Before designing any part of the system, you must determine the amount of power to be transmitted, or the electrical load. Electrical loads are generally measured in terms of amperes, kilowatts, or kilovoltamperes. In general, electrical loads are seldom constant for any appreciable time, but fluctuate constantly. To calculate the electrical load, determine the connected load first. The connected load is the sum of the rated capacities of all electrical appliances, lamps, motors, and so on, connected to the wiring of the system. The maximum demand load is the greatest value of all connected loads that are in operation over a specified period of time. Knowledge of the maximum demand of groups of loads is of great importance because the group maximum demand determines the size of generators, conductors, and apparatuses throughout the electrical system.

The ratio between the actual maximum demand and the connected load is called the demand factor. If a group of loads were all connected to the supply source and drew their rated loads at the same time, the demand factor would be 1.00. There are two main reasons why the demand factor is usually less than 1.00. First, all load devices are seldom in use at the same time and, even if they are, they will seldom reach maximum demand at the same time. Second, some load devices are usually slightly larger than the minimum size needed and normally draw less than their rated load. Since maximum demand is one of the factors determining the size of conductors, it is important to establish the demand factor as closely as possible.

The demand factor varies considerably for different types of loads, services, and structures. The National Electrical Code®, Article 220 provides the requirements for determining demand factors. Demand factors for some military structures are given in *Table 2-1*.

Table 2-1 – Demand Factor.

Structure	Demand Factor
Housing	0.9
Aircraft Maintenance Facilities	0.7
Operation Facilities	0.8
Administrative Facilities	0.8
Shops	0.7
Warehouses	0.5
Medical Facilities	0.8
Theaters	3.0
NAV Aids	0.5
Laundry, Ice Plants, and Bakeries	1.0
All others	0.9

Example: A machine shop has a total connected load of 50.3 kilowatts. The demand factor for this type of structure is taken at 0.70. The maximum demand is 50.3 x 0.70 = 35.21 kilowatts.

21.0.0 POWER FACTOR

The power factor is a number (represented as a decimal or a percentage) that represents the portion of the apparent power dissipated in a circuit. If you are familiar with trigonometry, the easiest way to find the power factor is to find the cosine of the phase angle (θ). The cosine of the phase angle is equal to the power factor. You do not need to use trigonometry to find the power factor. Since the power dissipated in a circuit is true power, then:

Apparent Power x PF = True Power. Therefore, PF = $\frac{True\ Power}{Apparent\ Power}$.

If true power and apparent power are known you can use this formula. Going one step further, another formula for power factor can be developed. By substituting the equations for true power and apparent power in the formula for power factor, you get:

$$PF = \frac{(I_R)^2 R}{(I_Z)^2 Z}$$

Since current in a series circuit is the same in all parts of the circuit, I_R equals I_Z.

Therefore, in a series circuit, $PF = \frac{R}{Z}$.

For example, to compute the power factor for the series circuit shown in *Figure 2-63*, any of the above methods may be used.

Given: True Power = $1{,}500\ V$

Apparent Power = $2{,}500\ VA$

Solution: $PF = \frac{True\ Power}{Apparent\ Power}$

$$PF = \frac{1{,}500\ W}{2{,}500\ VA}$$

$$PF = .6$$

Another method:

Given: $R = 60\ \Omega$

$Z = 100\ \Omega$

Solution: $PF = \frac{R}{Z}$

$$PF = \frac{60\ \Omega}{100\ \Omega}$$

$$PF = .6$$

NOTE

As stated earlier, the power factor can be expressed as a decimal or percentage. In the examples above the decimal number .6 could be expressed as 60%.

22.0.0 POWER FACTOR CORRECTION

The apparent power in an ac circuit has been described as the power the source "sees." As far as the source is concerned, the apparent power is the power that must be provided to the current. You also know that the true power is the power actually used in the circuit. The difference between apparent power and true power is wasted because, in reality, only true power is consumed. The ideal situation would be for apparent power and true power to be equal. If this were the case the power factor would be 1 (unity) or 100 percent. There are two ways in which this condition can exist: (1) if the circuit is purely resistive or (2) if the circuit "appears" purely resistive to the source. To make the circuit appear purely resistive there must be no reactance. To have no reactance in the circuit, the inductive reactance (X_L) and capacitive reactance (X_C) must be equal.

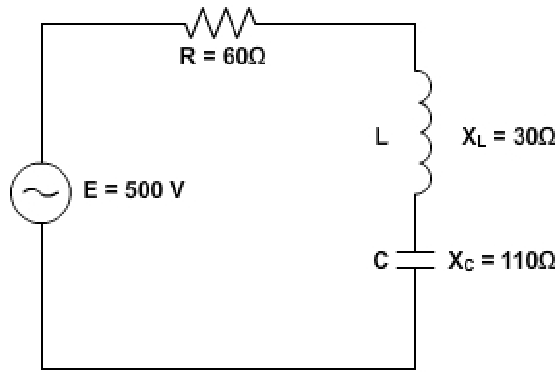

Figure 2-63 – Example circuit for determining power.

Remember: $X = X_L - X_C$, therefore when $X_L = X_C$ $X = 0$. The expression "correcting the power factor" refers to reducing the reactance in a circuit. The ideal situation is to have no reactance in the circuit. This is accomplished by adding capacitive reactance to a circuit which is inductive and inductive reactance to a circuit which is capacitive. For example, the circuit shown in *Figure 2-63* has a total reactance of 80 ohms capacitive and the power factor was .6 or 60 percent. If 80 ohms of inductive reactance were added to this circuit (by adding another inductor), the circuit would have a total reactance of zero ohms and a power factor of 1 or 100 percent. The apparent and true power of this circuit would then be equal.

23.0.0 VOLTAGE DROP

Voltage drop becomes important in industrial areas in which long runs of conductors are supplying large (ampacity) loads. Excessive voltage drop can cause overheating of breakers, conductors, and appliancies, creating a safety hazard.

Conductors for a branch circuit should be sized to prevent a voltage drop exceeding 3 percent at the farthest outlet of power, heating, or lighting load. Conductors supplying a feeder circuit should also be sized to prevent a voltage drop exceeding 3 percent at the farthest outlet.

Total voltage drop consists of the voltage drop in the feeder plus the voltage drop in the branch circuit. The maximum voltage drop of a combination feeder/branch circuit should not exceed 5 percent. The conductors of the feeder should be sized to prevent a voltage drop of more than 2 percent, and the conductors of the branch circuit should be sized to prevent a voltage drop exceeding 3 percent.

The basic formula for determining voltage drop in a circuit is as follows:

$$VD = \frac{2 \times r \times L \times I}{CM}$$

Where:

$VD = voltage\ drop$

$r = resistivity\ for\ conductor\ material:$

$Aluminum = 18\ ohms\ per\ CM - ft$

$Copper = 12\ ohms\ per\ CM - ft$

$L = one - way\ length\ of\ circuit\ conductor\ in\ feet$

$I = current\ in\ conductor\ in\ amperes$

$CM = conductor\ area\ in\ circular\ mils$

The following is a sample problem to help you understand better what has been discussed: Determine the voltage drop in a 230-volt, two-wire heating circuit. The load is 50 amps. The conductor size is No. 6 AWG THW copper, and the one-way circuit length is 150 feet.

$$VD = \frac{2 \times 12 \times 150\ ft \times 50}{26{,}240} = \frac{180{,}000}{26{,}240} = 6.86\,V$$

The maximum voltage drop is 5 percent of 240 volts, or 12 volts. A 6.86-volt drop is within the acceptable percentage. If the voltage drop had exceeded 5 percent, a larger size conductor would have to be used or the circuit length shortened.

24.0.0 HUNTING

Hunting is the sustained oscillation of the rotor following a change in load. The synchronizing torque T_S and the rotor moment of inertia J of the synchronous machine are analogous to the stiffness and mass of a spring-mass mechanical system. When subjected to an external disturbance, the load angle follows a simple harmonic motion and the natural frequency of oscillation is given by $\omega_n = \sqrt{\frac{T_S}{J}}$

If the driving torque provided by the prime mover is cyclic with a frequency close to ω_n, hunting may develop into vigorous rotor swings, with a consequent danger of instability.

In practice, some of the rotor energy is dissipated in the stator and field resistances; hence the oscillations will die down and the synchronous machine will settle to steady state again after a disturbance. A damper winding may be fitted to the pole surfaces of the salient-pole synchronous machine to prevent hunting and to improve stability. The TQG-B is automatic and is a synchronous machine.

Summary

Your knowledge, understanding, and application of the material presented in this chapter concerning power generation are very important to the Seabee community as a whole. As a Construction Electrician, you need the knowledge of the type of generators used and how to set up a power generating plant. During your career as a Construction Electrician, you will apply what has been presented in this chapter in your everyday conduct. You and your crew's safety will depend upon your knowledge of proper power generation and distribution whether in homeport or on deployment.

Remember that generators play an important part in everyday life of the Seabee. The power that you and your crew produce affects everyone's work whether you are operating a generator as a main power source or as standby power in an emergency.

Review Questions (Select the Correct Response)

1. What rule is used to determine the direction of current in a given situation in an external circuit to which the voltage is applied?

   A. Left-hand
   B. Right-hand
   C. Ohm's law
   D. Henry's law

2. **(True or False)** Field excitation occurs when a dc voltage is applied to the field windings of a dc generator, and current flows through the windings and sets up a steady magnetic field.

   A. True
   B. False

3. What term is used to describe a generator that supplies its own field excitation?

   A. Armature
   B. Self-excited
   C. Compound wound
   D. Parallel

4. A series-wound dc generator has the characteristic that the output voltage ________ with the load current.

   A. stops
   B. increases
   C. decreases
   D. varies

5. Which of the following field windings does it take to make a compound-wound generator?

   A. Self-excited
   B. Series
   C. Shunt
   D. Both A and B

6. **(True or False)** Sparking between the brushes and the commutator is an indication of improper commutation.

   A. True
   B. False

7. When you are performing an inspection of the armature winding what should be the first test?

   A. Open circuit
   B. Grounded circuit
   C. Color
   D. Burn

8. Which material can be used to make slip rings used on rotors?

   A. Steel
   B. Stainless steel
   C. Iron
   D. Bronze

9. **(True or False)** All electrical generators, whether dc or ac, depend upon the principle of magnetic induction.

   A. True
   B. False

10. In a dc generator the emf generated in the armature windings is converted from ac to dc by what means?

    A. Exciter
    B. Shunt field
    C. Commutator
    D. Stator

11. **(True or False)** A typical rotating-field ac generator consists of an alternator and a smaller dc generator built into a single unit.

    A. True
    B. False

12. What are the names of the two types of rotors used in rotating-field alternators?

    A. Turbine-driven and salient-pole
    B. Manual-driven and salient-pole
    C. Wound-pole and salient-pole
    D. Wound-pole and turbine-driven

13. How are alternators rated?

    A. Voltage produced and maximum current they can provide
    B. Voltage produced only
    C. Maximum current they can provide only
    D. Maximum heating loss that can be sustained only

14. What name is given to a generator that produces a single, continuously alternating voltage?

    A. Multiphase alternator
    B. Polyphase alternator
    C. Single-phase alternator
    D. None of the above

15. How many single-phase windings does a three-phase alternator contain?

    A. 2
    B. 3
    C. 4
    D. 5

16. When a three-phase stator is connected to a three-phase alternator so that the phases are connected end-to-end, it is called a _________ connection.

    A. Wye
    B. Delta
    C. Loop
    D. Charlie

17. **(True or False)** The output frequency of alternator voltage depends upon the speed of rotation of the the rotor and one pole.

    A. True
    B. False

18. What is the minimum distance,in feet, that a generator should be is set up from a load?

    A. 10
    B. 20
    C. 25
    D. 30

19. Which of the following is an acceptable grounding method for a generator set?

    A. Underground metallic water piping system
    B. Driven metal rod
    C. Buried metal plate
    D. All of the above

20. What minimum size AWG copper wire must be used for a ground lead?

    A. 2
    B. 3
    C. 4
    D. 6

21. The National Electri9cal Code® states that a single electrode consisting of a rod, pipe, or plate that does not have a resistance to ground of _____ ohms or less will be augmented by additional electrodes.

A. 25
B. 30
C. 40
D. 50

22. What percent of rated generator amperes should a feeder conductor be capable of carrying to eliminate overloading and voltage drop problems?

A. 75
B. 100
C. 125
D. 150

23. **(True or False)** The load cable must be installed underground only.

A. True
B. False

24. What is the primary purpose of the generator watch?

A. Maintain the equipment.
B. Keep the operator's log.
C. Produce power in a safe and responsible manner.
D. Keep power plant area clean.

25. **(True or False)** As the plant supervisor you should establish a prestart checklist for each generating plant.

A. True
B. False

26. How many minutes should you allow a generator set to warm-up prior to applying a load if it is not an emergency situation?

A. 1
B. 3
C. 5
D. 10

27. At what time interval, at minimum, should you monitor the generator set when it is in operation for signs indicating possible future malfunctions?

A. Every hour
B. Every two hours
C. Every eight hours
D. Every day

28. What type engine does the Tactical Quiet Generator (TQG) Bravo model have?

A. Briggs and Stratton 480 Gasoline
B. Cummings 3500 Diesel
C. John Deere JP-8 Diesel
D. Murray-Ohio JP-6 Diesel

29. **(True or False)** The TQG-B and TQG-A can be run in parallel.

