CHAPTER 2

PRINCIPLES AND CONFIGURATIONS OF UNINTERRUPTIBLE POWER SUPPLY (UPS) SYSTEMS

2-1. Principles of static UPS systems

The basic static UPS system consists of a rectifier-charger, inverter, static switch, and battery as shown in figure 2-1. The rectifier receives the normal alternating current (ac) power supply, provides direct current (dc) power to the inverter, and charges the battery. The inverter converts the dc power to ac power to supply the intended loads. The dc power will normally be provided from the rectifier, and from the battery upon failure of the primary ac power source or the rectifier. The inverter will supply the loads under normal conditions. In the event of the failure of the inverter, the static switch transfers the load to an alternate ac source.

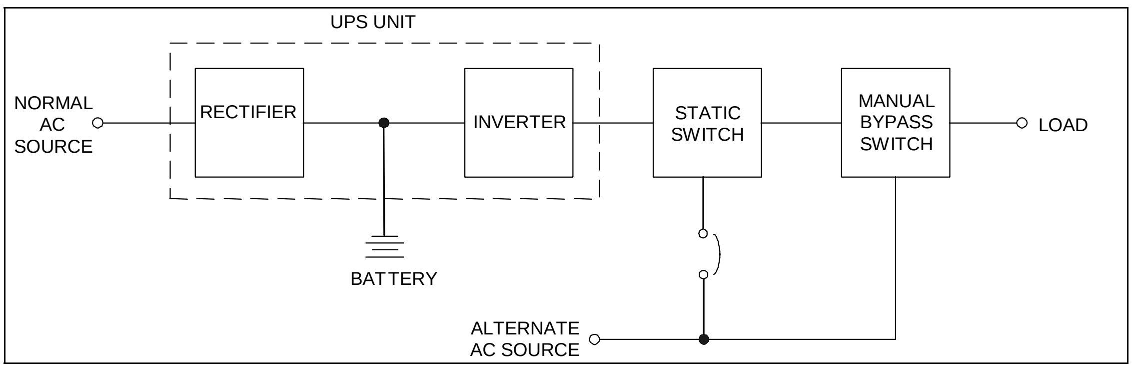

Figure 2-1. Basic static UPS system

a. Normal operation. During normal operation, the rectifier converts the ac input power to dc power with regulated voltage. The rectifier output is normally set at the battery float voltage to charge the battery while supplying dc power to the inverter. The rectifier output voltage is periodically set at the battery equalize voltage to maintain the battery capacity. The dc filter (inductor) is provided for smoothing out the rectifier output current to reduce the current ripple content. The battery acts as a capacitor and in conjunction with the filter, smoothes out the output voltage and reduces the dc voltage ripple content. The inverter converts the dc power to ac power with regulated voltage and frequency. An internal oscillator maintains the inverter frequency by controlling the timing of the silicon controlled rectifier (SCR) firing signals and matches the ac input frequency. The filters at the output transformer secondary are provided to filter out the harmonics in the inverter output. Tuned L-C filters are used - when required - to filter out the 5^{th} and 7^{th} harmonics while a capacitor is adequate for filtering out the higher order harmonics.

(1) Loss of normal power. Upon loss of ac power supply or upon failure of the rectifier, the battery maintains the dc supply to the inverter. The battery can maintain the dc supply to the inverter until the ac supply is restored or to the end of the battery duty cycle. Under this condition, the inverter continues to supply the connected loads without interruption. This mode of operation continues until the system is shut down if the battery reaches the discharged state before the charger output is restored. A system shutdown may be initiated manually or automatically by a dc undervoltage sensing device.

(2) Restoration of power. Upon restoration of the ac supply after extended outage while the battery has been discharged, the rectifier output voltage is set at the equalizing voltage to recharge the battery. This can be done manually or automatically. The charger will also supply the inverter while recharging the battery. At the end of the battery recharging time, the battery charger returns to the floating mode and the system returns to normal operation.

(3) Momentary loss of power. During momentary ac power interruptions or when the ac supply voltage sags below acceptable limits, the battery maintains the dc supply to the inverter. Under this condition, the inverter continues to supply the connected loads with regulated power without interruption.

b. Bypass mode. The static UPS systems may have three bypass switching arrangements: the UPS static switch (SS), the UPS static switch circuit breaker (SS-CB), and the maintenance circuit breaker.

