances. If an undervoltage, overvoltage, underfrequency, overfrequency, or a phase reversal fault occurs, the GPM disconnects external power from the power distribution system.

When all the power parameters are within tolerance, the GPM relay energizes, supplying 28 Vdc from the GPM transformer-rectifier to pin F of the external power panel.

**NOTE:** Pins E and F are jumpered in the external power plug.

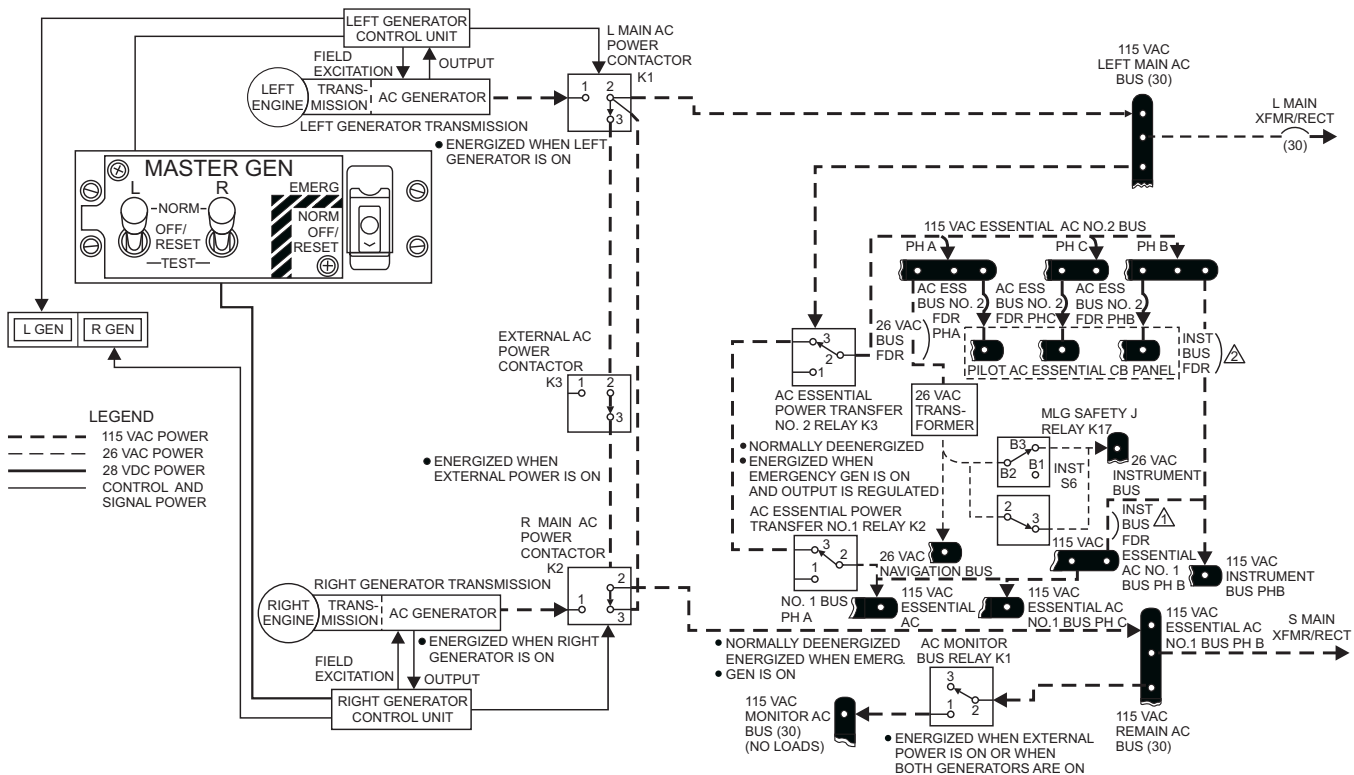
The power then runs through pin E and energizes the external power contactor. Three-phase power at pin one of the external power contactor then runs to the left main ac bus and right main ac bus through their respective contactors. Power from the left main ac bus (fig. 2-10) goes to the left TR unit. It also goes through the de-energized contacts of both ac essential power transfer relays to all essential ac buses and to the 26-volt ac transformer. This transformer, in turn, feeds power to the 26 Vac instrument and navigational buses. The right main ac bus supplies power to the right TR unit. Both left and right TR units (fig. 2-11) provide power to all dc buses through their respective power contactors and power transfer relays.

External electrical power is automatically inhibited from some systems when external air conditioning is not being supplied to the aircraft.

After aircraft engines start and the left generator comes on line, the left main contactor automatically disconnects external power. Some aircraft have a light on the caution/advisory panel that is illuminated by a switch, mounted on the external power receptacle, when the door is open. However, there is no cockpit indication of external power application. The only control the pilot has over external power being applied or removed is the hand signals between the pilot and the plane captain.

### Main Generators

Refer to figure 2-10 as you read. With external power connected and engine start initiated, the left generator comes on line when all parameters are within tolerance. With the left generator on line, the left main ac power contactor energizes. The left generator now supplies power through the left main ac power contactor (K1) pins one and two to the left and right main ac buses. These two buses, in turn, provide power to both TR units, all other 115-volt ac buses, and the 26-volt ac transformer. The TR units and the 26-volt ac transformer provide power to all other respective buses.



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Figure 2-10.—Simplified ac power distribution schematic.