A. True
B. False

30. Where is the digital control system (DCS) located on the TQG-Bravo?

A. Front
B. Rear
C. Right side
D. Left side

31. The TQG-B has (a) how many, and (b) what type batteries?

A. (a) 1 (b) dry cell
B. (a) 2 (b) dry cell
C. (a) 1 (b) 12-volt dc maintenance-free
D. (a) 2 (b) 12-volt dc maintenance-free

32. When conducting the before operations checks, what should be your first inspection?

A. Housing door fasteners and hinges
B. Identification plate
C. Ground rod and generator ground stud
D. Indicators and controls

33. **(True or False)** The TQG-B generator can be operated in enclosed areas without exhaust discharge venting.

A. True
B. False

34. When starting the TQG-B turn the Dead Crank Switch to the __________ position.

A. ON
B. OFF
C. NORMAL
D. RUN

35. What is the purpose of the During Operations Checklist for the TQG-B?

    A. Reduces the likelihood of damage to the generator.
    B. Allows you to identify maintenance issues before they become a problem.
    C. Increases the chances of supplying power to those Seabees that need it when they need it.
    D. All of the above

36. When you are shutting down the TQG-B, in what position must the Master Control Switch be placed?

    A. ON
    B. OFF
    C. NORMAL
    D. RUN

37. Before two ac generators can be paralleled, which of the following conditions have to be fulfilled?

    A. Their terminal voltages have to be equal.
    B. Their frequencies have to be equal.
    C. Their voltages have to be in phase.
    D. All of the above

38. What, if any, of the following is the primary consideration in paralleling generator sets?

    A. Achieving the proper division of the load
    B. Achieving overall proper power
    C. Achieving 50 percent load to each generator set
    D. None of the above

39. **(True or False)** Loads that are connected to a panelboard should be divided as evenly as possible between the supply conductors.

    A. True
    B. False

40. Concerning frequency of a generator, which of the following statements, if any, is correct?

    A. The slower the speed, the higher the frequency.
    B. The faster the speed, the higher the frequency.
    C. The faster the speed, the lower the frequency.
    D. None of the above

41. **(True or False)** The voltage regulation of an alternator is the change of voltage from full load to no load, expressed as a percentage of full-load volts, when the speed and dc field current are held constant.

    A. True
    B. False

42. Which of the following terms are generally used to measure electrical loads?

   A. Amperes
   B. Kilowatts
   C. Kilovoltamperes
   D. All of the above

43. **(True or False)** The power factor is a number that can be represented by either a decimal or a percentage.

   A. True
   B. False

44. What does the expression “correcting the power factor” refer to?

   A. No reactance in a circuit
   B. No more than 50% reactance in a circuit
   C. Reducing the reactance in a circuit
   D. Adding reactance in a circuit

45. What is the maximum allowable percentage for a voltage drop of a combination feeder/branch circuit and should not be exceeded?

   A. 2
   B. 3
   C. 4
   D. 5

Trade Terms Introduced in This Chapter

Armature	The loop of wire that rotates through the field is called the armature.
Slip rings	The ends of the armature loop are connected to rings called slip rings.
Commutator	The two segments of the split metal ring are insulated from each other. This forms a simple commutator.
Ripple	The voltage developed across the brushes is pulsating and unidirectional (in one direction only). It varies twice during each revolution between zero and maximum. This variation is called ripple.
Residual magnetism	Self-excitation is possible only if the field pole pieces have retained a slight amount of permanent magnetism, called residual magnetism.
Field excitation	When a dc voltage is applied to the field windings of a dc generator, current flows through the windings and sets up a steady magnetic field and is know as field-excitation.

Additional Resources and References

This chapter is intended to present thorough resources for task training. The following reference works are suggested for further study. This is optional material for continued education rather than for task training.

NAVEDTRA 14026A Construction Electrician Basic

NAVEDTRA 14174 Navy Electricity and Electronics Training Series, Module 5

National Electrical Code® (NEC) 2008

Marine Corps TM 09244B/09245B-14/1 Technical Manual Operator, Unit, Direct Support and General Support Maintenance Manual for Generator Set, Skid Mounted, Tactical Quiet

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Chapter 3

ABFC Power Plant Maintenance

Topics

To hear audio, click on the box.

Overview

Your knowledge of the various uses and types of generators is very important for the safe conduct and completion of your job as a Construction Electrician. Upon completion of this chapter, you should have an understanding of the types of generator systems used by the Seabees and how to regulate the voltage output. You should also be able to use technical manuals that are associated with the generator sets. As a Construction Electrician, you will apply this knowledge to do troubleshooting and maintenance so that power can be maintained.

Objectives

When you have completed this chapter, you will be able to do the following:

1. Describe the uses of generators.
2. Describe the different types of generator systems.
3. Describe the purpose of voltage regulation.
4. Describe the proper use of technical manuals associated with generators.
5. Describe the proper use of AC/DC troubleshooting diagrams and schematics.

Prerequisites

This course map shows all of the chapters in Construction Electrician Advanced. The suggested training order begins at the bottom and proceeds up. Skill levels increase as you advance on the course map.

Solid State Devices	↑	C E
ABFC Power Plant Maintenance		A D
ABFC Power Plant Operations and Procedures		V A N C
Advanced Electrical Theory		E D

Features of this Manual

This manual has several features which make it easy to use online.

- Figure and table numbers in the text are italicized. The figure or table is either next to or below the text that refers to it.
- The first time a glossary term appears in the text, it is bold and italicized. When your cursor crosses over that word or phrase, a popup box displays with the appropriate definition.
- Audio and video clips are included in the text, with italicized instructions telling you where to click to activate it.
- Review questions that apply to a section are listed under the Test Your Knowledge banner at the end of the section. Select the answer you choose. If the answer is correct, you will be taken to the next section heading. If the answer is incorrect, you will be taken to the area in the chapter where the information is for review. When you have completed your review, select anywhere in that area to return to the review question. Try to answer the question again.
- Review questions are included at the end of this chapter. Select the answer you choose. If the answer is correct, you will be taken to the next question. If the answer is incorrect, you will be taken to the area in the chapter where the information is for review. When you have completed your review, select anywhere in that area to return to the review question. Try to answer the question again.

1.0.0 USES of GENERATORS

As a Construction Electrician, you may have the responsibility for the installation, maintenance, and repair of electrical power generation equipment. In time of war or national emergency, Advanced Base Functional Components (ABFC) will normally be used at temporary overseas bases. Even in peacetime, generation equipment is used at remote bases or as emergency and backup power on most naval bases.

A power distribution system includes all parts of an electrical system between the power source and the load. This chapter discusses the types of generating systems used for power generation and its uses.

1.1.0 Power Generation

The characteristics built into naval electrical installations are simplicity, ruggedness, reliability, and flexibility to permit continued service. Those who operate these plants must make full use of the installation's inherent capabilities and maintain, as far as possible, uninterrupted availability of electrical power where it is needed. To do this, operating personnel must possess the following:

- Thorough knowledge of how to operate and maintain the components of an electrical plant
- Complete familiarity with the electrical plant's distribution capabilities
- Understanding of the electrical system operation of the base
- The ability to apply electrical and electronic principles to specific installations
- The sizing and installation of secondary conductors

1.2.0 Emergency/Standby Power

When you set up an emergency/standby power system, you must consider numerous factors. The following will cover a few of the situations you may encounter. This chapter does not include the automatic transfer aspect of switching to backup power, because this task is performed by someone with a Navy Enlisted Classification (NEC) code, CE-5601. For our discussion in this section, the term "emergency" and the concepts involved are equally applicable to standby systems. Remember that the National Electrical Code ® (NEC) requires emergency and standby systems to be kept entirely separate from all other wiring and equipment. For more detailed information, see article 705 of the National Electrical Code®.

1.2.1 System Design

Whether you are designing and installing an emergency backup system or operating and maintaining an existing system, you must be completely familiar with the installation requirements and physical characteristics of the equipment. The design, material, and installation must comply with electrical safety standards and codes.

In general, emergency power replaces normal power. The choice of arrangement and the size and the type of equipment depend in large measure on the loads to be fed from the emergency system. The system includes all devices, wiring, raceways, transfer switch, energy sources, and other electrical equipment required to supply power to selected loads. These selected loads will be determined by the available power from your emergency power source. *Figures 3-1* and *3-2* show two possible arrangements for emergency/standby power hookups.

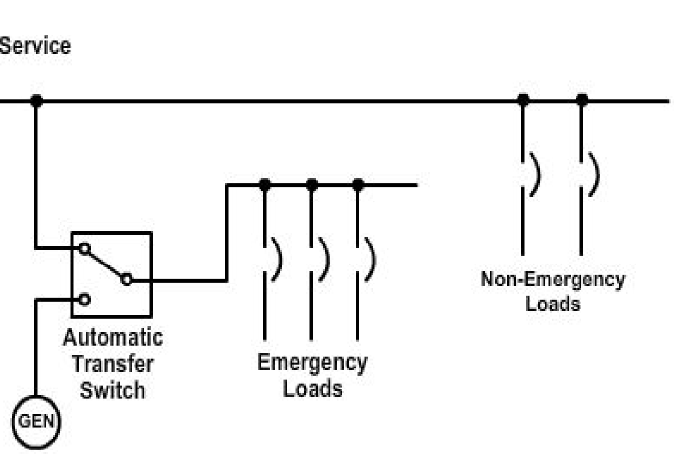

Figure 3-1 – Single transfer switch.

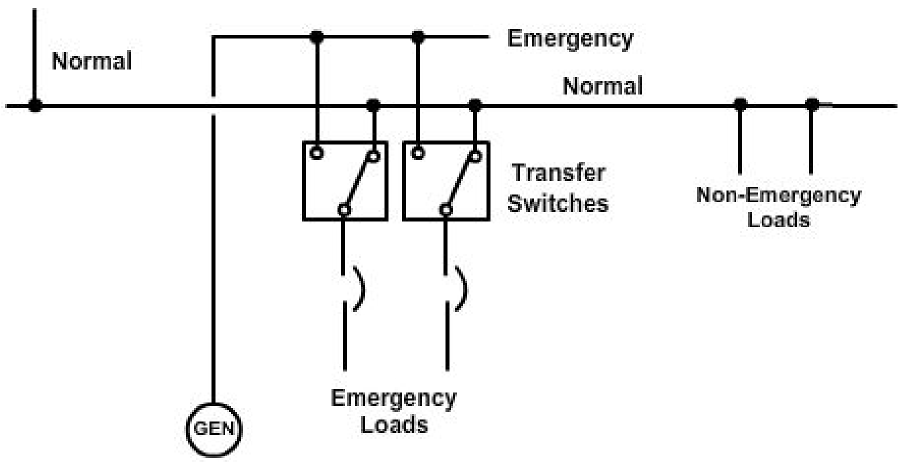

Figure 3-2 – Multiple transfer switches.

2.0.0 TYPES of GENERATOR SYSTEMS

When an overseas base is first established and electrical power is required in a hurry, you will not have time to set up a centrally located generating station; instead, you will spot a portable plant at each important location requiring power. *Table 3-1* lists some of the standard alternating current (ac) generators available. These standard generators are capable of meeting the power requirements of advanced bases and also those for permanent or portable emergency power.

The electrical loads to be supplied power, voltage, phase, frequency, and duty cycle requirements govern the selection of generating equipment. Portable load deviation, probable life of the installation, availability of fuels, and availability of skilled personnel are other important factors.

Electrical plants at advanced bases serve a varied load of lighting, heating, and power equipment, most of which demand power day and night. The annual load factor (the ratio of average power to peak power) of a well-operated active base should be 50 percent or more with a power factor (explained in detail in CE Advanced, Chapter 2) of 80 percent or higher. If the load is more than a few hundred feet from the power source, a high-voltage distribution system may be required.

Table 3-1 – Types of Portable Generators.

	Alternating current					
Frequency			60-hertz			
Voltage	120		120/208		120/208 240/416	
Phase	1		1 & 3		3	
Wires	2		4*		4	
Fuel	G	D	G	D	G	D
kW Rating						
5	X		X	X		X
10			X	X		
15			X	X		
30				X		X
60				X		
100				X		X
200						X

G – Gasoline driven. D – Diesel driven.

* – Panel connections permit, at rated kW output: 120/208V 3-phase 4-wire, 120V 3-phase 3-wire, 120V single-phase 2-wire, 120/240V single-phase 3-wire.

If several generators are to serve primary distribution systems, they should generate the same voltage to avoid the need for voltage transformation. The number of phases required by the load may differ from that produced by the generator. As loads usually can be divided and balanced between phases, most generators of appreciable size are wound for three-phase operation.

3.0.0 VOLTAGE REGULATION

The selection of voltage is affected by the size, the character, and the distribution of the load; length, capacity, and type of transmission and distribution circuits; and size, location, and connection of generators. Practically all general-purpose lighting in the United States and at United States overseas bases is 120 volts. The lighting voltage may be obtained from a three-wire, 120/240-volt, single-phase circuit or a 120/208-volt, three-phase, four-wire circuit.