(1) UPS static switch. When an UPS equipment problem occurs, the load is automatically transferred by the static switch bypass to an alternate power source to prevent power interruption to the loads. The static switch is also useful in clearing load faults downstream of the UPS. The static switch will transfer to the alternate power source on a setting of 110 to 125 percent of rated load. Without this feature, the inverter would be driven to current limit on a fault. The inverter would not supply sufficient current to trip the breaker and would continue to feed the fault causing a potential hazard. The transfer of the fault to the alternate power source by the static switch allows full short circuit current to pass through, thus tripping the circuit breaker. The static switch will then transfer back to the UPS for normal operation. Because the circuit cannot differentiate between an inrush and a fault current, it is common for the initial energization of a load to cause a temporary transfer to the alternate source power. When the inverter logic drops below a predetermined value, the bypass SCRs are gated-on by the static switch logic board and the UPS bypass line will supply the load. Retransfer to the UPS module can occur automatically when the logic senses that the UPS output problem has been eliminated. The logic system circuitry maintains the inverter output in synchronization with the UPS bypass power. The configuration of figure 2-2 does not provide the isolation capability of the figure 2-3 system. Reverse parallel SCRs can also be used as UPS power interrupters, that is, as an on-off switch to isolate a failed inverter occurring in a redundant UPS configuration.

(2) UPS static switch with circuit breaker (SS-CB). A hybrid UPS system uses an electromechanical switch in the inverter output with the reverse parallel SCRs provided only in the UPS bypass line. With an UPS output malfunction, the UPS bypass static switch will be turned on before the inverter output circuit breaker automatically opens. This type of hybrid switching will need only a short-term static switch current carrying (heat) rating and provides a normally reliable configuration if there are no problems with the circuit breaker closing in the static switch's 300 milliseconds (ms) rating. Figure 2-4 shows a SS-CB configuration where circuit breaker SS-CB closes after the UPS bypass static switch closes. The circuit breaker SS-CB provides a bypass for the static switch and therefore allows for the use of a short-term static switch current carrying (heat) rating. To prevent any damage to the static switch the circuit breaker must be able to close within the static switch's short time rating. There have been problems even though manufacturers quote a 450,000-hour mean-time-before-failure, so this system cannot be considered as reliable as a fully rated UPS bypass static switch. Hybrid switching is used as a method of combining the merits of both a static switch and a circuit breaker, that is, both speed and economy.