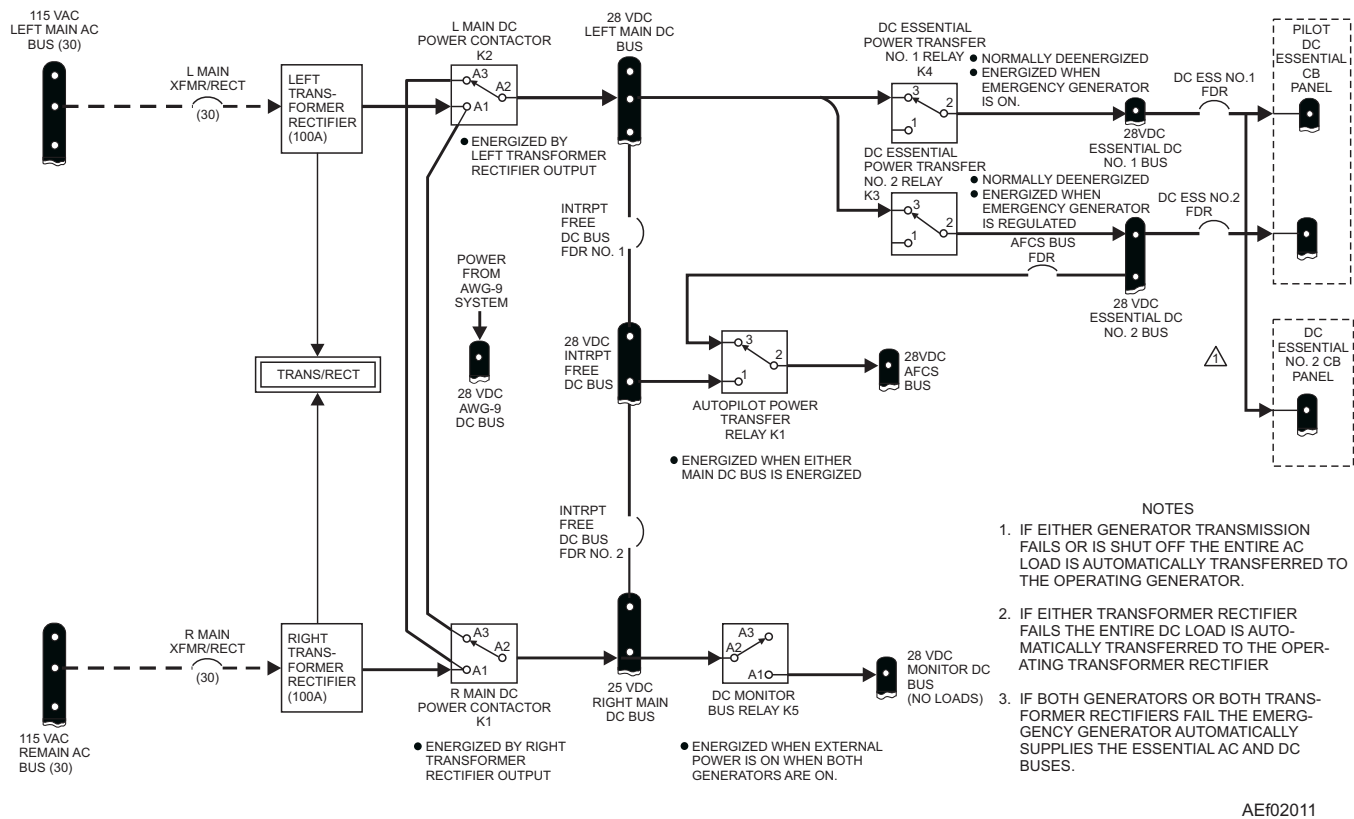


Figure 2-11.—Simplified dc power distribution schematic.

When the left main contactor energizes, it removes external power from the aircraft bus system. The external power unit is now shut down and cable removal may be done safely.

With the right generator on line, the right main contactor energizes, allowing the right generator to power the right main bus. The energized contacts of the right main ac power contactor (K2) prevent the left generator from powering the right main bus. Likewise, the energized left main contactor prevents the right generator from applying power to the left main bus.

When both generators are operating, the left generator powers the left main bus. The left main bus powers all 115-volt ac essential and instrument buses through the ac essential power transfer relays and through the 26-volt ac transformer. The transformer powers the instrument and navigation buses.

The left TR unit (fig. 2-11) receives power from the left main bus. It provides power to the left main dc bus through contact A1 of the energized left main dc power contactor. The left main dc bus provides power to the essential dc buses through the contacts of de-energized dc essential power transfer relays. In addition, the left main dc bus powers the interruption-free dc bus. This

bus, in turn, powers the 28-volt dc AFCS bus through the energized autopilot power transfer relay.

The right generator provides power to the right main bus, which through the ac monitor bus relay powers the monitor ac bus. The 28-volt dc right main bus receives power from the TR unit through the energized contacts of the right main dc power contactor. The right main dc bus energizes the monitor dc bus through the dc monitor bus relay. It also energizes the 28-volt dc interruption-free bus. Because the interruption-free bus receives power from both TR units, the bus is not affected by a loss of either main generator or either TR unit.

### Component Failures

The power distribution system design ensures power is available to operate all aircraft equipment. This includes all equipment essential to accomplish the assigned mission and ensure safety of flight. If a component or engine should fail, power must be available for continued safe operation. The distribution system design provides a continuous power source under all adverse conditions. As you know, either of the generators is capable of supplying the entire load of the

aircraft. Likewise, either of the TR units is able to supply the entire dc load. Adverse conditions that could occur in the aircraft's electrical systems include the following:

- Left generator failure
- Right generator failure
- Left TR unit failure
- Right TR unit failure

**NOTE:** The emergency generator will automatically come on line if both generators fail or if both TR units fail.

The following paragraphs discuss each adverse condition. Refer to figures 2-10 and 2-11 as you read about each condition.

**LEFT GENERATOR FAILURE.**—When the left generator drops off line, the left main ac power contactor de-energizes. The right generator now powers the left main ac bus through contacts three and two of the de-energized external ac power contactor. All other buses receive power except for the 115-volt ac and 28-volt dc monitor buses. Both generators must be operating for the monitor buses to receive power because of the action of the monitor bus relays.

**RIGHT GENERATOR FAILURE.**—If the right generator or associated equipment should fail, the left

generator supplies power to both main ac buses. Power goes to the right main ac bus through de-energized contacts three and two of the right main ac power contactor. Power for the other ac buses and the TR units is as previously described.

**LEFT TR UNIT FAILURE.**—When the left TR unit fails, the left main dc power contactor de-energizes. Power then goes across de-energized contacts A3 to A2, powering the left main dc bus. The right TR unit also continues to power the right main dc bus. Power distribution to the remaining dc buses is normal operation, except for the dc monitor bus. To power the monitor bus, both TR units must be operating. This is because of the action of the dc monitor bus relay.