Small motors can be supplied by single-phase ac at normally 120 volts. Large three-phase, ac motors above 5 horsepower generally operate satisfactorily at any voltage between 200 and 240. The use of combined light and power circuits will be accomplished by the use of 240-volt or 208-volt systems.

3.1.0 Computation of the Load

As mentioned earlier in this chapter, there are various factors that must be taken into consideration in the selection of the required generating equipment. The following technical data will help you in computing the load.

Before any part of the system can be designed, the amount of power to be transmitted, or the electrical load, must be determined. Electrical loads are generally measured in terms of amperes, kilowatts, or kilovoltamperes. In general, electrical loads are seldom constant for any appreciable time, but fluctuate constantly. In calculating the electrical load, you must determine the connected load first. The connected load is the sum of the rated capacities of all electrical appliances, lamps, motors, and so forth, connected to the wiring of the system. The maximum demand load is the greatest value of all connected loads that are in operation over a specified period of time. Knowledge of the maximum demand of groups of loads is of great importance because it is the group maximum demand that determines the size of generators, conductors, and apparatus throughout the electrical system.

The ratio between the actual maximum demand and the total connected load is called the demand factor (explained in detail in CE Advanced, Chapter 2). If a group of loads were all connected to the supply source and drew their rated loads at the same time, the demand factor would be 1.00. There are two main reasons why the demand factor is usually less than 1.00. First, all load devices are seldom in use at the same time and, even if they are, they will seldom reach maximum demand at the same time. Second, some load devices are usually slightly larger than the minimum size needed and normally draw less than their rated load. Since the maximum demand is one of the factors determining the size of conductors, it is important that the demand factor be established as closely as possible.

The demand factor varies considerably for different types of loads, services, and structures. The National Electrical Code®, Article 220 provides the requirements for determining demand factors. Demand factors for some military structures are given in *Table 3-2*.

Table 3-2 – Demand Factor.

Structure	Demand Factor
Housing	0.9
Aircraft maintenance facilities	.7
Operation facilities	.8
Administrative facilities	.8
Shops	.7
Warehouses	.5
Medical facilities	.8
Theaters	.5
NAV aids	.5
Laundry, ice plants, and bakeries	1.0
All others	.9

Example: A machine shop has a total connected load of 50.3 kilowatts. The demand factor for this type of structure is taken at 0.70. The maximum demand is 50.3 x 0.70 = 35.21 kilowatts.

4.0.0 STATICALLY REGULATED BRUSHLESS GENERATOR

Revolving-field-type generators have a dc field revolving within a stationary ac winding called the stator. *Figure 3-3* is a generator schematic. AC power is distributed from the generator through leads connected to the stator windings. There are no sliding contacts between the ac winding and the load; therefore, great amounts of power may be drawn from this generator.

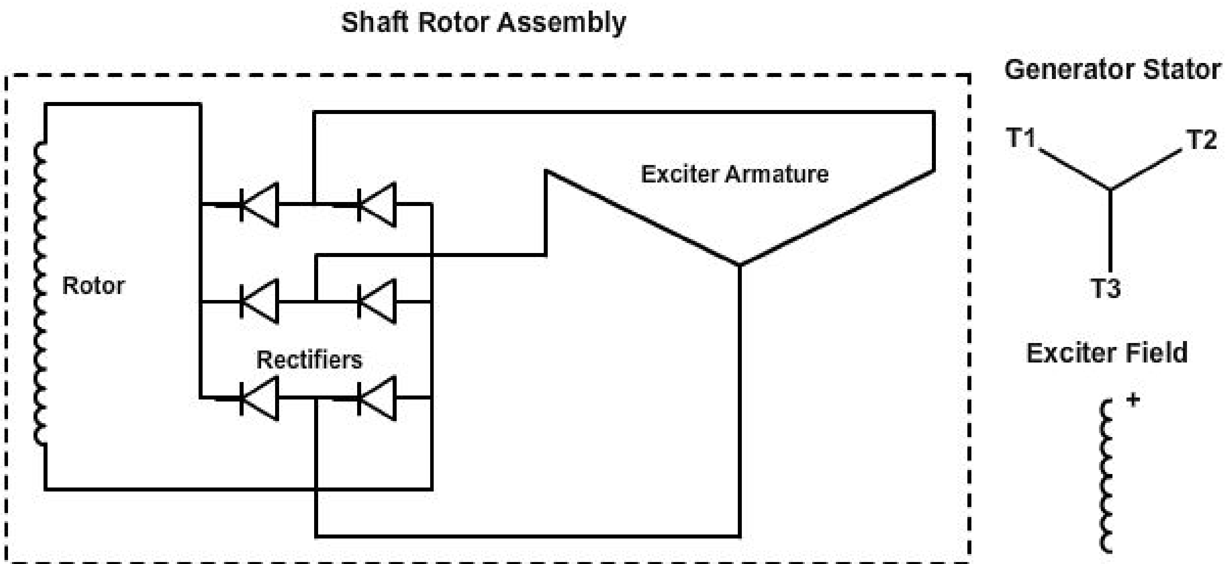

Figure 3-3— Brushless generator schematic.

To energize the field, dc excitation must be applied to the generator field coils. The excitation current is supplied from a brushless exciter mounted on the generator shaft.

The brushless exciter is actually an ac generator with its output rectified through a full-wave bridge circuit. This type of brushless exciter will provide the necessary excitation current. The generator set field flash circuit, activated during each engine start, applies voltage to the exciter stator to begin the voltage build-up process to energize the generator field.

The generator output voltage is controlled by controlling the alternating field current. This is accomplished by regulating the exciter field coil voltage. The exciter field coil voltage is regulated with a solid-state type of automatic voltage regulator.

4.1.0 Damper Bars

Damper bars are inserted through the field laminations and welded at the end to a solid copper plate. The damper windings provide stable parallel operation, reduce damping current losses, and limit the increase of third harmonic voltage with increase in load.

4.2.0 Brushless Exciter

The brushless exciter consists of an armature with a three-phase ac winding and rotating rectifier within a stationary field. The stationary exciter field assembly is mounted in the main generator frame. The exciter armature is press fit and keyed onto the shaft assembly. The rotating rectifier assembly slides over the bearing end of the generator rotor shaft and is secured with bolts and washers to an adapter hub, which is shrunk on the generator shaft.

4.3.0 Rotating Rectifier Bridge

The rotating rectifier bridge consists of rectifying diodes mounted on a brass heat sink which is in turn mounted on an insulating ring. The entire assembly bolts to the adapter on the generator shaft; therefore, the rotating rectifier assembly will rotate with the exciter armature, eliminating the need for any sliding contacts between the exciter output and the alternator field.

4.4.0 Exciter Field

The exciter field on the high frequency exciter consists of laminated segments of high carbon steel that are fitted together to make up the field poles. The field coils are placed into the slots of the field poles.

4.5.0 Exciter Field Coil Voltage Source

Field coil dc voltage is obtained by rectifying the voltage from a phase to neutral line of the generator output or other appropriate terminal to provide the needed voltage reference.

The rectifier bridge is an integral part of the static regulator. The static regulator senses a change in the generator output and automatically regulates current flow in the exciter field coil circuit to increase or decrease the exciter field strength. An external adjust rheostat sized to be compatible with the regulator is used to provide adjustment to the regulator sensing circuit.

4.6.0 Balance

The rotor assembly is precision balanced to a high degree of static and dynamic balance. Balance is achieved with the balance lugs on the field pole tips. The balance will remain dynamically stable at speeds in excess of the design frequencies.

4.7.0 Bearing

The generator rotor assembly is suspended on shielded, factory-lubricated ball bearings. They are greased for life and do not require lubrication.

4.8.0 Stator Assembly

The stator assembly consists of laminations of steel mounted in a rolled steel frame. Random wound stator coils are fitted into the insulated slots.

5.0.0 USE of TECHNICAL MANUALS

In TM 09244A/09245A-14 (Tactical Quiet Generator Set) paragraphs are underlined and sections and chapters appear in capital letters. The location of additional material that must be referenced is clearly marked. All illustrations in the manual are located as close as possible to the references. The use of this technical manual is recommended for any operator or unit operation or maintenance. The content of this technical manual is summarized below:

Chapter 1 - INTRODUCTION; contains general information, equipment description and data, and principles of operation for the generator set

Chapter 2 - OPERATING INSTRUCTIONS; contains description and use of operator controls and indicators, preventive maintenance checks and services (PMCS), procedures for inspecting and servicing the generator set, and instructions for operating the generator set under usual and unusual conditions

Chapter 3 - OPERATOR MAINTENANCE INSTRUCTIONS; contains troubleshooting procedures used to recognize and correct operator level generator set malfunctions, and all maintenance procedures authorized to be performed on the generator set at the operator level

Chapter 4 - UNIT MAINTENANCE INSTRUCTIONS; contains troubleshooting procedures used to recognize and correct generator set malfunctions at the unit level, and all maintenance procedures authorized to be performed on the generator set at the unit level

Chapter 5 - DIRECT SUPPORT MAINTENANCE INSTRUCTIONS; contains direct support level troubleshooting procedures used to recognize and correct generator set malfunctions at the direct support evel, and all maintenance procedures authorized to be performed on the generator set at the direct support level

Chapter 6 - GENERAL SUPPORT MAINTENANCE INSTRUCTIONS; there are no general support level maintenance tasks for the generator set

Appendices:

Appendix A - lists publications referenced in this manual and should be used in conjunction with this manual.

Appendix B - the maintenance allocation chart (MAC), which designates all maintenance and repair functions authorized to be performed at the different maintenance levels

Appendix C - lists the components of end item (COEI) and basic issue items (BII)

Appendix D - lists items authorized for use with the generator set, but not issued with it or supported by generator set engineering drawings

Appendix E - the expendable/durable supplies and materials list (EDSML) which lists all expendable/durable supplies and materials required in performing the maintenance procedures presented in this manual

Appendix F - contains lubrication procedures for the generator set at the operator level

Appendix G - lists all parts that require fabrication or assembly for the maintenance of the generator set; includes required materials and procedures

Appendix H - provides torque limits for fasteners used in maintenance of the generator set

Appendix I - lists parts that must be replaced when maintenance tasks require their removal

Index - contains key technical manual subjects arranged in alphabetical order; to find information on a specific subject (for example, Time Meter), use to locate specific paragraph

6.0.0 DC SCHEMATIC

The technician's main aid in troubleshooting a circuit in a piece of equipment is the ***schematic diagram***. The schematic diagram is a picture of the circuit that uses symbols to represent the various circuit components. Physically large or complex circuits can be shown on a relatively small diagram. Before studying the basic schematic, look at *Figure 3-4*. This figure shows the symbols that are used. These symbols and others like them are referred to and used throughout the study of electricity and electronics.

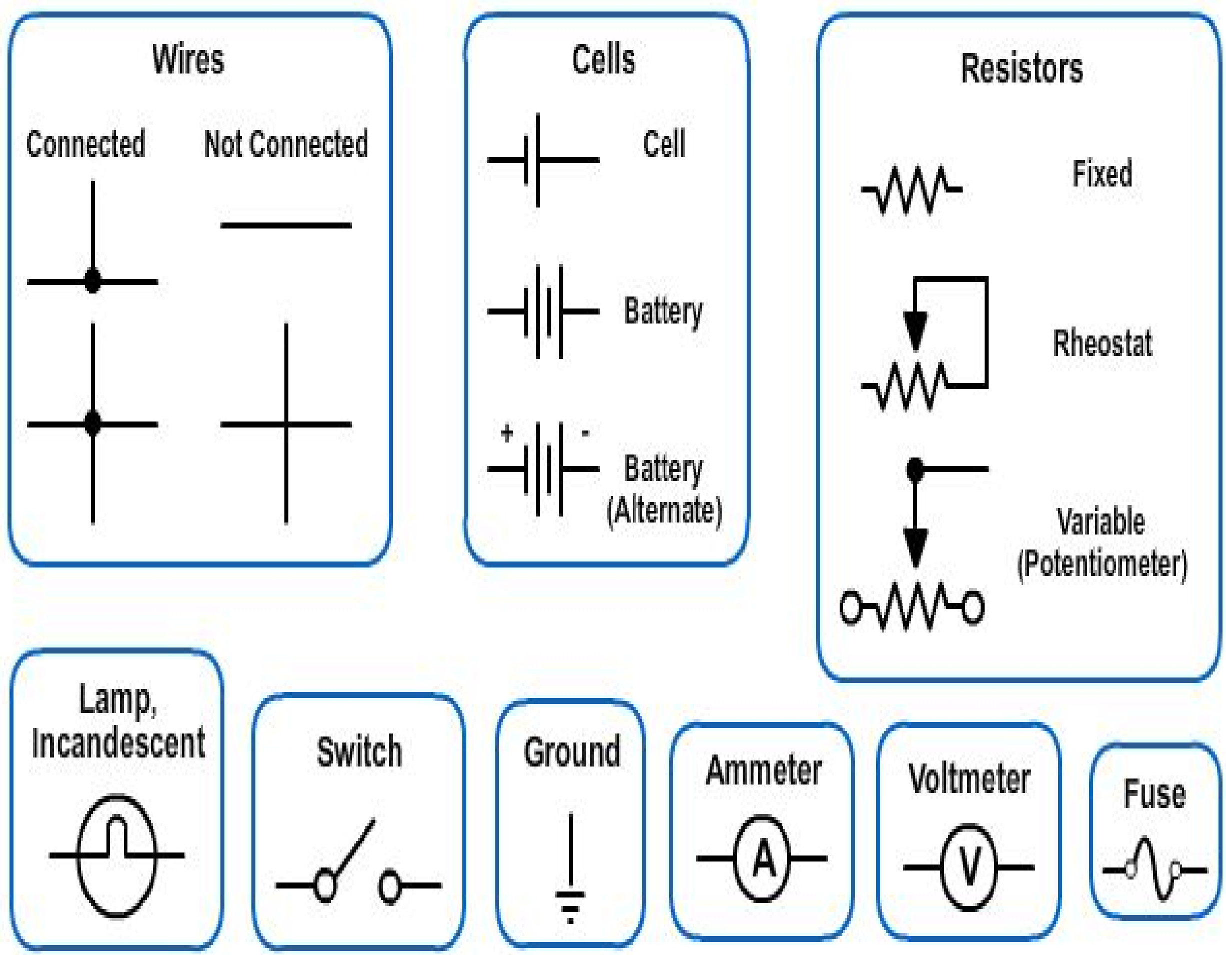

Figure 3-4 – Symbols commonly used in electricity.