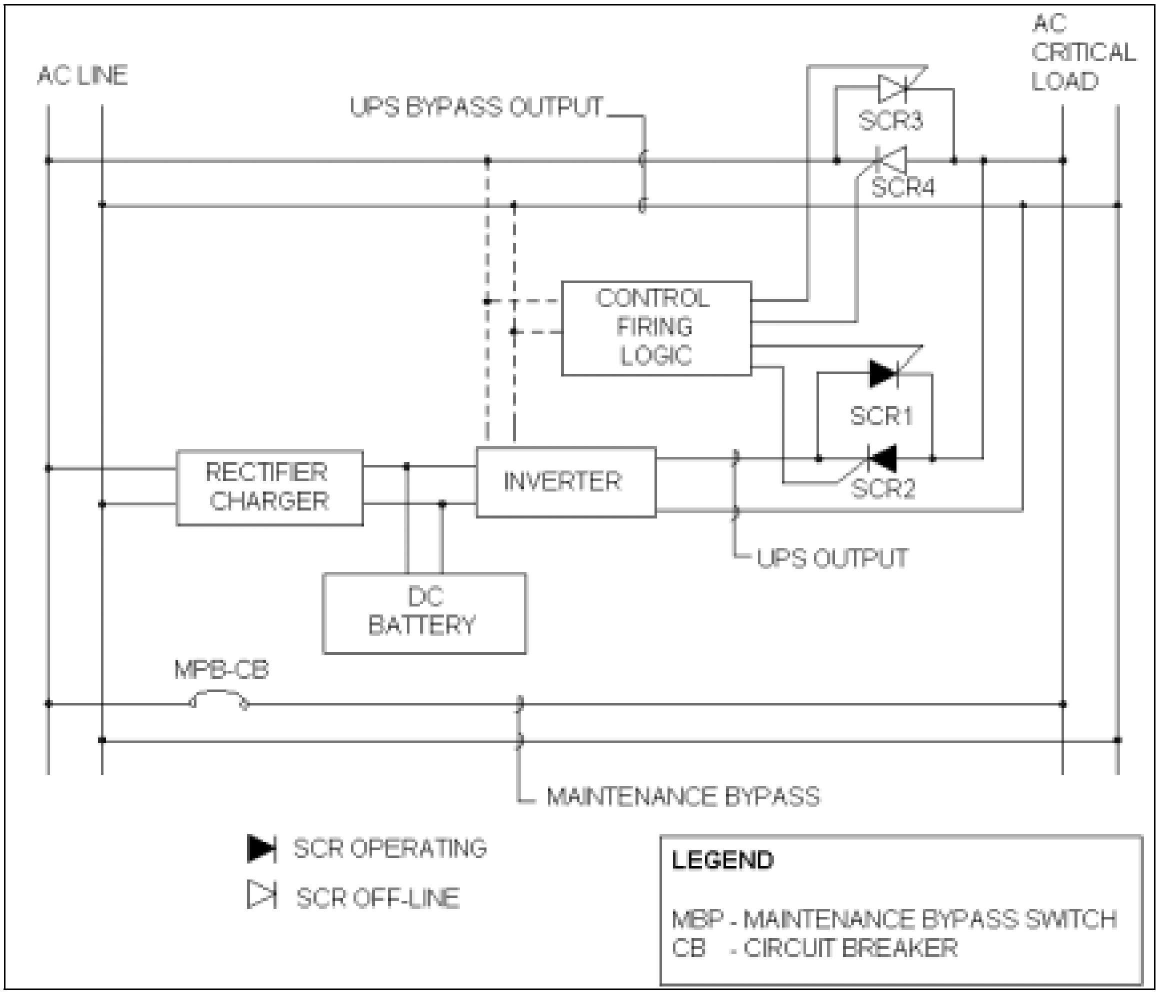

Figure 2-2. SCR static switching transfer

(3) *Maintenance bypass circuit breaker*. A bypass circuit breaker is provided to bypass the complete UPS system when maintenance of the UPS system is required. The UPS bypass line provides power continuity during UPS module malfunction periods. If the malfunction is such as to require UPS maintenance, then the load must be shifted to a maintenance bypass line, as shown on figure 2-5. An explanation as to why such a transfer is needed and the how such a transfer is configured is basic to comprehending UPS maintenance procedures.

(a) *Purpose of maintenance bypass switch*. It is unsafe to work on an energized UPS system. The complete system must be isolated from ac inputs, ac outputs, and the dc link whenever maintenance requires that the cabinet doors be opened and/or protective panels be removed. There are lethal voltages present in UPS cabinetry, resulting from the ac power applied to the converter or the dc power available from the battery. When energized, these circuits provide high voltage. Any portions of the system providing a redundant path, such as more than one UPS module or the static bypass, are tied together by the system logic so partial system shutdown for maintenance is not acceptable. Shutting off the battery for maintenance and running the UPS portion as a power conditioner should not be attempted since this also impacts on the system logic. After shutdown, all UPS systems should be load tested off-line. Approximately 85 percent of system failures occur after maintenance shutdowns which were not