**RIGHT TR UNIT FAILURE.**—When the right TR unit fails, the right main dc contactor de-energizes. Power from the left TR unit runs across de-energized contacts A3 to A2 of the right dc contactor. From here power goes to the right main dc bus, thus maintaining operation of the entire dc distribution system except for the loss of the monitor dc bus.

As shown, the power distribution system maintains its integrity with a loss of either generator or TR unit. This ensures all systems are available for safe flight and mission accomplishment.

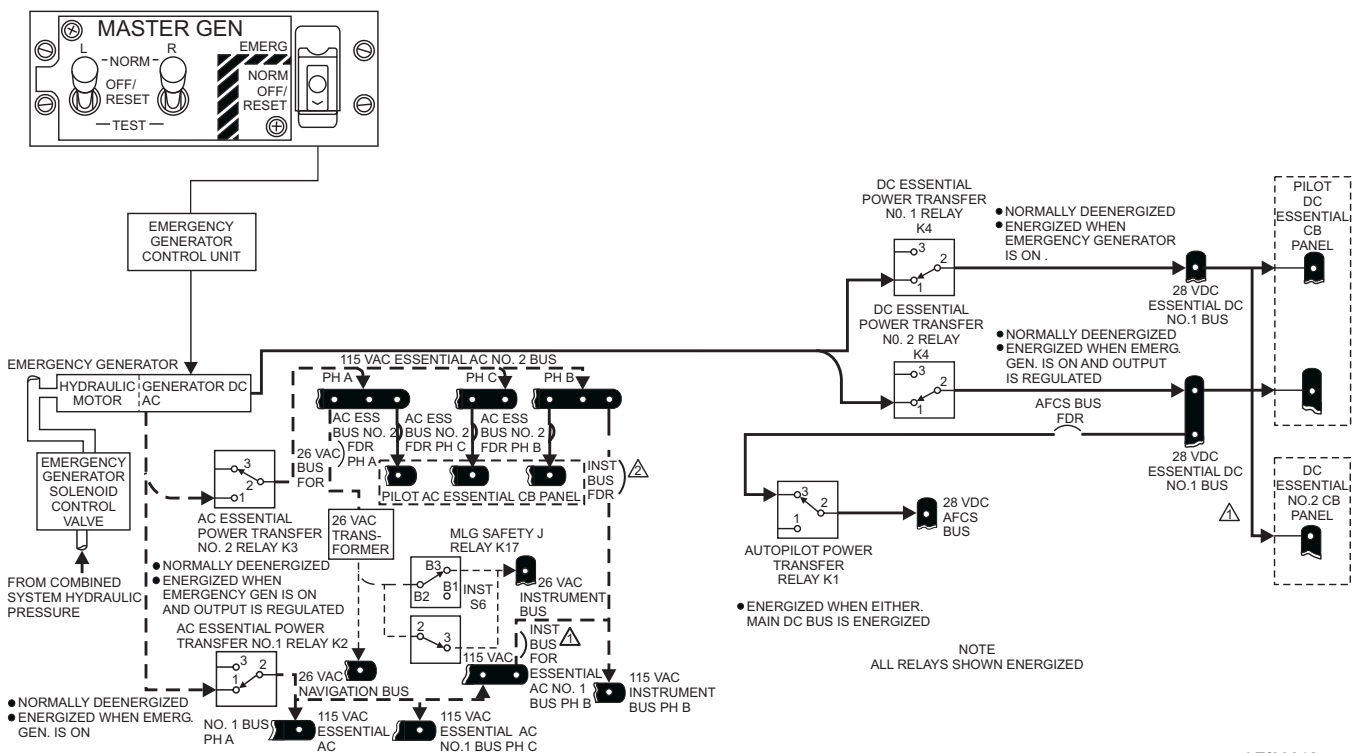


Figure 2-12.—Emergency generator power distribution system.



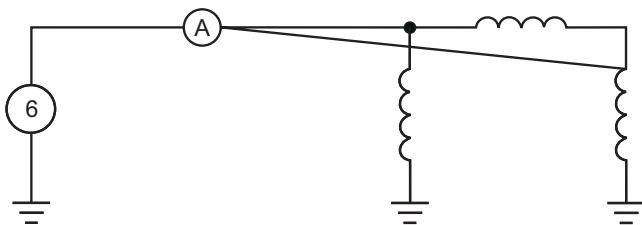
## Emergency Generator Operation

The emergency generator system (fig. 2-12) automatically activates when the left main dc bus loses power. The emergency generator solenoid de-energizes, activating the hydraulic motor that drives the emergency generator. The emergency generator provides ac and dc power to the essential bus circuits when normal power fails. The emergency system is completely self-sufficient and independent of the primary and secondary power sources.

The emergency generator control unit monitors ac output and regulates the output at 115 volts. This voltage is available as long as the hydraulic motor is operating under full system pressure. If both engines flame out, the hydraulic pressure produced by windmilling engines cannot operate the hydraulic motor at optimum output. This causes the left and right generator outputs to drop below tolerance. The emergency generator control unit disconnects the essential ac and dc power transfer number two relays. Equipment on essential ac and dc number one buses must be capable of operating on below normal voltage in an emergency.

When the emergency generator activates (both generators or both TR units failed), ac power routes through both transfer relays to essential ac buses. Dc power goes through the dc essential power transfer relays to the dc essential and AFCS buses. Not all ac and dc main and monitored buses receive power during emergency generator operation.

If both engines fail, the windmilling effect drives the emergency generator below normal performance levels. The ac essential and dc essential power transfer number two relays now de-energize. Only the ac essential and dc essential number one buses receive power. This configuration enables the flight crew to jettison aircraft stores, communicate, and destroy classified equipment before taking emergency escape procedures.



AEF02013

Figure 2-13.—Grounded system.

## Grounded Systems

The term *grounded system* means that one leg of the system connects to a common conductor. This common conductor can be the Earth, the skin of the aircraft, or a structural member of the aircraft. When the grounded leg of the circuit connects to a good electrical conductor, this conductor may serve as one leg of the circuit, cutting out the need for a separate conductor.