The schematic in *Figure 3-5* represents a flashlight. *Figure 3-5, View A* shows the flashlight in the off or deenergized state. The switch (S1) is open. There is no complete path for current (I) through the circuit, and the bulb (DS1) does not light. In *Figure 3-5, View B*, switch S1 is closed. Current flows in the direction of the arrows from the

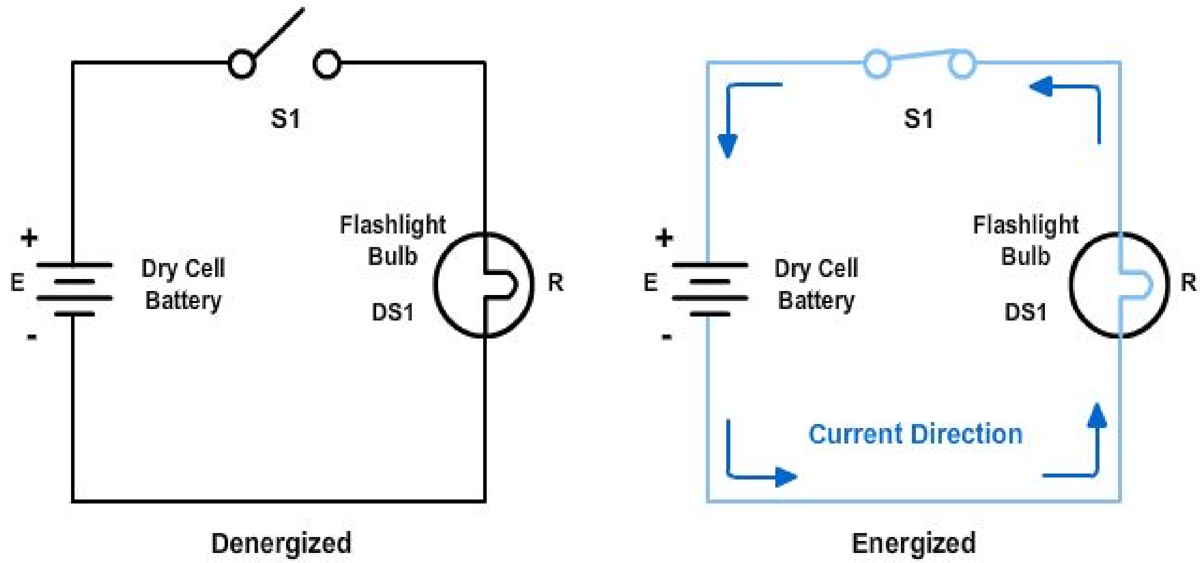

Figure 3-5 — Basic flashlight schematic.

negative terminal of the battery (BAT), through the switch S1, through the lamp (DS1), and back to the positive terminal of the battery. With the switch closed, the path for current is complete. Current will continue to flow until the switch (S1) is moved to the open position or the battery is completely discharged.

7.0.0 DC TROUBLESHOOTING DIAGRAM

In this section, an example of troubleshooting a specific problem with the Tactical Quiet Generator (TQG) will be explored using the schematic and troubleshooting diagram. For specific troubleshooting at the operator or unit level, you must use the current edition of the Technical Manual TM 09244B/09245B-14/1.

At this point, it is very important for you to pay particular attention to the warning labels contain within the equipment operator's manual and the TM 09244B/09245B-14/1. For the troubleshooting procedure for DC to be performed in this section, two particular warnings are especially pertinent and they are as follows:

WARNING

DC voltages are present at generator-set electrical components even with generator shut down. Avoid shorting any positive terminal with ground/negative. Failure to comply can cause injury to personnel and damage to equipment.

WARNING

Metal jewelery can conduct electricity. Remove metal jewelery when working on electrical systems or components. Failure to comply can cause injury or death to personnel by electrocution.

7.1.0 Troubleshooting Problem

The following troubleshooting will be used as an example of the Unit Troubleshooting Diagram described in Technical Manual TM 09244B/09245B-14/1. *Figure 3-6* is a full schematic of the TQG generator and will be used in conjunction with *Figure 3-7*, which is a symptom diagram for a specific problem with the generator.

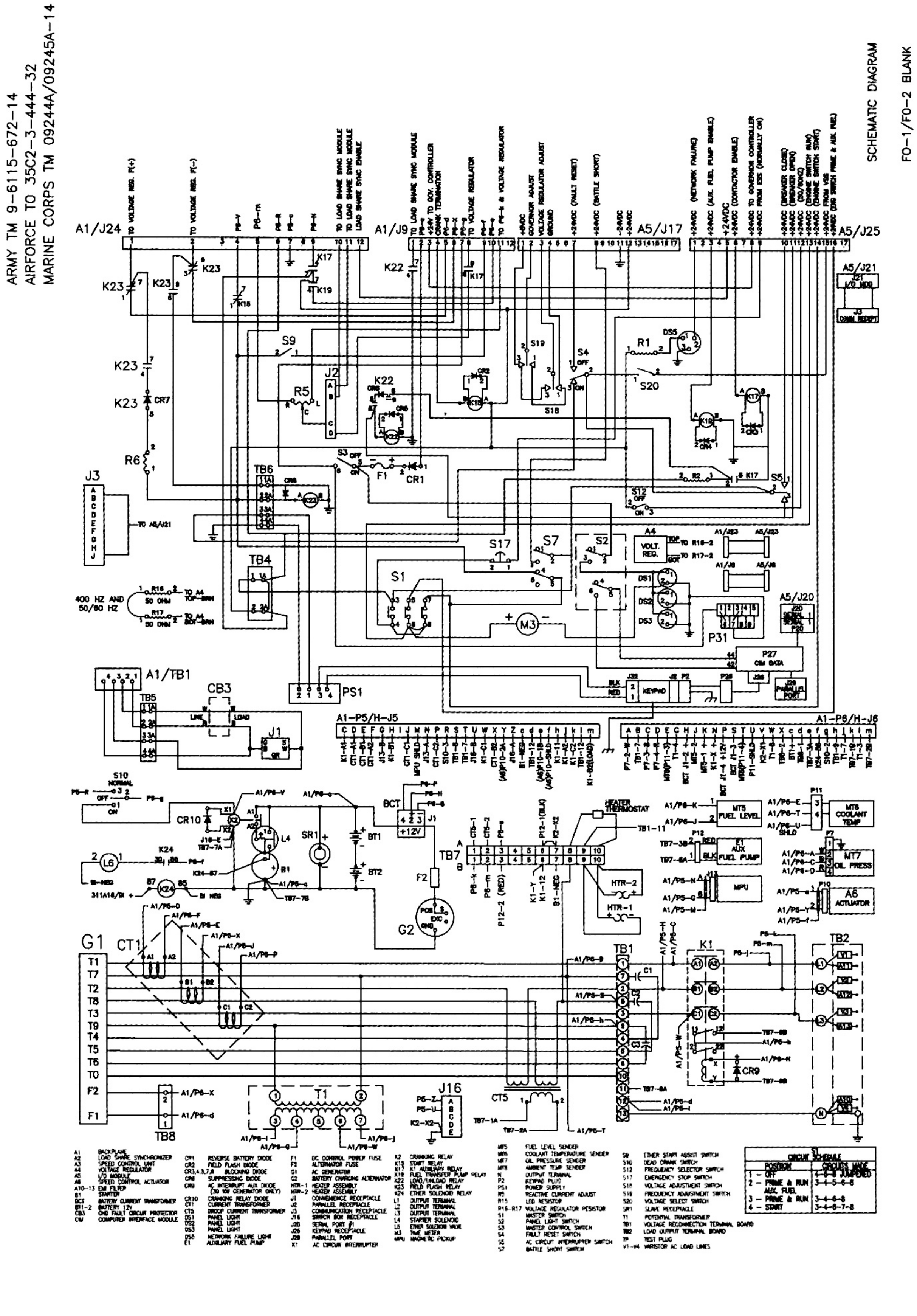

Figure 3-6 — Schematic FO-1 of TQG generator.

Figure 3-7 has the feature of showing the portion of the schematic involved with the specific problem symptom and maintenance procedure to fix problem.

7.1.1 DC Scenario

The operator of the TQG reports to the unit that the Computer Interface Module (CIM) display screen does not respond to keypad input. Using *Figure 3-7* click on the boxes to find the problem and repair instructions, and to see the section of the schematic involved.

You will notice that when you click the block for "Check keyboard power supply (PS-1) for 24VDC," the response is **Not OK**. The same is true for block "Check for 24VDC at TB4," with response **Not OK,** which refers you to the schematic. When you click on the block for "Check for approximately 24VDC at J24-6," the reading is **OK**. At this point, you are guided to the block for "Check wiring to J24-6 at TB4" and you have a reading of **Not OK,** which states that the problem is to replace the keypad power supply (PS-1).

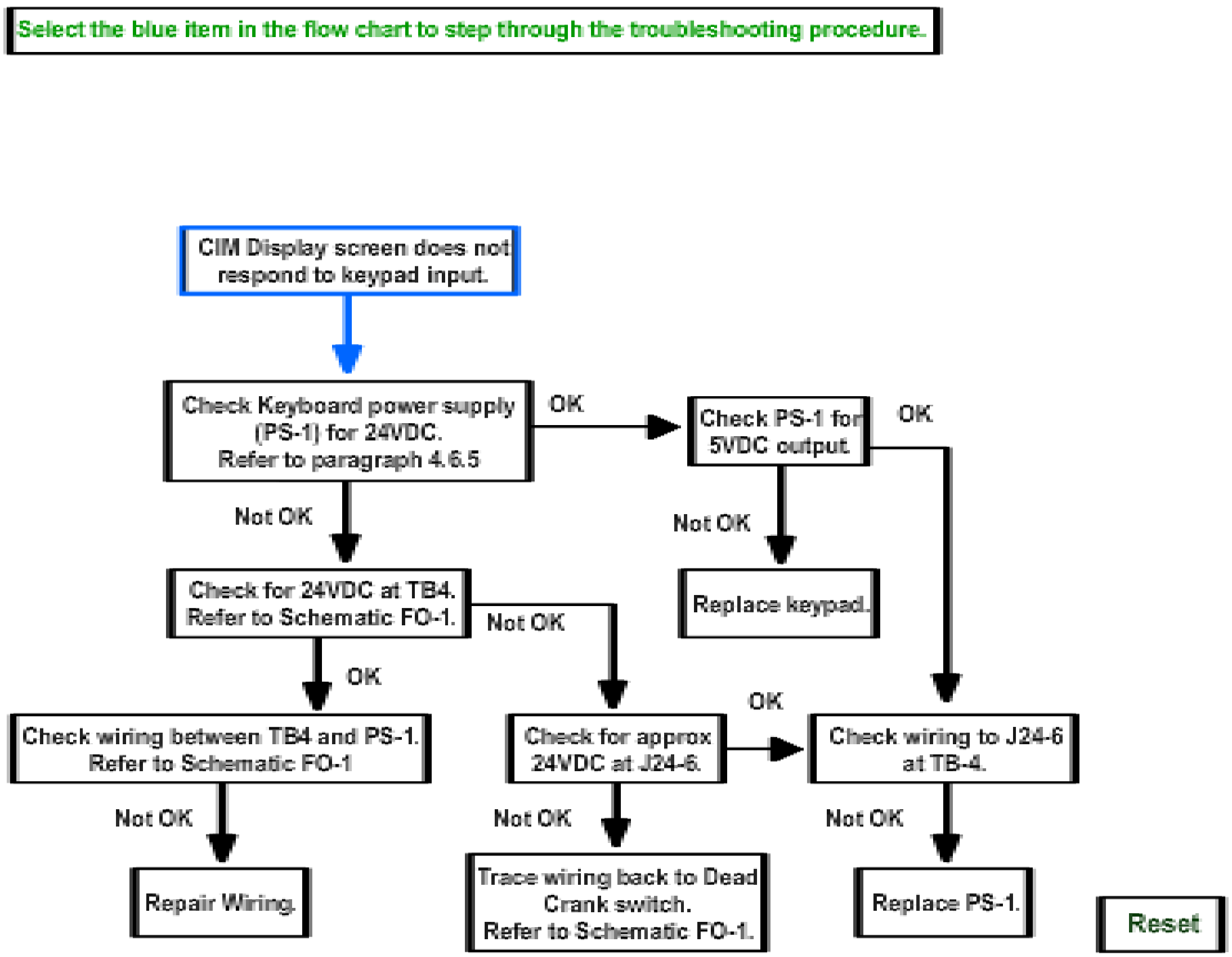

Figure 3-7 — Symptom diagram for CIM display screen not responding.