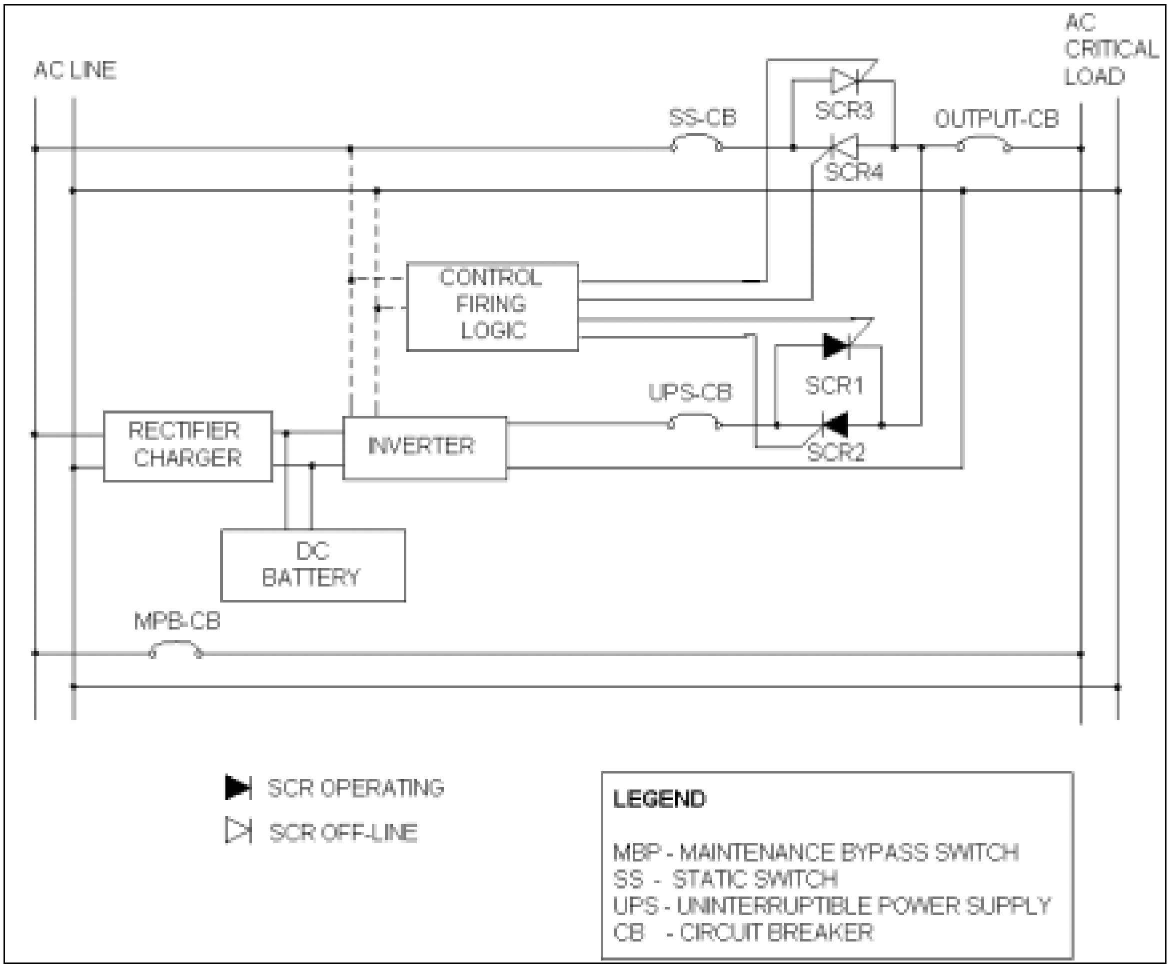

Figure 2-3. SCR switching transfer with UPS isolation

off-line load tested to assure proper operation. In order to shut down the complete UPS system, the load must be transferred to a line which is isolated electrically from the power and logic circuitry of the entire UPS installation.

(b) Operation of maintenance bypass switch. Close the UPS static bypass, which automatically opens the UPS module output circuit breaker (UPS-CB), allowing closing of the maintenance bypass circuit breaker (MBP-CB) before opening the UPS output circuit breaker (OUTPUT-CB). A closed transition has been made to an alternate supply for input to the critical load with no interruption. Now the UPS system as a whole can be de-energized for maintenance and off-line load testing. This is the basis for the interlocking requirements shown on figure 2-5.

c. Test mode. Off-line load testing of UPS systems after installation and scheduled maintenance is always necessary. A permanent load test tap or a circuit breaker and interlocking circuitry may be provided as part of the installation. Otherwise a temporary connection must be provided.

d. Characteristics and limitations. To avoid drawing heavy inrush currents from the power source upon initial energization, the battery charger is designed to assume the load gradually. Normally, the start-up current is limited to a maximum of 25 percent of the full load current. The