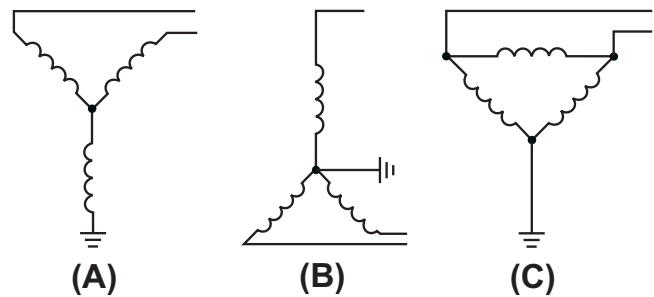
Figure 2-13 shows a simple grounded system. Although the grounds are at different points, the potential at these points is the same since they connect to a common conductor.

The letter N designates any wire that completes the equipment circuit to the ground network. Any wire designated as N may come in contact with ground at any point without causing the equipment to malfunction.

Grounding three-wire systems can be done by grounding one of the phases, usually the B-phase in aircraft. Make sure you ground the same phase in all equipment. Figure 2-14 shows the grounded three-phase systems. In four-wire systems, the neutral is ground.

The grounded circuit is better than the ungrounded one because it reduces overall weight by using fewer conductors. This results in a reduction in cost and space requirements. Other advantages are that troubleshooting is simplified and the impedance of the ground return path is lower than that of a run conductor.

A disadvantage of a grounded system is that short circuits result when a bare spot on any ungrounded conductor touches ground. Another disadvantage is having circuits of different potentials and frequencies use a common ground. There is a possibility of one circuit feeding into another. This problem often happens in electronic circuits.



AEF02014

Figure 2-14.—Grounded three-phase systems. (A) Grounded three-wire wye; (B) grounded four-wire wye; (C) grounded delta.

## Ungrounded Systems

The term *ungrounded system* means that the circuit in no way connects to ground. All conductors run from the power source to the loads. Circuits of this type are often referred to as being above ground. The ungrounded system has one advantage—it prevents one circuit from feeding into another because the circuits are completely insulated from each other. The system has the disadvantage of adding more weight because it requires more conductors than the grounded system. This results in added cost and space requirements. Both the grounded and ungrounded systems are used for specific purposes in modern aircraft.

## Single-phase and Polyphase Systems

Single-phase systems are of simple design and construction. They are used when there are relatively low power requirements. Polyphase systems are more complicated in construction and design. These systems are used when high power is required. These systems provide a smoother source of power. Single-phase power is available from polyphase systems. When doing this, the load on the polyphase system must be kept balanced.

*Q2-31. In an F-14 aircraft, what is the purpose of the GPM?*

*Q2-32. How will the pilot of an F-14 know if external power is applied to or disconnected from his aircraft?*

*Q2-33. What is the purpose for jumping pins E and F on the external power receptacle?*

*Q2-34. In an F-14 aircraft, with both main generators on line, which buses does the left main generator power?*

*Q2-35. With both generators on line, 115-Vac essential bus number two fails to be powered. Which components could be faulty?*

*Q2-36. External power is applied to the aircraft, the right generator comes on line, and only the main ac bus loses power. What component could be faulty?*

*Q2-37. If the right TR fails, what bus, if any, will be lost?*

*Q2-38. What will cause the monitor bus to lose power?*

*Q2-39. What ac bus does the emergency generator supply power to?*

*Q2-40. What is the main advantage of a grounded system?*

*Q2-41. What are the disadvantages of ungrounded systems?*

## CHAPTER 2

# ANSWERS TO REVIEW QUESTIONS

- A2-1. *Varying the current to the field windings*
- A2-2. *It helps to maintain a constant load on the generator and simplifies generator construction*
- A2-3. *Ac voltage induction occurs*
- A2-4. 1. *The number of turns of conductor per winding*  
2. *Generator rpm*  
3. *Magnetic field strength*
- A2-5. 1. *Over- or undervoltage*  
2. *Over- or underfrequency*  
3. *Improper phase sequence*
- A2-6. *Change the rotating ac output voltages of the exciter to dc voltages*
- A2-7. *Each generator has its own independent source of excitation so no external source of electrical power is necessary*
- A2-8. *Exciter control relay*
- A2-9. *Regulator circuitry increases the field strength of the ac exciter*
- A2-10. *CR1*
- A2-11. *Underspeed switch*
- A2-12. *The generator has a fixed number of poles*
- A2-13. *Engine and generator*
- A2-14. *Hydraulic pump, hydraulic motor, governing system, gear pump, charge pump, replenishing pump, and scavenge pump*
- A2-15. *The pump supplies more oil to the hydraulic motor causing it to increase rpm*
- A2-16. *An underspeed pressure switch is used to break the electrical circuit*
- A2-17. *Supervisory panel*
- A2-18. *Over-/underfrequency*  
*Over-/undervoltage*  
*Feeder fault*
- A2-19. *600 Hz*
- A2-20. *1.7 amps*
- A2-21. *When one or more phases drops to 90 volts or less*
- A2-22. *When one or more phases is 129 volts or greater*
- A2-23. *A condition where the current leaving the generator does not pass through the load*

- A2-24. *A primary power distribution point that is connected to the main power source  
Usually holds systems of like priority*
- A2-25. *By the priority of the equipment it powers*
- A2-26. *Circuit breakers, fuses, or current limiters*
- A2-27. *Single coil and double coil*
- A2-28. *Left main generator, right main generator, emergency power, and external power*
- A2-29. *Left and right main ac buses, number one and two ac essential buses, and the ac monitor bus*
- A2-30. *Dc monitor bus*
- A2-31. *It prevents external power from being applied if it is not within specified tolerances*
- A2-32. *Hand signals from the plane captain*
- A2-33. *It energizes the external power contactor*
- A2-34. *All 115-Vac essential and instrument buses, and 26-Vac instrument and navigation buses*
- A2-35. *Power contactor K3*
- A2-36. *Power contactor K2*
- A2-37. *None*
- A2-38. *If both TRs fail*
- A2-39. *Essential bus*
- A2-40. *It alleviates an extra conductor*
- A2-41. *Added weight, cost, and space*

## APPENDIX I

# GLOSSARY

**AC**—Alternating current.

**AFCS**—Automatic flight control system.

**ALTERNATING CURRENT (AC)**—An electrical current that constantly changes amplitude and changes polarity at regular intervals.