8.0.0 AC TROUBLESHOOTING DIAGRAM

In this section, an example of troubleshooting a specific problem with the Tactical Quiet Generator (TQG) will be explored using the troubleshooting diagram. For specific troubleshooting at the operator or unit level, you must use the current edition of the Technical Manual TM 09244B/09245B-14/1.

The following troubleshooting will be used as an example of the Operator Troubleshooting Diagram described in Technical Manual TM 09244B/09245B-14/1. *Figure 3-8* is a condensed version of the symptom diagram for a specific problem with the generator. *Figure 3-8* has the feature of showing the portion of the technical manual involved with the specific problem symptom and maintenance procedure to fix problem.

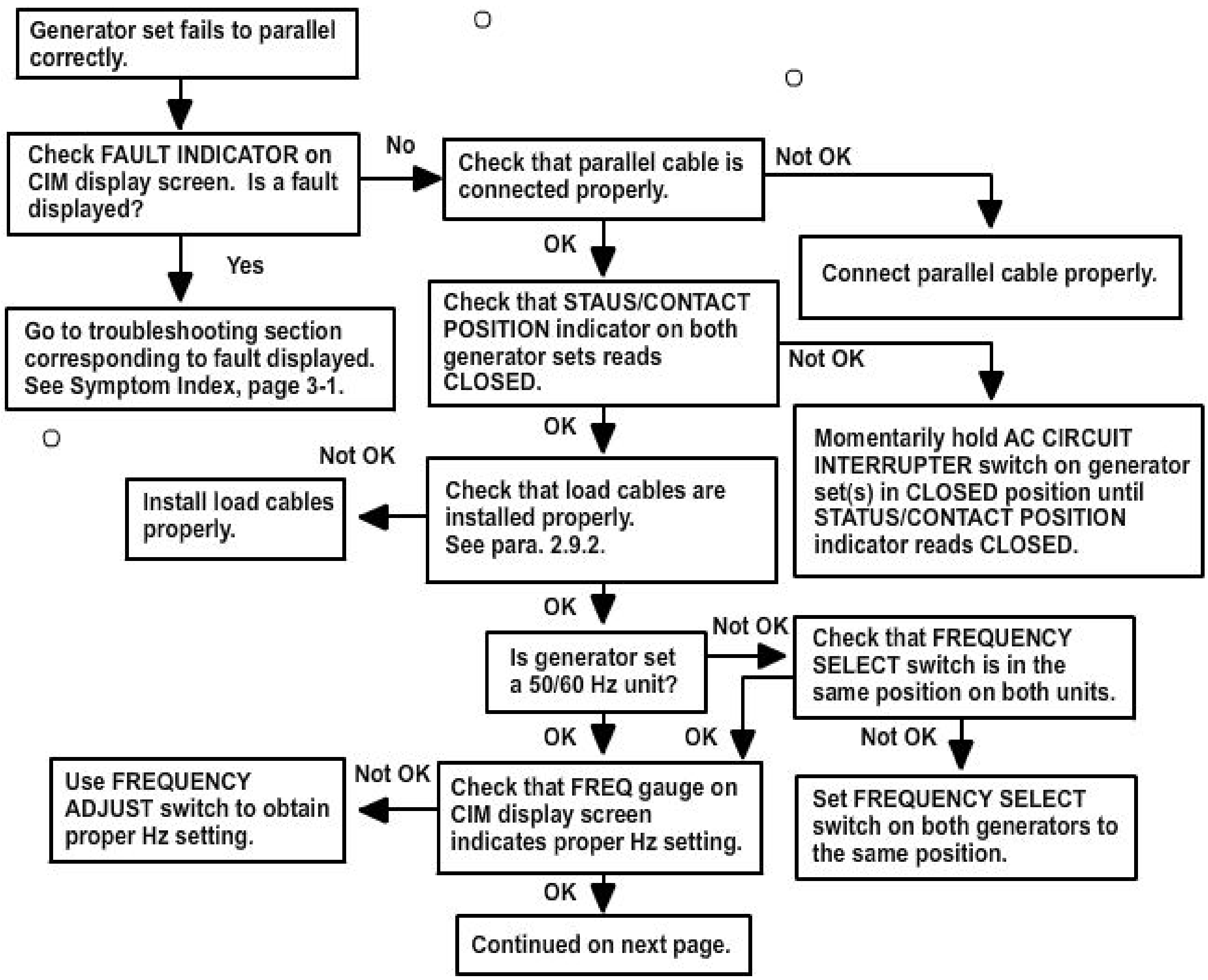

Figure 3-8 — Symptom diagram for generator set fails to parallel correctly.

8.1.0 Troubleshooting Problem

At this point it is very important for you to pay particular attention to the warning labels contained within the equipment operator's manual and the TM 09244B/09245B-14/1. For the troubleshooting procedure for ac to be performed in this section one caution and two particular warnings are especially pertinent and they are as follows:

CAUTION

Ensure generator sets are the same size and mode before attempting parallel operation.

WARNING

Prior to making any connections for parallel operation or moving a generator set that has been operating in parallel, ensure that there is no input to the load output terminal board and that the generator set is shut down. Failure to comply can cause injury or death to personnel by electrocution.

WARNING

High voltage is produced when the generator set is in operation. Never attempt to start the generator set unless it is properly grounded. Failure to comply can cause injury or death to personnel.

8.1.1 AC Scenario

The operator of two TQG generators is attempting to parallel the two generators and they fail to parallel properly.

You will notice that when you click the block for “Check Fault Indicator on CIM display screen. Is a fault displayed?” the response is **No**. When you click on the block for “Check that parallel cable is connected properly,” the reading is **Not OK**. At this point, you are guided to the block for “Connect parallel cable properly.” This leads you to the explanation of the problem being the cable connection and how to accomplish the repair.

Summary

Your knowledge and understanding of the types of generators in use by the United States Navy is very important for the safe conduct and completion of your job as a Construction Electrician. As a Construction Electrician, you need the knowledge of the troubleshooting techniques to include the use of schematics when dealing with alternating and direct current. During you career as a Construction Electrician, you will be called upon to make sure that generator equipment is maintained properly and power is maintained for your fellow Seabees. It is highly recommended that you read NAVEDTRA 14177, Navy Electricity and Electronics Training Series, Module 5 for detailed information concerning generators.

Review Questions (Select the Correct Response)

1. The annual load factor of a well-operated active base should be _____ percent or more with a power factor of _____ percent or higher.

   A. 25, 50
   B. 30, 60
   C. 35, 70
   D. 50, 80

2. How many volts is practically all general-purpose lighting in the United States and at United States overseas bases?

   A. 100
   B. 110
   C. 120
   D. 220

3. Which of the following terms is generally used to measure electrical loads?

   A. Amperes
   B. Kilowatts
   C. Kilovoltamperes
   D. All of the above

4. **(True or False)** The ratio between the actual maximum demand and the total connected load is called the demand factor.

   A. True
   B. False

5. Which, if any, of the following statements is correct concerning statically regulated brushless generators?

   A. AC power is distributed from the generator through leads connected to the stator windings.
   B. There are sliding contacts between the ac winding and the load.
   C. The generator output voltage is controlled by controlling the dc field current.
   D. None of the above.

6. What is the technician's main aid in troubleshooting a circuit in a piece of equipment?

   A. Ohmmeter
   B. Technical manual
   C. Schematic diagram
   D. Screwdriver

Trade Terms Introduced in this Chapter

Schematic diagram	A picture of the circuit that uses symbols to represent the various circuit components; physically large or complex circuits can be shown on a relatively small diagram.

Additional Resources and References

This chapter is intended to present thorough resources for task training. The following reference works are suggested for further study. This is optional material for continued education rather than for task training.

NAVEDTRA 14177 Navy Electricity and Electronics Training Series, Module 5

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Chapter 4

Solid State Devices

Topics

1.0.0 Introduction to Solid-State Devices

2.0.0 Semi Conductor Diode

3.0.0 Diode Application

4.0.0 Filter Circuits

5.0.0 Types of Power Supply Filters

6.0.0 Introduction to Transistors

7.0.0 Zener Diode

8.0.0 Silicon Controlled Rectifier (SCR)

9.0.0 Traic

10.0.0 Diac

11.0.0 Unijunction Transistor (UJT)

12.0.0 Transducers

13.0.0 Integrated Circuit (IC)

14.0.0 Printed Circuits

To hear audio, click on the box.

Overview

As the applications of solid-state devices mount, the need for knowledge of these devices becomes increasingly important. As a Construction Electrician in the United States Navy today, you have to understand solid-state devices if you are to become proficient in the repair and maintenance of electronic equipment. The objective of this chapter is to provide a broad coverage of solid-state devices. In this chapter, you will be introduced to the common semiconductor components and some of their applications in field equipment. Also, you will be introduced to transistors and test equipment used on the transistors.

Objectives

When you have completed this chapter, you will be able to do the following:

1. Describe the purpose of semi conductor diodes.
2. Describe the different types of diode applications.
3. Identify the different types of filter circuits.
4. Identify the different types of power supply filters.
5. Identify the different types of transistor classifications.
6. Understand transistor theory.
7. Understand transistor identification.
8. Describe testing procedures associated with transistors.
9. Describe the purpose and use of Zener diodes.
10. Describe the purpose and use of silicon controlled rectifiers (SCR).
11. Describe the purpose and use of Traic diodes.
12. Describe the purpose and use of Diac diodes.
13. Describe the purpose and use of Unijunction Transistors.
14. Describe the purpose and use of transducers.
15. Describe the purpose and use of Integrated circuits (IC).
16. Describe the purpose and use of Printed circuits.

Prerequisites

None

This course map shows all of the chapters in Construction Electrician Advanced. The suggested training order begins at the bottom and proceeds up. Skill levels increase as you advance on the course map.

Solid State Devices	↑	C E
ABFC Power Plant Maintenance		A D
ABFC Power Plant Operations and Procedures		V A N
Advanced Electrical Theory		C E D

Features of this Manual

This manual has several features which make it easy to use online.

- Figure and table numbers in the text are italicized. The figure or table is either next to or below the text that refers to it.
- The first time a glossary term appears in the text, it is bold and italicized. When your cursor crosses over that word or phrase, a popup box displays with the appropriate definition.
- Audio and video clips are included in the text, with italicized instructions telling you where to click to activate it.
- Review questions that apply to a section are listed under the Test Your Knowledge banner at the end of the section. Select the answer you choose. If the answer is correct, you will be taken to the next section heading. If the answer is incorrect, you will be taken to the area in the chapter where the information is for review. When you have completed your review, select anywhere in that area to return to the review question. Try to answer the question again.
- Review questions are included at the end of this chapter. Select the answer you choose. If the answer is correct, you will be taken to the next question. If the answer is incorrect, you will be taken to the area in the chapter where the information is for review. When you have completed your review, select anywhere in that area to return to the review question. Try to answer the question again.

1.0.0 INTRODUCTION to SOLID-STATE DEVICES

Semiconductors have electrical properties somewhere between those of insulators and conductors. The use of semiconductor materials in electronic components is not new. Some devices are as old as the electron tube. Two of the most widely known semiconductors in use today are the ***junction diode*** and ***transistor***. These semiconductors fall under a more general heading called solid-state devices. A ***solid-state device*** is nothing more than an electronic device, which operates by virtue of the movement of electrons within a solid piece of semiconductor material.

Since the invention of the transistor, solid-state devices have been developed and improved at an unbelievable rate. Great strides have been made in the manufacturing techniques, and there is no foreseeable limit to the future of these devices. Solid-state devices made from semiconductor materials offer compactness, efficiency, ruggedness, and versatility. Consequently, these devices have invaded virtually every field of science and industry. In addition to the junction diode and transistor, a whole new family of related devices has been developed: the ***zener diode;*** the ***light-emitting diode***; the ***field effect transistor***; and so forth. One development that has dominated solid-state technology, and probably has had a greater impact on the electronics industry than either the electron tube or transistor, is the ***integrated circuit***. The integrated circuit is a minute piece of semiconductor material that can produce complete electronic circuit functions.

1.1.0 Semiconductor Development

Although the semiconductor was late in reaching its present development, its story began long before the electron tube. Historically, you can go as far back as 1883, when Michael Faraday discovered that silver sulfide, a semiconductor, has a negative temperature coefficient. The term negative temperature coefficient is just another way of saying its resistance to electrical current flow decreases as temperature increases. The opposite is true of the conductor. It has a positive temperature coefficient. Because of this particular characteristic, semiconductors are used extensively in power-measuring equipment.

Only 2 years later, another valuable characteristic was reported by Munk A. Rosenshold. He found that certain materials have rectifying properties. Strange as it may seem, his finding was given such little notice that it had to be rediscovered 39 years later by F. Braun.