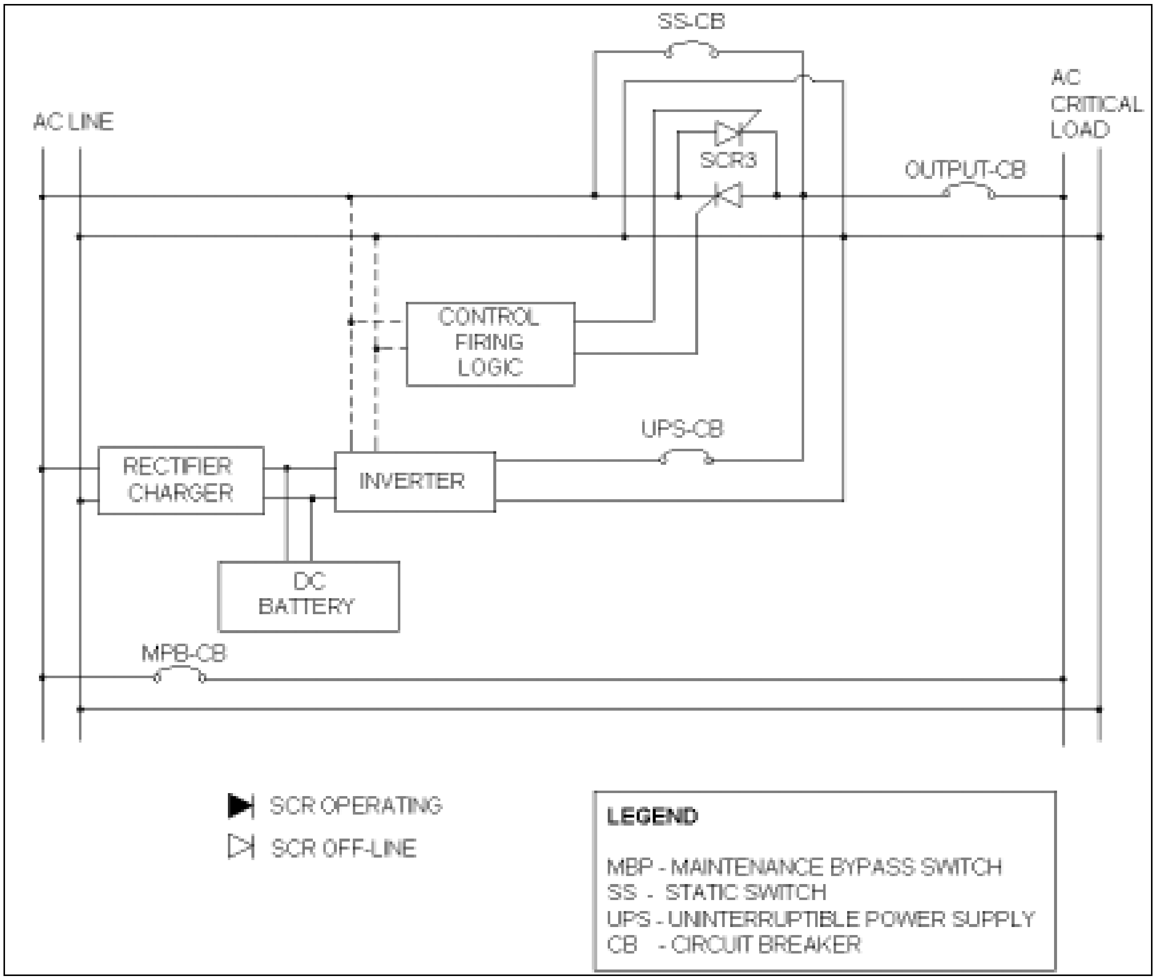

Figure 2-*4. Static switching transfer with circuit breaker*

current is then automatically increased gradually to the full load value in 15 to 30 seconds; this time is termed the "walk-in" time. For this reason all loads cannot be switched simultaneously if the battery has been fully discharged. Upon sudden application or removal of a load, the inverter's output voltage will drop or rise beyond the steady-state level. The voltage then returns to the steady-state condition after some short time which depends on the inverter's voltage control circuit design. These voltage variations are termed "transient voltage response" and the time required to return to steady-state conditions is termed the "recovery time." Generally, due to the absence of feedback regulating circuits in inverters with a ferroresonant transformer, the transient response is slower than that of inverters with pulse width or pulse width modulation (PWM) control techniques. SCRs have a limited overload capability. Also, heavy load currents may cause commutation failures. Therefore, the rectifier and inverter are designed to be self protected from overloads. The self protection circuit reduces the output voltage at currents exceeding the full load current. Normally, the inverter is designed to reduce the output voltage to zero at overloads of 115 to 135 percent rated load. The value of overcurrent at which the voltage is reduced to zero is termed "current limit." The inverter may reach the current limit condition when energizing a load with a high inrush current or during a load branch circuit fault.

e. Basic static UPS system without a dedicated battery. The basic system discussed above utilizes a dedicated battery as a backup source. The UPS system is provided with a controlled rectifier to supply the inverter and float/equalize charge the battery. In other applications, a large battery bank may be available for supplying the UPS system as well as other loads. In such applications, a separate battery charger is provided to supply the connected load and float/equalize the battery. In this case, the UPS system is provided with a rectifier that only supplies the inverter and is isolated from the battery and other loads by a blocking diode. The blocking diode allows current to flow from the battery to the inverter while blocking the flow of current from the rectifier to the battery. Upon failure of the ac input power, the battery supplies the inverter as discussed above.