**AMPLITUDE**—The maximum instantaneous value of an alternating voltage or current, measured in either the positive or negative direction.

**APU**—Auxiliary power unit.

**ARMATURE**—The windings in which the output voltage is generated in a generator or in which input current creates a magnetic field that interacts with the main field in a motor.

**AUTOTRANSFORMER**—A transformer in which the primary and secondary are connected together in one winding. Used to step up or step down voltages.

**AUXILIARY POWER UNIT (APU)**—An aircraft mounted gas turbine power plant with an attached generator, capable of providing electricity, engine starting air, and air conditioning for the aircraft. Requires only the aircraft battery and fuel for starting.

**BATTERY**—A device for converting chemical energy into electrical energy.

**BRUSH**—The conducting material, usually a block of carbon, bearing against a commutator or slip ring assembly that allows current to flow in or out of a component.

**BUS**—Systems of like priority on a common line.

**BUS BAR**—A primary power distribution point connected to the main power source.

**CAPACITOR**—Two electrodes or sets of electrodes in the form of plates, separated from each other by insulating material called the dielectric, capable of storing electrical energy in an electrostatic field.

**COMMUTATOR**—(1) The copper segment on the armature of a motor or generator. It is cylindrical in shape and is used to pass power into or from the brushes. (2) A mechanical device that reverses

armature connections in motors and generators at the proper instant so that current continues to flow in only one direction. In effect, the commutator changes ac to dc.

**CONSTANT SPEED DRIVE (CSD)**—A mechanical unit mounted to aircraft engines which converts variable engine speed to a constant output speed. Generators are mounted to constant speed drives in order to maintain the proper generator output frequency.

**CSD**—Constant speed drive.

**CURRENT**—The movement of electrons past a reference point. The passage of electrons through a conductor. Measured in amperes.

**DC**—Direct current.

**DIODE**—A material of either germanium or silicon that is manufactured to allow current to flow in only one direction. Diodes are used as rectifiers and detectors.

**DIRECT CURRENT (DC)**—An electrical current that flows in one direction only.

**EXCITER**—Auxiliary dc generator.

**FIELD WINDING**—The coil used to provide the magnetizing force in motors and generators.

**FREQUENCY**—The number of complete cycles per second existing in any form of wave motion, such as the number of cycles per second of an alternating current.

**GENERATOR**—A machine that converts mechanical energy into electrical energy.

**GPU**—Ground power monitor.

**GROUND**—A metallic connection with the earth to establish ground potential. A common return to a point of zero potential.

**GTCP-95 UNIT**—Gas turbine power plant unit, an APU.

**HERTZ (HZ)**—A unit of frequency equal to one cycle per second.

**HZ**—Hertz.

**INVERTER**—A mechanical device that converts a dc input to an ac output. Usually converts 26 volts dc to 115 volts ac for an emergency source of ac power for safety of flight systems and instrumentation.

**MAGNETIC FLUX**—The total number of lines of force issuing from a pole of a magnet.

**MIM**—Maintenance instruction manual.

**NICAD BATTERY**—Nickel-cadmium battery.

**PERMANENT MAGNET GENERATOR**—Furnishes control voltage and power for the voltage regulator.

**PHASE**—The angular relationship between two alternating currents or voltages when the voltage or current is plotted as a function of time. When the two currents or voltages are in phase, the angular difference is zero, and both reach their peak simultaneously. When the two currents or voltages are out of phase, one will lead or lag the other, and reach their peaks at different times. These differences in may differ in polarity as well as magnitude.

**PMG**—Permanent magnet generator.

**POWER**—The rate of doing work or the rate of expending energy. The unit of electrical power is the watt.

**PRIME MOVER**—A device such as aircraft engines, gearboxes, or constant speed drives that provide the driving force for a generator.

**RECTIFIER**—A device used to convert ac to pulsating dc.

**RF**—Radio frequency.

**ROTOR**—(1) The revolving part of a rotating electrical machine. The rotor may be either the field or the armature, depending on the design of the machine. (2) The rotating member of a synchro that consists of one or more coils of wire wound on a laminated core. Depending on the type of synchro, the rotor functions similarly to the primary or secondary winding of a transformer.

**RPM**—Revolutions per minute.

**SALIENT POLE**—A pole consisting of a separate radial projection having its own iron pole piece and its own field coil, used in the field system of a generator or motor.

**SHUNT**—A resistive device placed in parallel with another component. Appreciable current may flow through it and an appreciable voltage may exist across it.

**SLAB**—Sealed lead-acid battery.

**SLIP RINGS**—(1) Contacts that are mounted on the shaft of a motor or generator to which the rotor windings are connected and against which the brushes ride. (2) Devices for making electrical connections between stationary and rotating contacts.

**SOLENOID**—An electromagnetic coil that contains a movable plunger.

**SOLID-STATE DEVICE**—An electronic device that operates by the movement of electrons within a solid piece of semiconductor material.

**STATOR**—(1) The stationary part of a rotating electrical machine. The stator may be either the field or the armature, depending on the design of the machine. (2) The stationary member of a synchro that consists of a cylindrical structure of slotted laminations on which three Y-connected coils are wound with their axes 120 degrees apart.

**SYNCHRO**—A small motor-like analog device that operates like a variable transformer and is used primarily for the rapid and accurate transmission of data among equipments and stations.

**TACHOMETER**—(1) A small ac or dc generator, sometimes referred to as a rate generator, that converts its shaft speed into an electrical output. The tachometer is frequently used in servo systems to sense the velocity of a load. (2) An instrument that measures the rate at which a shaft is turning.

**TORQUE**—The turning effort or twist that a shaft sustains when transmitting power. A force tending to cause rotational motion; the product of the force applied times the distance from the force to the axis of rotation.