Toward the close of the 19th century, experimenters began to notice the peculiar characteristics of the chemical element selenium. They discovered that in addition to its rectifying properties (the ability to convert ac to dc), selenium was also light sensitive, meaning that its resistance decreased with an increase in light intensity. This discovery eventually led to the invention of the photophone by Alexander Graham Bell. The photophone, which converted variations of light into sound, was a predecessor of the radio receiver; however, it was not until the actual birth of radio that selenium was used to any extent. Today, selenium is an important and widely used semiconductor.

Many other materials were tried and tested for use in communications. Silicon was found to be the most stable of the materials tested while galena, a crystalline form of lead sulfide, was found the most sensitive for use in early radio receivers. By 1915, Carl Beredicks discovered that germanium, another metallic element, also had rectifying capabilities. Later, it became widely used in electronics for low-power, low-frequency applications.

Although the semiconductor was known long before the electron tube was invented, the semiconductor devices of that time could not match the performance of the tube. Radio needed a device that could not only handle power and amplify, but also rectify and detect a signal as well. Since tubes could do all of these things, whereas semiconductor devices of that day could not, the semiconductor soon lost out.

It was not until the beginning of World War II that interest was renewed in the semiconductor. There was a dire need for a device that could work within the ultra-high frequencies of radar. Electron tubes had interelectrode capacitances that were too high to do the job. The point-contact semiconductor diode, on the other hand, had a very low internal capacitance. Consequently, it filled the bill; it could be designed to work within the ultra-high frequencies used in radar, whereas the electron tube could not.

As radar took on greater importance and communication-electronic equipment became more sophisticated, the demands for better solid-state devices mounted. The limitations of the electron tube made necessary a quest for something new and different. An amplifying device was needed that was smaller, lighter, more efficient, and capable of handling extremely high frequencies. This was asking a lot, but if progress was to be made, these requirements had to be met. A serious study of semiconductor materials began in the early 1940s and has continued since.

In June 1948, a significant breakthrough took place in semiconductor development. This was the discovery of point-contact transistor. Here at last was a semiconductor that could amplify. This discovery brought the semiconductor back into competition with the electron tube. A year later, junction diodes and transistors were developed. The junction transistor was found superior to the point-contact type in many respects. By comparison, the junction transistor was more reliable, generated less noise, and had higher power-handling ability than its point-contact brother. The junction transistor became a rival of the electron tube in many uses previously uncontested.

Semiconductor diodes were not to be slighted. The initial work of Dr. Carl Zener led to the development of zener diode, which is frequently used today to regulate power supply voltages at precise levels. Considerably more interest in the solid-state diode was generated when Dr. Leo Esaki, a Japanese scientist, fabricated a diode that could amplify. The device, named the tunnel diode, has amazing gain and fast switching capabilities. Although it is used in the conventional amplifying and oscillating circuits, its primary use is in computer logic circuits.

Another breakthrough came in the late 1950s when it was discovered that semiconductor materials could be combined and treated so that they functioned as an entire circuit or subassembly rather than as a circuit component. Many names have been given to this solid-circuit concept, such as integrated circuits, microelectronics, and microcircuitry.

So as you can see, in looking back, the semiconductor is not something new, but it has come a long way in a short time.

1.2.0 Semiconductor Applications

Semiconductor devices are all around us. They can be found in just about every commercial product you touch, from the family car to the pocket calculator. Semiconductor devices are contained in television sets, portable radios, stereo equipment, and much more.

Science and industry also rely heavily on semiconductor devices. Research laboratories use these devices in all sorts of electronic instruments to perform tests, measurements, and numerous other experimental tasks. Industrial control systems (such as those used to manufacture automobiles) and automatic telephone exchanges also use semiconductors. Even today, heavy-duty versions of the solid-state rectifier diode are being use to convert large amounts of power for electric railroads. Of the many different applications for solid-state devices, space systems, computers, and data processing equipment are some of the largest consumers.

The various types of modem military equipment are literally loaded with semiconductor devices. Many radars, and communication, and airborne equipment are transistorized. Data display systems, data processing units, computers, and aircraft guidance-control assemblies are also good examples of electronic equipment that use semiconductor devices. All of the specific applications of semiconductor devices make a long, impressive list. The fact is, semiconductors are being used extensively in commercial products, industry, and the military.

1.3.0 Semiconductor Competition

It should not be difficult to conclude, from what you already know, that semiconductor devices can and do perform all the conventional functions of rectification, amplification, oscillation, timing, switching, and sensing. Simply stated, these devices perform the same basic functions as the electron tube, but they perform more efficiently, more economically, and for a longer period of time; therefore, it should be no surprise to see these devices used in place of electron tubes. Keeping this in mind, you can see that it is only natural and logical to compare semiconductor devices with electron tubes.

Physically, semiconductor devices are much smaller than tubes. You can see in *Figure 4-1* that the difference is quite evident. This illustration shows some commonly used tube sizes alongside semiconductor devices of similar capabilities. The reduction in size can be as great as 100:1 by weight and 1000:1 by volume. It is easy to see that size reduction favors the semiconductor device; therefore, whenever miniaturization is required or is convenient, transistors are favored over tubes. Bear in mind, however, that the extent of practical size reduction is a big factor; many things must be considered. Miniature electron tubes, for example, may be preferred in certain applications to transistors, thus keeping size reduction to a competitive area.

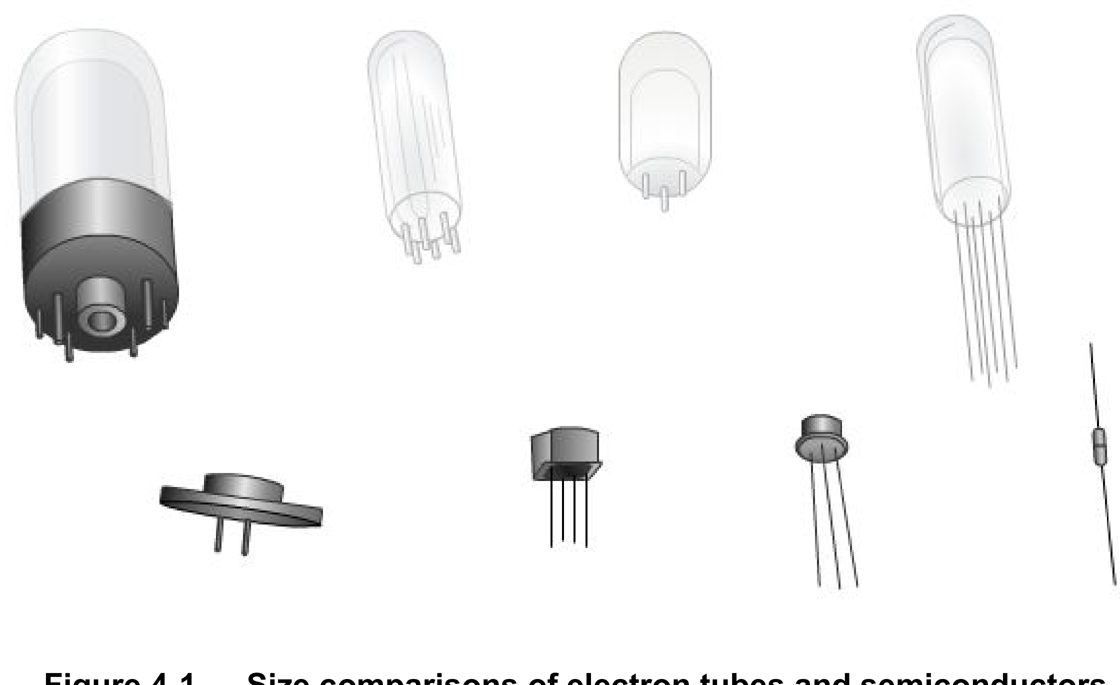

Figure 4-1 — Size comparisons of electron tubes and semiconductors.

Power is also a two-sided story. For low-power applications, where efficiency is a significant factor, semiconductors have a decided advantage. This is true mainly because semiconductor devices perform very well with an extremely small amount of power. In addition, they require no filaments or heaters as in the case of the electron tube. For example, a computer operating with over 4,000 solid-state devices may require no more than 20 watts of power. However, the same number of tubes requires several kilowatts of power.

For high-power applications, it is a different story and tubes have the upper hand. The high-power tube has no equivalent in any semiconductor device. This is because a tube can be designed to operate with over a thousand volts applied to its plate, whereas the maximum allowable voltage for a transistor is limited to about 200 volts (usually 50 volts or less). A tube can also handle thousands of watts of power. The maximum power output for a transistor generally ranges from 30 milliwatts to slightly over 100 watts.

When it comes to ruggedness and life expectancy, the tube is still in competition. Design and functional requirements usually dictate the choice of device. However, semiconductor devices are rugged and long lived. They can be constructed to withstand extreme vibration and mechanical shock. They have been known to withstand impacts that would completely shatter an ordinary electron tube. Although some specially designed tubes render extensive service, the life expectancy of transistors is better than three to four times that of ordinary electronic tubes. There is no known failure mechanism (such as an open filament in a tube) to limit the semiconductor's life. However, semiconductor devices do have some limitations. They are usually affected more by temperature, humidity, and radiation than tubes are.

1.4.0 Semiconductor Theory

To understand why solid-state devices function as they do, you will have to examine closely the composition and nature of semiconductors. This entails theory that is fundamental to the study of solid-state devices.

1.4.1 Energy Bands

Orbiting electrons contain energy and are confined to definite energy levels. The various shells in an atom represent these levels; therefore, to move an electron from a lower shell to a higher shell, a certain amount of energy is required. This energy can be in the form of electric fields, heat, light, and even bombardment by other particles. Failure to provide enough energy to the electron, even if the energy supplied is just short of the required amount, will cause it to remain at its present energy level. Supplying more energy than is needed will only cause the electron to move to the next higher shell and the remaining energy will be wasted. In simple terms, energy is required in definite units to move electrons from one shell to the next higher shell. These units are called ***quanta*** (for example 1, 2, or 3 quanta).

Electrons can also lose energy as well as receive it. When an electron loses energy, it moves to a lower shell. The lost energy, in some cases, appears as heat.

If a sufficient amount of energy is absorbed by an electron, it is possible for that electron to be completely removed from the influence of the atom. This is called ***ionization***. When an atom loses electrons or gains electrons in this process of electron exchange, it is said to be ionized. For ionization to take place, there must be a transfer of energy that results in a change in the internal energy of the atom. An atom having more than its normal amount of electrons acquires a negative charge and is called a ***negative ion***. The atom that gives up some of its normal electrons is left with fewer negative charges than positive charges and is called a ***positive ion***. Thus, you can define ionization as the process by which an atom loses or gains electrons.

Up to this point in our discussion, we have spoken only of isolated atoms. When atoms are spaced far enough apart, as in a gas, they have very little influence upon each other, and are very similar to lone atoms. But atoms within a solid have a marked effect upon each other. The forces that bind these atoms together greatly modify the behavior of the other electrons. One consequence of this close proximity of atoms is to cause the individual energy levels of an atom to break up and form bands of energy. Discrete (separate and complete) energy levels still exist within these energy bands, but there are many more energy levels than there were with the isolated atom. In some cases, energy levels will have disappeared. *Figure 4-2* shows the difference in the energy arrangement between an isolated atom and the atom in a solid. Notice that the isolated atom (such as in gas) has energy levels, whereas the atom in a solid has energy levels grouped in energy bands.

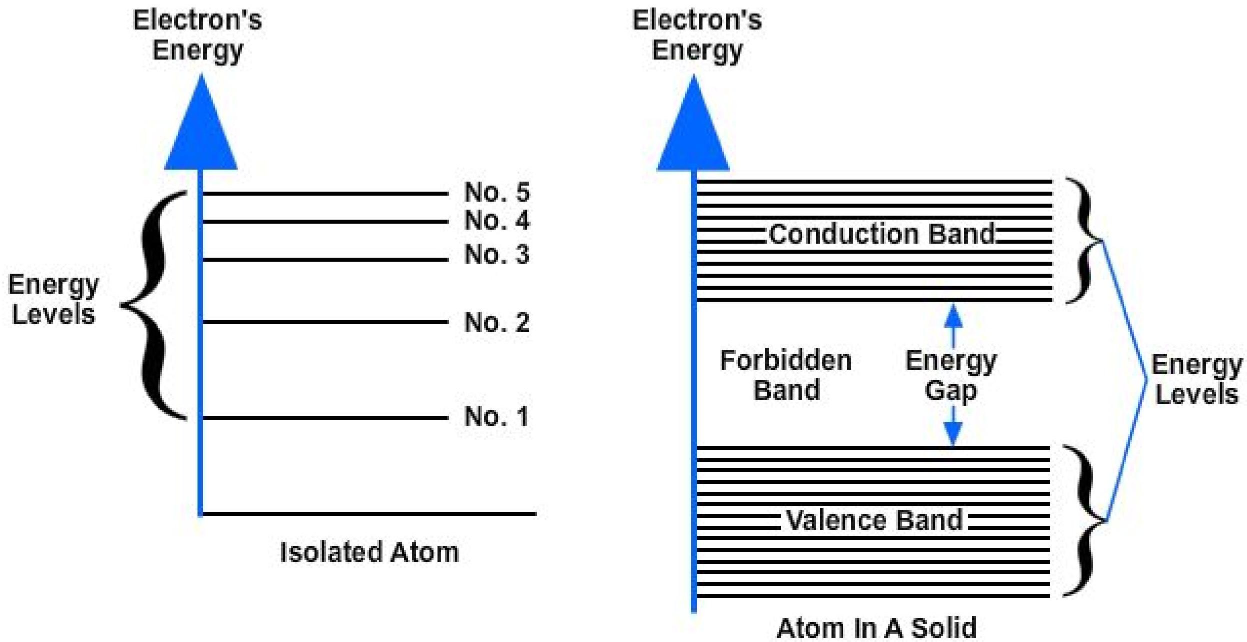

Figure 4-2 — Energy arrangement in atoms.