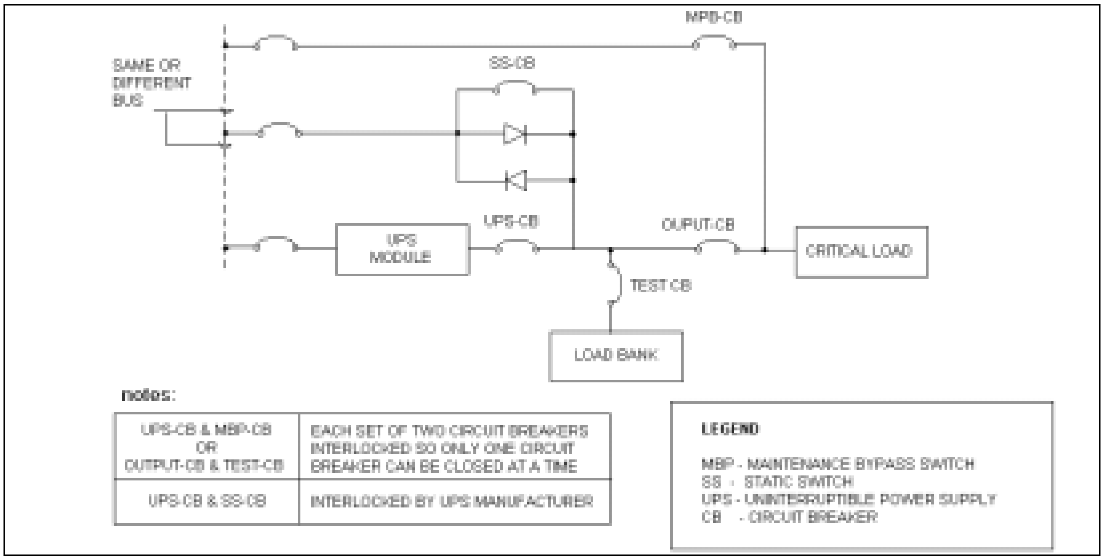

Figure 2-5. UPS maintenance bypass switching

f. Principles of rectifiers and inverters. UPS systems use power semiconductors in the construction of the rectifiers, inverters, and static switches. These solid-state devices control the direction of power flow and switch on and off very rapidly allowing for the conversion of power from ac to dc and dc to ac.

(1) Power semiconductor characteristics. A power semiconductor is an electronic device consisting of two layers of silicon wafer with different impurities forming a junction made by diffusion. The joining of these two wafers provides control of the current flow. Referring to figure 2-6, the power semiconductor permits the current to flow in one direction from the anode A to the cathode K, whenever the anode voltage is positive relative to the cathode. When the anode voltage is negative relative to the cathode, the power diode blocks the flow of current from the cathode to the anode. The power semiconductors may be either SCR or transistors. The types of transistors are bipolar transistors, field effect transistors (FET), and insulated gate bipolar transistors (IGBT). The devices most commonly used are the SCRs and the IGBTs. The IGBTs are relatively new and have been gaining in popularity. The IGBTs are significantly more efficient and easier to control than the other power semiconductors. The use of IGBTs has allowed for static UPS as large as 750 kVA without paralleling units.

(2) Single-phase SCR characteristics. An SCR allows for forward flow of current through the device similar to a diode. The SCR differs from a diode in that the SCR will not conduct until a current pulse is received at the gate. Once the SCR is conducting, it will only turn off with the