**TR**—Transformer-rectifier.

**TRANSFORMER**—A device composed of two or more coils, linked by magnetic lines of force, used to transfer energy from one circuit to another.

**VLAB**—Vented lead-acid battery.

**VOLT**—The unit of electromotive force or electrical pressure. One volt is the pressure required to send 1 ampere of current through a resistance of 1 ohm.

**WYE (Y)**—A three phase connection in which one end of each phase winding is connected to a common ground.

**ZENER DIODE**—A PN-junction diode designed to operate in the reverse-bias breakdown region.

## APPENDIX II

### REFERENCE LIST

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# *Assignment Questions*

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**Information:** The text pages that you are to study are provided at the beginning of the assignment questions.



# ASSIGNMENT 1

Textbook Assignment: "Aircraft Electrical Power Sources," Pages 1-1 through 1-17; and "Circuit Protection and Distribution," Pages 2-1 through 2-20.

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1-1. Primary power sources include which of the following?

1. Main generators, inverters, and external power supplies
2. Main generators, inverters, and transformers
3. Batteries, inverters, and electronic power supplies
4. Batteries, transformers, and electronic power supplies

1-2. Which of the following factors determines the frequency of an ac generator?

1. The field strength and rotor rpm
2. The number of conductors and field strength
3. The number of conductors and rotor rpm
4. The number of magnetic poles and rotor rpm

1-3. Which of the following statements describes an advantage of the ac power systems over dc power systems?

1. Current is transmitted at a lower level
2. Smaller wiring is used
3. The ac generator and control/protection components are lighter
4. Each of the above

1-4. Which of the following is NOT considered common to all ac generators?

1. The output frequency is controlled by regulating the rpm of the PMG field
2. The output is taken from the stationary armature windings
3. Voltage control is accomplished by controlling the strength of the magnetic field
4. The output frequency is controlled by regulating the rpm of the rotating magnetic field

IN ANSWERING QUESTIONS 1-5 AND 1-6, REFER TO FIGURE 1-1(B) IN YOUR TEXT.

1-5. Which of the following generator connections will supply 208 volts ac to the aircraft?

1. A to b
2. B to c
3. Both 1 and 2 above
4. C to ground

1-6. The power generated by a 120-/208-volt ac generator is normally powered by what type of system?

1. A four-wire, wye connected, common neutral system
2. A four-wire, delta connected, common neutral system
3. A three-wire, wye connected system
4. A three-wire, delta connected system

1-7. What phase connects to the aircraft for ground in a four-wire grounded neutral system?

1. A phase
2. B phase
3. C phase
4. Neutral

1-8. Which of the following is an advantage of a brushless aircraft generator?

1. Less regulation only
2. Longer overhaul period only
3. More reliable only
4. More reliable and longer overhaul periods

1-9. What device provides the driving force for a generator?

1. A slipping clutch
2. A prime mover
3. A permanent magnet generator
4. A variable pitch clutch

- 1-10. In comparison to a three-wire inverter power system, what does a four-wire 120-volt, three-phase, 400-Hz power system provide?
1. Automatic distribution so that equal power is maintained in each phase
  2. Automatic distribution so that equal current and voltages are maintained in each phase
  3. Improved load balancing per phase
  4. Current flow stoppage when the leads are unbalanced
- 1-11. What is the purpose of series starting windings in larger inverters?
1. Provide a higher starting torque
  2. Increase starting current
  3. Limit frequency build-up
  4. Improve frequency stability
- 1-12. What determines the number of phases in an inverter?
1. The independent voltages in the input
  2. The sets of windings on the rotor
  3. The poles in the generator field
  4. The sets of windings on the stator
- 1-13. What do we control in order to maintain the output voltage of an inverter at the correct level?
1. The dc input voltage to the motor
  2. The speed of the motor
  3. The ac excitation current in the rotor field of the generator
  4. The dc excitation current in the rotor field of the generator
- 1-14. Which of the following factors determines the current capabilities of a typical transformer-rectifier
1. The cooling available
  2. The number of phases
  3. The input lines
  4. The physical size
- 1-15. When an overheat occurs in a transformer-rectifier, which of the following functions does the thermostat perform?
1. Turns off the overheat warning light
  2. Disconnects the input ac voltage
  3. Disengages the overrunning clutch
  4. Engages the fan motor
- 1-16. In which of the following ways does an auto-transformer differ from a conventional transformer?
1. It is used to power high voltage circuits
  2. It has multi-tap outlets
  3. It has one winding that is common to both the primary and secondary windings
  4. It is used to step down voltage only
- 1-17. Refer to figure 1-10 in your text and assume that an auto transformer has a 120-volt input, a turns ratio of 3:1 step-down, and a load current of 15 amperes. What is the value of the power load in the circuit?
1. 260 watts
  2. 480 watts
  3. 600 watts
  4. 720 watts
- 1-18. A variac transformer provides which of the following functions?
1. Continuous control of line voltage only
  2. Maximum transfer of power to the load only
  3. Control of only 10% of line voltage
  4. Voltage adjustment, regulation, and control
- 1-19. Why is it necessary for high-performance aircraft to have several electronic power supply systems?
1. To isolate the systems from each other
  2. To make changes within a particular system easier
  3. To provide back-up for a failed system
  4. To provide sufficient power for all systems
- 1-20. Refer to figure 1-13 in your text. When a positive potential is applied from the secondary of transformer T7 to the junction between CR7 and CR9, what combination of rectifiers will conduct?
1. CR7 and CR8
  2. CR7 and CR9
  3. CR8 and CR9
  4. CR8 and CR10