The upper band in the solid lines in *Figure 4-2* is called the ***conduction band*** because electrons in this band are easily removed by the application of external electric fields. Materials that have a large number of electrons in the conduction band act as good conductors of electricity.

Below the conduction band is the ***forbidden band***, or energy gap. Electrons are never found in this band, but may travel back and forth through it, provided they do not come to rest in the band.

The last band, or ***valence band***, is composed of a series of energy levels containing valence electrons. Electrons in this band are more tightly bound to the individual atom than the electrons in the conduction band. However, the electrons in the valence band can still be moved to the conduction band with the application of energy, usually thermal energy. There are more bands below the valence band, but they are not important to the understanding of semiconductor theory and will not be discussed.

The concept of energy bands is particularly important in classifying materials as conductors, semiconductors, and insulators. An electron can exist in either of two energy bands: the conduction band or the valence band. All that is necessary to move an electron from the valence band to the conduction band so it can be used for electric current, is enough energy to carry the electron through the forbidden band. The width of the forbidden band or the separation between the conduction and valence bands determines whether a substance is an insulator, semiconductor, or conductor. *Figure 4-3* uses energy level diagrams to show the difference between insulators, semiconductors, and conductors.

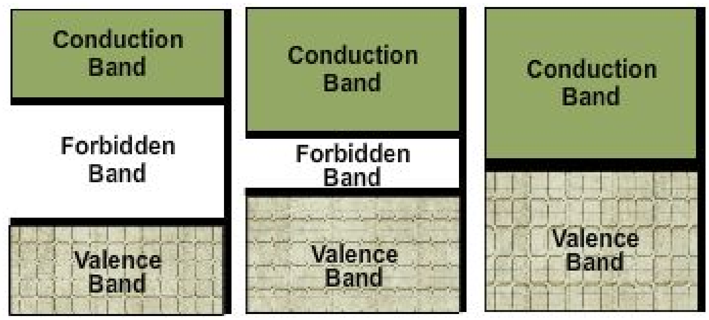

Figure 4-3 — Energy level diagram.

The energy diagram for the insulator shows the insulator with a very wide energy gap. The wider this gap, the greater the amount of energy required to move the electron from the valence band to the conduction band; therefore, an insulator requires a large amount of energy to obtain a small amount of current. The insulator insulates because of the wide forbidden band or energy gap.

The semiconductor, on the other hand, has a smaller forbidden band and requires less energy to move an electron from the valence band to the conduction band; therefore, for a certain amount of applied voltage, more current will flow in the semiconductor than in the insulator.

The last energy level diagram in *Figure 4-3* is that of a conductor. Notice that there is no forbidden band or energy gap and the valence and conduction bands overlap. With no energy gap, it takes a small amount of energy to move electrons into the conduction band; consequently, conductors pass electrons very easily.

1.4.2 Covalent Bonding

The chemical activity of an atom is determined by the number of electrons in its valence shell. When the valence shell is complete, the atom is stable and shows little tendency to combine with other atoms to form solids. Only atoms that possess eight valence electrons have a complete outer shell. These atoms are referred to as inert or inactive atoms. However, if the valence shell of an atom lacks the required number of electrons to complete the shell, then the activity of the atom increases.

Silicon and germanium, for example, are the most frequently used semiconductors. Both are quite similar in their structure and chemical behavior. Each has four electrons in the valence shell. Consider just silicon. Since it has fewer than the required number of eight electrons needed in the outer shell, its atoms will unite with other atoms until eight electrons are shared. This gives each atom a total of eight electrons in its valence shell: four of its own and four that it borrowed from the surrounding atoms. The sharing of valence electrons between two or more atoms produces a covalent bond between the atoms. It is this bond that holds the atoms together in an orderly structure called a crystal. A crystal is just another name for a solid whose atoms or molecules are arranged in a three-dimensional geometrical pattern, commonly referred to as a lattice. *Figure 4-4* shows a typical crystal structure. Each sphere represents the nucleus of an atom, and the arms that join the atoms and support the structure are the covalent bonds.

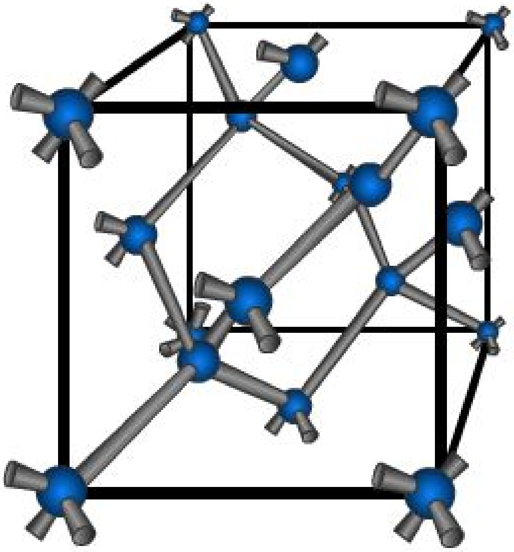

Figure 4-4 – A typical crystal structure.

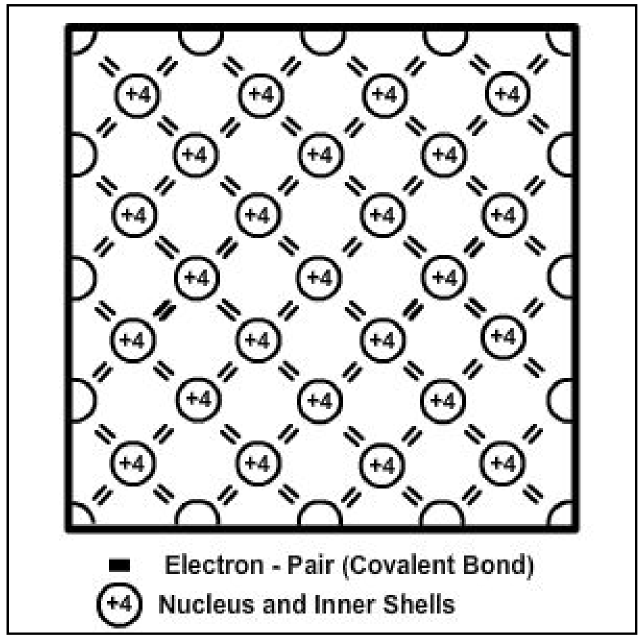

Figure 4-5 – Two-dimensional view of a silicon cubic lattice.

As a result of this sharing process, the valence electrons are held tightly together. This can best be illustrated by the two-dimensional view of the silicon lattice in *Figure 4-5.* The circles in the figure represent the nuclei of the atoms. The +4 in the circles is the net charge of the nucleus plus the inner shells (minus the valence shell). The shorter lines indicate valence electrons. Because every atom in this pattern is bonded to four other atoms, the electrons are not free to move within the crystal. As a result of this bonding, pure silicon and germanium are poor conductors of electricity. The reason they are not insulators but semiconductors is that with the proper application of heat or electrical pressure, electrons can be caused to break free of their bonds and move into the conduction band. Once in this band, they wander aimlessly through the crystal.

1.4.3 Conduction Process

As stated earlier, energy can be added to electrons by applying heat. When enough energy is absorbed by the valence electrons, it is possible for them to break some of their covalent bonds. Once the bonds are broken, the electrons move to the conduction band, where they are capable of supporting electric current. When a voltage is applied to a crystal containing these conduction band electrons, the electrons move through the crystal toward the applied voltage. This movement of electrons in a semiconductor is referred to as electron current flow.

There is still another type of current in a pure semiconductor. This current occurs when a covalent bond is broken and a vacancy is left in the atom by the missing valence electron. This vacancy is commonly referred to as a hole. The hole is considered to have a positive charge because its atom is deficient by one electron, which causes the protons to outnumber the electrons. As a result of this hole, a chain reaction begins when a nearby electron breaks its own covalent bond to fill the hole, leaving another hole. Then another electron breaks its bond to fill the previous hole, leaving still another hole. Each time an electron in this process fills a hole, it enters into a covalent bond. Even though an electron has moved from one covalent bond to another, the most important thing to remember is that the hole is also moving. Since this process of conduction resembles the movement of holes rather than electrons, it is termed hole flow (short for hole current flow or conduction by holes). Hole flow is very similar to electron flow except that the holes move toward a negative potential and in an opposite direction to that of the electron. Since hole flow results from the breaking of covalent bonds, which are at the valence band level, the electrons associated with this type of conduction contain only valence band energy and must remain in the valence band. However, the electrons associated with electron flow have conduction band energy and can, therefore, move throughout the crystal. A good analogy of hole flow is the movement of a hole through a tube filled with balls (*Figure 4-6*).

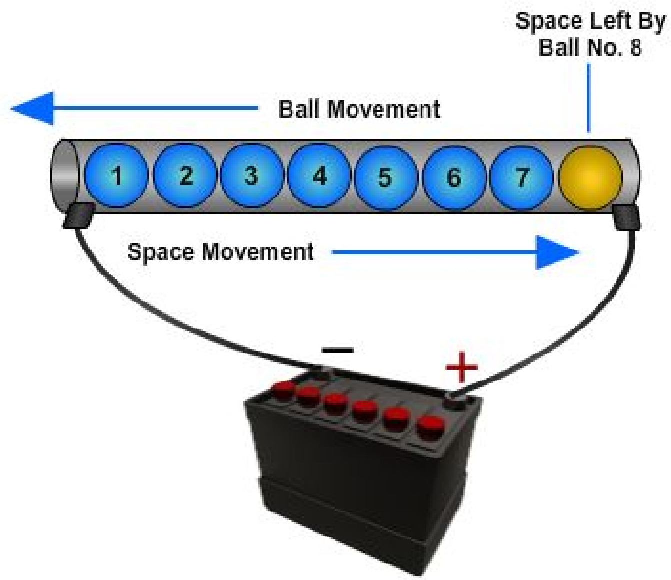

Figure 4-6 — Analogy of hole flow.

When ball number 1 is removed from the tube, a hole is left. This hole is then filled by ball number 2, which leaves still another hole. Ball number 3 then moves into the hole left by ball number 2. This causes still another hole to appear where ball 3 was. Notice the holes are moving to the right side of the tube. This action continues until all the balls have moved one space to the left, in which time the hole moved eight spaces to the right and came to rest at the right-hand end of the tube.

In the theory just described, two current carriers were created by the breaking of covalent bonds – the negative electron and the positive hole. These carriers are referred to as electron-hole pairs. Since the semiconductor being discussed contains no impurities, the number of holes in the electron-hole pairs is always equal to the number of conduction electrons. Another way of describing this condition where no impurities exist is by saying the semiconductor is ***intrinsic***. The term intrinsic is also used to distinguish the pure semiconductor with which you have been working from one containing impurities.

1.4.4 Doping Process

The pure semiconductor mentioned earlier is basically neutral. It contains no free electrons in its conduction bands. Even with the application of thermal energy, only a few covalent bonds are broken, yielding a relatively small current flow. A much more efficient method of increasing current flow in semiconductors is by adding very small amounts of selected additives to them, generally no more than a few parts per million. These additives are called impurities and the process of adding them to crystals is referred to as ***doping***. The purpose of semiconductor doping is to increase the number of free charges that can be moved by an external applied voltage. When an impurity increases the number of free electrons, the doped semiconductor is negative or N type, and the impurity that is added is known as an N-type impurity. However, an impurity that reduces the number of free electrons, causing more holes, creates a positive or P-type semiconductor, and the impurity that was added to it is known as a P-type impurity. Semiconductors that are doped in this manner – either with N or P-type impurities are referred to as ***extrinsic*** semiconductors.

1.4.4.1 N-Type Semiconductor

The N-type impurity loses its extra valence electron easily when added to a semiconductor material, and in so doing, increases the conductivity of the material by contributing a free electron. This type of impurity has 5 valence electrons and is called a ***pentavalent*** impurity. Arsenic, antimony, bismuth, and phosphorous are pentavalent impurities. Because these materials give or donate one electron to the doped material, they are also called donor impurities.

When a pentavalent (donor) impurity, such as arsenic, is added to germanium, it will form covalent bonds with the germanium atoms. *Figure 4-7* illustrates this by showing an arsenic atom (AS) in a germanium (GE) lattice structure. Notice the arsenic atom in the center of the lattice. It has 5 valence electrons in its outer shell but uses only 4 of them to form covalent bonds with the germanium atoms, leaving 1 electron relatively free in the crystal structure. Pure germanium may be converted into an N-type semiconductor by doping it with any donor impurity having 5 valence electrons in its outer shell. Since this type of semiconductor (N-type) has a surplus of electrons, the electrons are considered majority carriers, while the holes, being few in number, are the minority carriers.