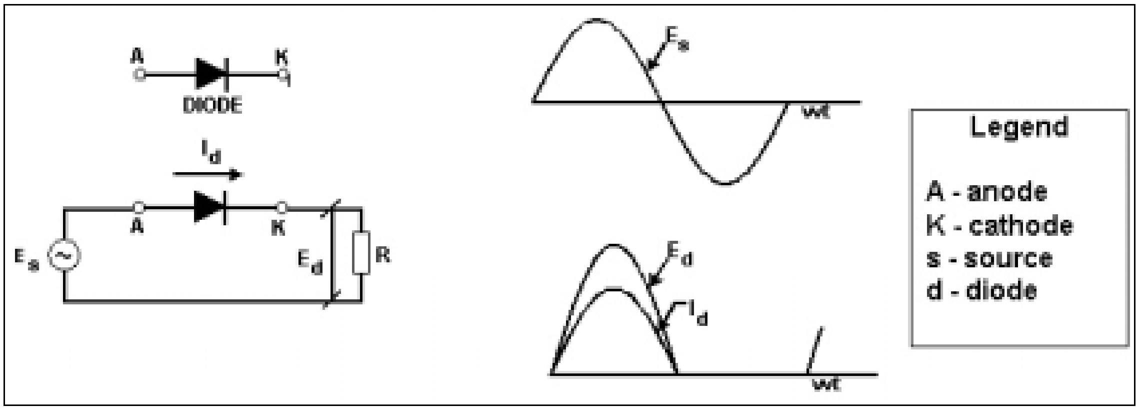

Figure 2-6. Half-wave diode rectifier with resistive load

current falling to zero or through a reverse current being applied. Referring to figure 2-7, the anode voltage is positive relative to the cathode between wt = o and wt = α; the SCR begins conducting when a firing pulse is applied at wt = α. Here, α is called the firing angle. Also, the SCR blocks at wt > π when the anode voltage becomes negative relative to the cathode. The SCR does not conduct again until a firing pulse is reapplied at wt = 2π + α. While turning on the SCR is very efficient, the SCRs require a commutation circuit to turn it off. It is necessary to be able to turn off the device for use in the inverter to generate the ac wave. The turn-off time is slow in comparison to the transistors which are not latching devices. The other drawbacks to the commutation circuit are that it adds more equipment to the circuit, adds audible noise to the unit, and consumes power.

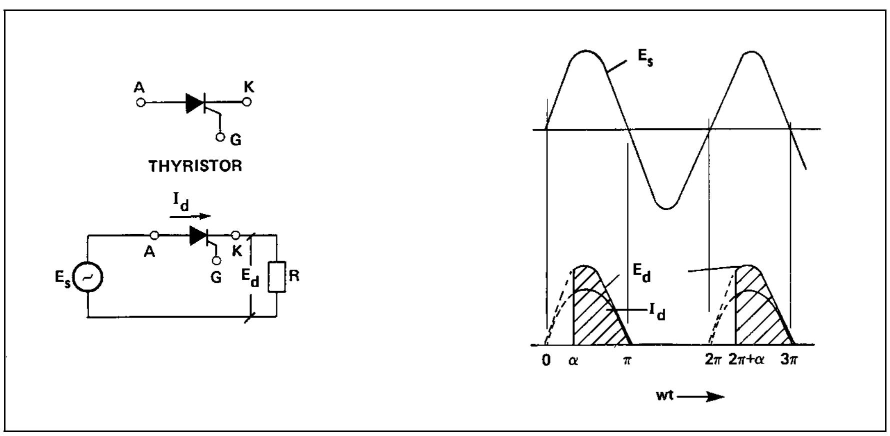

Figure 2-7. Half-wave SCR rectifier with resistive load

(3) Bipolar transistors. Bipolar transistors permit current to flow through the circuit when current is applied to the base. The flow of the power through the device is proportional to the current applied to the base. Unlike SCRs, transistors are not latching. Upon removing the current from the base, the circuit will be turned off. This allows for much quicker switching time than the SCRs. However, bipolar transistors experience high saturation losses during power conduction which requires drive circuits to minimize switching losses.

(4) FET. FETs are turned on and off by applying voltage to the gate. This is more efficient than applying current to the base as done with the bipolar transistors. The FETs experience saturation losses and require drive circuits to minimize the switching losses.

Moreover, the high resistance characteristics of the power conducting portion make this device inefficient and undesirable for large applications.

(5) IGBT. The IGBT combines the desirable characteristics of the bipolar transistor and the FET. Voltage is applied to the base to turn the device on and off and the collector/emitter has low resistance. IGBTs have a greater tolerance to temperature fluctuations than the FETs. The IGBTs have the drawback of saturation losses and switching losses like all of the other transistors. These must be taken into consideration in the designing of the UPS. Overall, the IGBT is more efficient and easier to control than the other power semiconductors.

g. Rectification. Rectification is the conversion of ac power to dc power. Rectification is accomplished by using unidirectional devices such as SCRs or IGBTs. Rectifiers can be built to convert single-phase or three-phase ac power to controlled or uncontrolled dc power. In a controlled rectifier, the output dc voltage can be continuously maintained at any desired level whereas in an uncontrolled rectifier the output dc voltage (at no load) is a fixed ratio of the input ac voltage. Moreover, the output dc voltage of an uncontrolled rectifier varies with the load level due to voltage drops in the various circuit elements. Generally, single-phase rectifiers may be used in ratings up to 5 kilowatt (kW) whereas three-phase rectifiers are used in higher ratings. When controlled dc voltage is required, SCRs are normally used.