- 1-21. Refer to figure 1-14 in your text. If the dc voltage input increases, which of the following events will occur?
1. The voltage drop across R1 will increase
  2. The voltage drop across R2 will decrease
  3. The input voltage to amplifier A1 will decrease
  4. The feedback voltage across R3 and R4 to the input of amplifier A1 will increase
- 1-22. Which of the following uses will shorten the life of an aircraft battery, if done frequently?
1. Servicing equipment only
  2. Engine starts only
  3. Engine starts and servicing equipment
  4. Charging from the ac generator and transformer rectifiers
- 1-23. In a battery vent system, what is the purpose of the sump jar?
1. To act as an electrolyte reservoir
  2. To prevent battery overcharging
  3. To prevent electrolyte spillage
  4. To neutralize gases and excess battery solution
- 1-24. The ac/dc hydraulic motor driven generator provides power to which of the following circuits?
1. Flight control circuits only
  2. Bombing circuits only
  3. Essential circuits only
  4. Tactical equipment circuits only
- 1-25. Why are APUs particularly useful in aircraft?
1. They automatically replace malfunctioning main generators
  2. They provide a variable frequency output
  3. They depend upon aircraft engines for their source of power
  4. They make the aircraft independent of ground power sources
- QUESTIONS 1-26 THROUGH 1-31 RELATE TO THE GTCP-95 POWER PLANT.
- 1-26. What section of the compressor and turbine assembly supplies bleed air for pneumatic power?
1. Turbine
  2. Turbine wheel
  3. Compressor
  4. Compressor wheel
- 1-27. What are the four main systems of the gas turbine engine?
1. Electrical, fuel control, bleed air, and lubrication
  2. Turbine, accessory, compressor, and electrical
  3. Turbine, accessory, bleed air, and electrical
  4. Turbine, electrical, bleed air, and main output drive
- 1-28. Which of the following statements describes the operation of the ignition system?
1. A continuous spark ignition is required during run time
  2. The high-energy ignition source is obtained by discharging a booster coil into the storage capacitors
  3. The high voltage required to fire the ignition plug is obtained by discharging the capacitors through a step-down transformer
  4. Ignition is required only during starts and automatically cuts out at 95% engine rpm
- 1-29. The three centrifugal speed sequence switches in the APU are adjusted to actuate at what percentage of turbine speed?
1. 30, 60, and 90
  2. 35, 95, and 106
  3. 35, 95, and 110
  4. 50, 75, and 100
- 1-30. What causes the overspeed switch to be checked?
1. When the turbine is operating it is checked automatically
  2. When turbine speed reaches 106% it activates and cuts off fuel to the engine
  3. It must be checked with the turbine operating
  4. The lever cannot be manually actuated
- 1-31. Which of the following is the function of the starter clutch assembly?
1. To prevent excessive torque between the starter and accessory drive gears only
  2. To automatically engage and disengage the starter with the gear train only
  3. To automatically engage the engine compressor and turbine sections only

- 1-32. Why are naval aircraft designed to accept external power?
1. To start aircraft engines so maintenance can be performed in the hangar
  2. To provide maintenance personnel with ground power without starting engines
  3. To provide interior lighting for night maintenance actions
  4. To provide air conditioning and heating during ground maintenance
- 1-33. The most common method of voltage regulation in ac and dc generators is varying what?
1. The current in the field winding
  2. The current in the shunt winding
  3. The resistance of the load
  4. The resistance of a parallel resistor
- 1-34. Amplitude of the output voltages of an ac generator may be controlled by which of the following methods?
1. Varying the generator rpm
  2. Changing the rectifier connections
  3. Varying the strength of the magnetic field
  4. Tapping off a varying number of turns per winding
- 1-35. Refer to figure 2-1, view (B) in your text. Which of the following components changes the exciter's variable output to dc?
1. Bridge rectifier
  2. Voltage regulator
  3. Exciter rotating field
  4. Main generator rotating field
- 1-36. What is the result of the action of the voltage regulator in controlling the strength of the generator's magnetic field?
1. Controlled output voltage
  2. Controlled current
  3. Controlled frequency
  4. Controlled single phase
- 1-37. What is represented by the magnitude of the control voltage applied to the control amplifier of a solid-state regulator?
1. The excitation voltage of the ac generator
  2. The sum of the generator's excitation and output voltages
  3. The difference between the generator's ac output voltage and a reference voltage
  4. The difference between the generator's dc excitation voltage and a reference voltage
- 1-38. Refer to figure 2-2 in your text. If there were a decrease in generator voltage, the voltage change would appear across which of the following components?
1. All components of the bridge except CR5, but the change would be greater across R2 than across any other resistor
  2. All components of the bridge, but the change would be greater across R2 than across any other component
  3. All components of the bridge except CR5, in equal amounts
  4. R2, R7, and R9, but the change would be greater across R2 than across R7 and R9
- IN ANSWERING QUESTIONS 1-39 AND 1-40, REFER TO FIGURE 2-6 IN YOUR TEXT.
- 1-39. A decrease in the generator output voltage causes an increase in emitter-collector current in all four transistors, producing which of the following results?
1. The exciter generator output increases, the ac generator field strength decreases, and the generator output increases
  2. The exciter generator output increases, the ac generator field strength increases, and the generator output increases
  3. The exciter generator output decreases, the ac field strength decreases, and the generator output decreases
  4. The exciter generator output increases, the ac generator field strength increases, and the generator output decreases
- 1-40. The exciter generator field is excited with a field-flash voltage from the +28-volt bus under which of the following conditions?
1. K1 energizes
  2. The underspeed switch closes
  3. Q1 receives a voltage-change indication
  4. The generator's armature begins to rotate
- IN ANSWERING QUESTIONS 1-41 AND 1-42, REFER TO FIGURE 2-3 IN YOUR TEXT.
- 1-41. Potentiometer R7 sets the bridge at the desired operating point; however, the reference voltage that determines if a change will occur in the generator's output voltage is developed across what component?
1. V1
  2. RT1
  3. CR5
  4. CR1