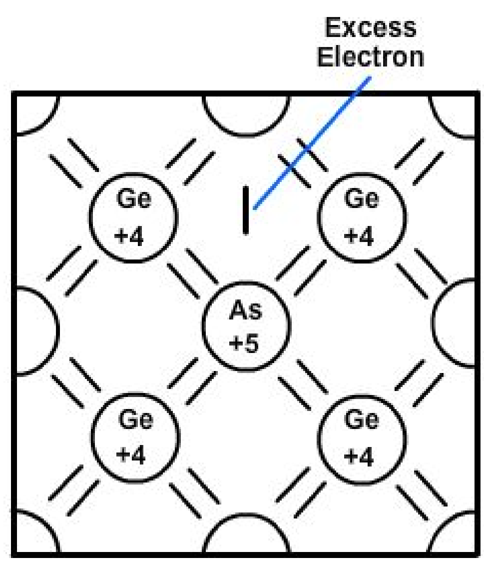

Figure 4-7 – Germanium crystal doped with arsenic.

1.4.4.2 P-Type Semiconductor

The second type of impurity, when added to a semiconductor material, tends to compensate for its deficiency of 1 valence electron by acquiring an electron from its neighbor. Impurities of this type have only 3 valence electrons and are called ***trivalent*** impurities. Aluminum, indium, gallium, and boron are trivalent impurities. Because these materials accept 1 electron from the doped material, they are also called acceptor impurities.

A trivalent (acceptor) impurity element can also be used to dope germanium. In this case, the impurity is 1 electron short of the required amount of electrons needed to establish covalent bonds with 4 neighboring atoms. Thus, in a single covalent bond, there will be only 1 electron instead of 2. This arrangement leaves a hole in that covalent bond. *Figure 4-8* illustrates this theory by showing what happens when germanium is doped with an indium (In) atom. Notice that the indium atom in the figure is 1 electron short of the required amount of electrons needed to form covalent bonds with 4 neighboring atoms and therefore creates a hole in the structure. Gallium and boron, which are also trivalent impurities, exhibit these same characteristics when added to germanium. The holes can only be present in this type of semiconductor when a trivalent impurity is used. Note that a hole carrier is not created by the removal of an electron from a neutral atom, but is created when a trivalent impurity enters into covalent bonds with a tetravalent (4 valence electrons) crystal structure. The holes in this type of semiconductor (P-type) are considered the majority carriers because they are present in the material in the greatest quantity. The electrons, on the other hand, are the minority carriers.

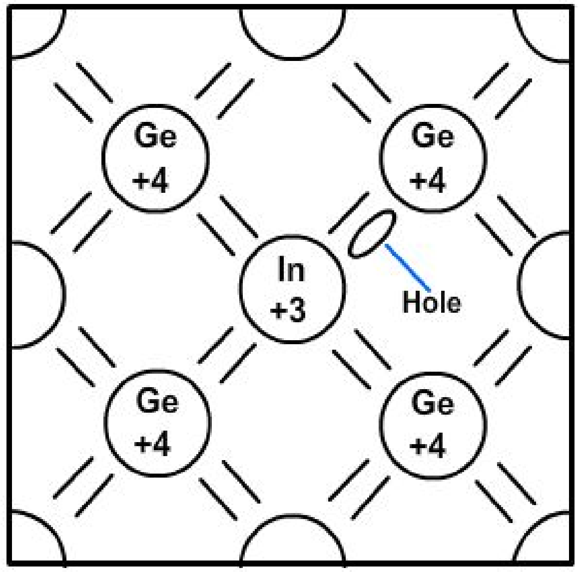

Figure 4-8 – Germanium crystal doped with indium.

2.0.0 SEMICONDUCTOR DIODE

If you join a section of N-type semiconductor material with a similar section of P-type semiconductor material, you obtain a device known as a PN junction. The area where the N and P regions meet is appropriately called the junction. The usual characteristics of this device make it extremely useful in electronics as a diode rectifier. The diode rectifier, or PN junction diode, performs the same function as its counterpart in electron tubes but in a different way. The diode is nothing more than a two-element semiconductor device that makes use of the rectifying properties of a PN junction to convert alternating current into direct current by permitting current flow in only one direction. The schematic symbol of a PN junction diode is shown in *Figure 4-9*. The vertical bar represents the cathode (N-type material) because it is the source of electrons and the arrow represents the anode (P-type material) because it is the destination of the electrons. The label “CR1” is

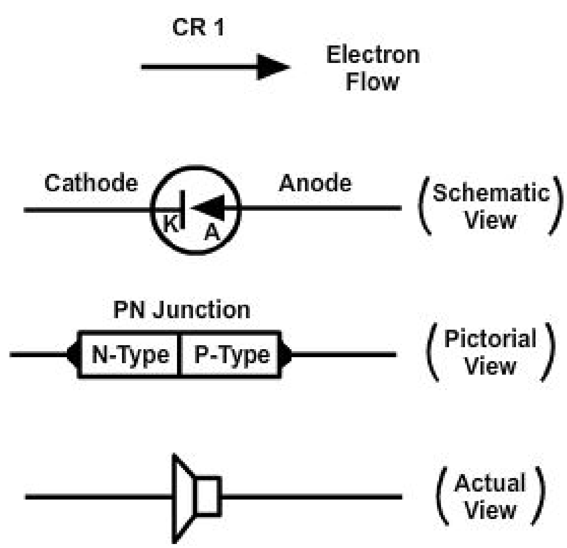

Figure 4-9 – The PN junction diode.

an alphanumerical code used to identify the diode. In this figure, you have only one diode so it is labeled CR1 (crystal rectifier number one). If there were four diodes shown in the diagram, the last diode would be labeled CR4. The heavy dark line shows electron flow. Notice it is against the arrow. For further clarification, a pictorial diagram of a PN junction and an actual semiconductor (one of many types) are also illustrated.

2.1.0 Construction

Merely pressing together a section of P-material and a section of N-material, however, is not sufficient to produce a rectifying junction. The semiconductor should be in one piece to form a proper PN junction, but divided into a P-type impurity region and an N-type impurity region. This can be done in various ways. One way is to mix P-type and N-type impurities into a single crystal during the manufacturing process. By so doing, a P-region is grown over part of a semiconductor's length and N-region is grown over the other part. This is called a grown junction and is illustrated in *Figure 4-10, View A*. Another way to produce a PN junction is to melt one type of impurity into a semiconductor of the opposite type impurity. For example, a pellet of acceptor impurity is placed on a wafer of N-type germanium and heated. Under controlled temperature conditions, the acceptor impurity fuses into the wafer to form a P-region within it (*Figure 4-10, View B*). This type of junction is known as an alloy or fused-alloy junction, and is one of the most commonly used junctions. In *Figure 4-11*, a point-contact type of construction is shown. It consists of a fine metal wire, called a cat whisker, that makes contact with a small area on the surface of an N-type semiconductor, as shown in *Figure 4-11, View A*. The PN union is formed in this process by momentarily applying a high-surge current to the wire and the N-type semiconductor. The heat generated by this current converts the material nearest to the point of contact to a P-type material (*Figure 4-11, View B)*.

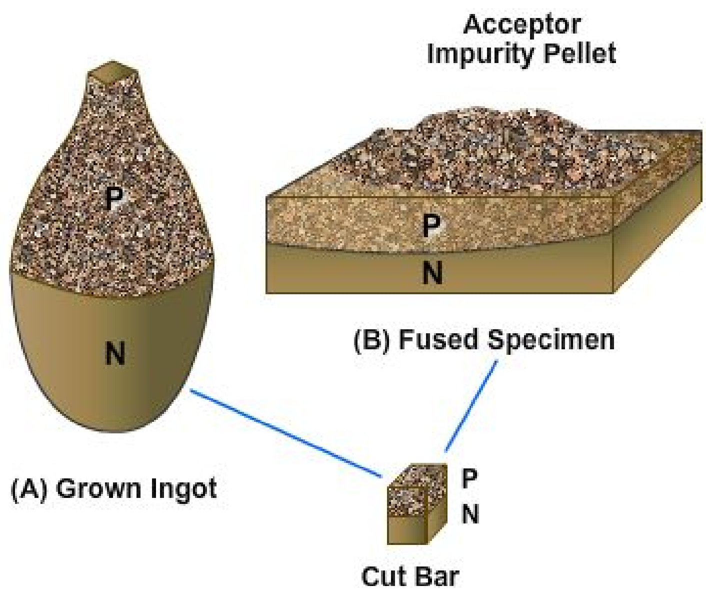

Figure 4-10 — Grown and fused PN junctions, from which bars are cut.

Still another process is to heat a section of semiconductor material to near melting and then diffuse impurity atoms into a surface layer. Regardless of the process, the objective is to have a perfect bond everywhere along the union (interface) between P- and N-materials. Proper contact along the union is important because, as we will see later, the union (junction or interface) is the rectifying agent in the diode.

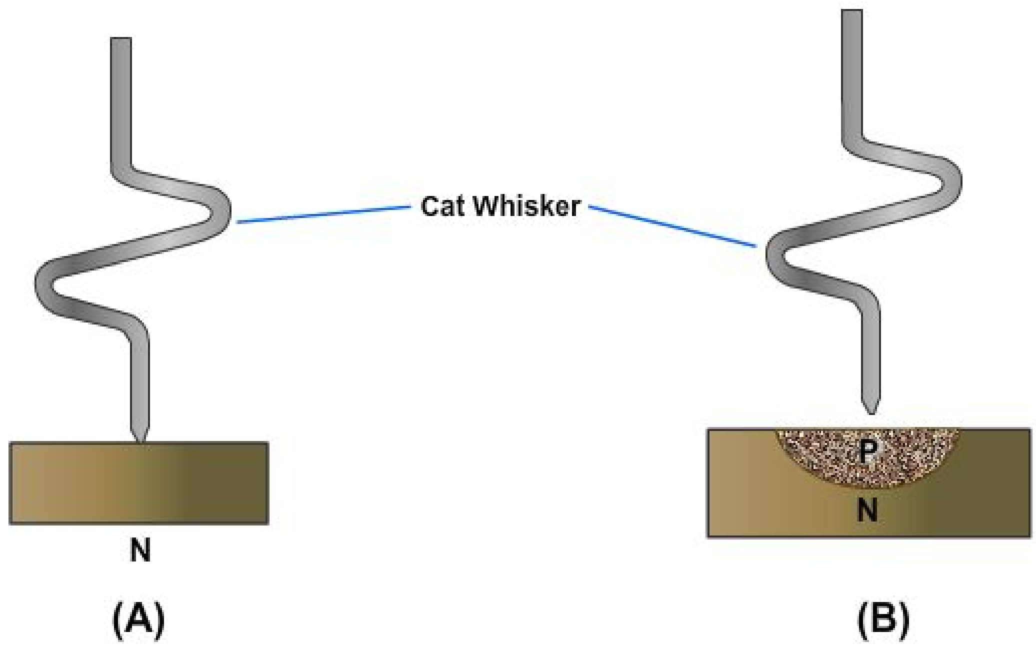

Figure 4-11 — Point-contact type of diode construction.

2.2.0 PN Junction Operation

Now that you are familiar with P-type and N-type materials, how these materials are joined together to form a diode, and the function of the diode, we will discuss the operation of the PN junction. Before you can understand how the PN junction works, you must first consider current flow in the materials that make up the junction and what happens initially within the junction when these two materials are joined together.

2.2.1 Current Flow in the N-Type Material

Conduction in the N-type semiconductor, or crystal, is similar to conduction in a copper wire. That is, with voltage applied across the material, electrons will move through the crystal just as current would flow in a copper wire. This is shown in *Figure 4-12*. The positive potential of the battery will attract the free electrons in the crystal. These electrons will leave the crystal and flow into the positive terminal of the battery. As an electron leaves the crystal, an electron from the negative terminal of the battery will enter the crystal, thus completing the current path; therefore, the majority current carriers in the N-type material (electrons) are repelled by the negative side of the battery and move through the crystal toward the positive side of the battery.

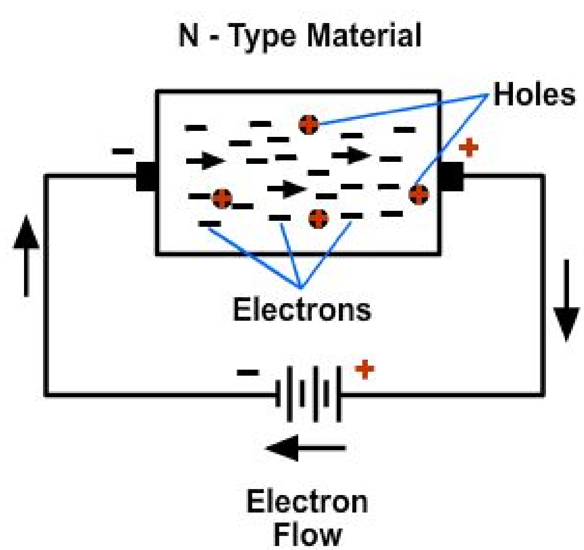

Figure 4-12 – Current flow in the N-type material.