- 1-42. What is the purpose of K1?
1. To provide exciter shunt field excitation
  2. To protect the transistors from generator overvoltage
  3. To prevent exciter excitation before the generator achieves a 90-volt output
  4. To provide exciter shunt field excitation from an external source during initial voltage buildup
- 1-43. Because a generator has a fixed number of poles, what is the only means of fine-tuning the output frequency?
1. Control stator revolutions per minute
  2. Control rotor revolutions per minute
  3. Increase the total number of slip rings
  4. Decrease the total number of slip rings
- 1-44. What device maintains an ac generator at a constant speed?
1. A constant-speed drive assembly
  2. A hydraulic motor
  3. A variable-speed drive assembly
  4. A variable displacement pump
- 1-45. On a helicopter, what drives the accessory gearbox?
1. An electric motor
  2. A hydraulic motor
  3. The main transmission
  4. The intermediate gearbox
- 1-46. What section of the CSD controls the rate of flow of the pump, thereby controlling the motor speed?
1. The variable displacement hydraulic pump
  2. The governing system
  3. The pump wobbler
  4. The constant displacement hydraulic pump
- 1-47. Which of the following is a phase of operation of the CSD?
1. Overdrive
  2. Underdrive
  3. Straight-through
  4. All of the above
- 1-48. What phase of operation is a CSD in when the output is rotating faster than the input?
1. Overdrive
  2. Underdrive
  3. Straight-through
  4. Line-out
- 1-49. Which of the following conditions will cause the CSD to go into underdrive?
1. An engine overspeed
  2. An intermediate gearbox overspeed
  3. An accessory gearbox overspeed
  4. A main gearbox overspeed
- 1-50. The electrical circuit of the ac control system is protected during an underspeed condition by what component?
1. A relay
  2. A diode
  3. A pressure switch
  4. A proximity switch
- 1-51. Which of the following is a function of the supervisory panel for the generator and its associated equipment?
1. Frequency regulation and circuit protection
  2. Circuit protection only
  3. Voltage regulation only
  4. Voltage regulation and circuit protection
- 1-52. Under which of the following conditions will the supervisory panel disconnect the generator from the load?
1. Frequency and undervoltage only
  2. Underfrequency, undervoltage, and overvoltage conditions only
  3. Feeder fault, underfrequency, and undervoltage only
  4. Feeder fault, overvoltage, undervoltage, underfrequency, and overfrequency
- 1-53. In a supervisory panel, voltage to the generator exciter stator coils is controlled by which of the following functions?
1. Polarity of the dc voltage
  2. Amplitude of the dc voltage
  3. Frequency of the ac voltage
  4. Amplitude of the ac voltage
- 1-54. Refer to figure 2-6 in your text. What component protects the circuit from overvoltage and undervoltage conditions?
1. Voltage sensors
  2. Monitoring switches
  3. K1 relay contacts
  4. K7 relay contacts

- 1-55 Under what condition will a voltage regulator de-energize the generator output?
1. Phase A output is 105 volts
  2. Phase B output is 89 volts
  3. Phase B output is 120 volts
  4. Phase C output is 127 volts
- 1-56. Electrical power is connected to electrical equipment by what system?
1. Power generation
  2. Electrical generation
  3. Power distribution
  4. Equipment distribution
- 1-57. Systems of like priorities are grouped to a common line known as a
1. Junction
  2. Terminal
  3. Bus
  4. Contactor
- 1-58. The highest priority equipment, such as emergency lighting and engine instruments, is connected to what bus?
1. Main bus
  2. Essential bus
  3. Flight-instrument bus
  4. Flight-essential bus
- 1-59. How is the emergency generator in an F-14 driven?
1. Ram air
  2. Hydraulically
  3. Electrically
  4. Pneumatically
- 1-60. What component is the main source of dc power in an F-14?
1. Battery
  2. Modulator
  3. Demodulator
  4. Transformer-rectifier
- 1-61. If only one main generator on an F-14 is operating, what buses will be energized?
1. Right main ac, monitor ac, and ac essential number one only
  2. Right main ac, left main ac, and ac essential number two only
  3. Right main ac, left main ac, ac essential number one, and ac essential number two only
  4. Left main, monitor, and ac essential number two only
- 1-62. During a complete propulsion system failure on an F-14, what buses are energized?
1. Ac essential number one and dc essential number one
  2. Ac essential number two and dc essential number two
  3. Ac monitor and dc monitor
  4. Ac essential number one and number two
- 1-63. If there is a phase reversal of external power, what device keeps this power from being applied to the aircraft?
1. External power contactor
  2. Ground power monitor
  3. Main power contactor K1
  4. Main power contactor K2
- 1-64. Why are pins E and F of the external power plug jumpered together?
1. To provide a ground for the ground power monitor
  2. To disconnect power when the main generators are put on-line
  3. To allow the external power contactor to energize when the ground power monitor relay energizes
  4. To ensure that three-phase power is supplied to the ground power monitor

- 1-65. Refer to figure 2-9 in your text. If an open were to occur between pins E and F of the external power plug, what would be the results at the right and left main buses?
1. Less than three phases of power would be available on the right main bus, and there would be no effect on the left main bus
  2. The external power contactor would not energize, and there would be no power available to either the right or left main buses
  3. Less than three phases of power would be available to the left main bus, and there would be no effect on the right main bus
  4. The ground power monitor relay would not energize
- 1-66. In a four-wire grounded system, if the N wire (common return) were accidentally placed in contact with a ground, what effect, if any, would this have on circuit operation?
1. It would cause one circuit to bleed into another
  2. It would cause intermittent operation of the circuit
  3. The circuit would not operate at all
  4. It would have no effect on circuit operation
- 1-67. In a grounded three-wire system, how is grounding normally accomplished?
1. Grounding the B phase only
  2. Grounding both the A and the B phases
  3. Grounding both the B phase and the neutral wire
  4. Grounding both the A phase and the neutral wire
- 1-68. Which of the following is an advantage of an ungrounded electrical system over a grounded electrical system?
1. The system is easier to troubleshoot
  2. Cost, weight and space are minimized
  3. One circuit may bleed into another
  4. Circuits are insulated from one another
- 1-69. Which of the following is a characteristic of a single-phase voltage regulating system?
1. Its complex design allows its use in low-power requirements
  2. Its simple design allows its use in high-power requirements
  3. Its simple design allows its use in low-power requirements
  4. Its complex design allows its use in high-power requirements
- 1-70. What type of system is used when high power is required?
1. Single-phase
  2. Poly-phase
  3. Bi-phase
  4. Mega-phase

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