(1) Single-phase uncontrolled rectifiers. The two most common configurations of single-phase uncontrolled rectifiers are the center-tap full wave rectifier shown in figure 2-8 and the single-phase bridge rectifier shown in figure 2-9. In the center-tap configuration, each diode conducts every half cycle when the anode voltage is positive relative to the cathode. In the bridge configuration a pair of diodes conducts every half cycle when their anode voltage is positive relative to the cathode. Comparison of the output voltage (E_d) and current wave shapes of the two configurations indicates that they are identical. However, a major difference between the two configurations is that for the same kW output, the center-tap configuration requires a transformer with a higher kVA than the bridge configuration and is more costly. For this and other reasons, the center-tap configuration is used mainly in ratings of less than one kW. Examining the output voltage wave shape for the two configurations indicates that it contains two pulses every cycle. This causes the output voltage, which is the average of these two pulses, to have a high ripple content. Also, comparison of the output current (I_d) wave shape for resistive and inductive loads indicates that with an inductive load, the output current is essentially constant throughout the cycle. Therefore, connecting a large inductor in series with the rectifier output smoothes the output current and minimizes the current ripples.

(2) Three-phase uncontrolled rectifiers. There are numerous possible configurations of three-phase rectifiers. However, the basic building blocks of these configurations are the three-phase single-way and the three-phase bridge rectifier configurations shown in figures 2-10 and 2-11 respectively. Comparison of the output voltage and output current wave shapes indicates that the bridge rectifier output wave shape contains six pulses while the wave shape for the single-way rectifier contains three pulses. This makes the ripple content of the bridge rectifier output less than that of the single-way rectifier. Another important difference is that the required transformer kVA in the single-way configuration is approximately 1.5 times that in the bridge configuration for the same kW output due to the low power factor of the single-way configuration. Normally three-phase rectifiers are used in ratings higher than 5 kW although it may also be used in lower ratings. The bridge rectifier configuration is commonly used in high power applications while the single-way configuration is mostly used in lower ratings. Generally, the selection of one configuration or another is up to the equipment designer and is based on cost considerations.

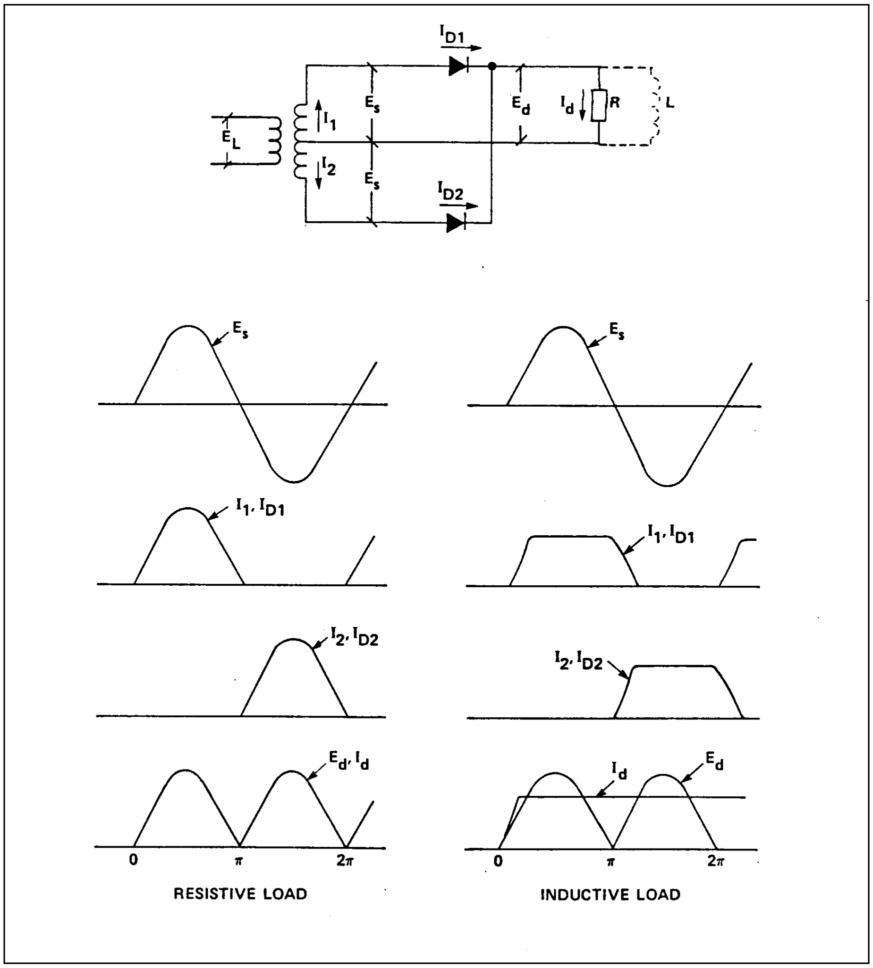

Figure 2-8. Center-tap full-wave uncontrolled rectifier

(3) Controlled rectifiers. In applications where a continuously adjustable dc voltage is desired, controlled rectifiers are used. Controlled rectifiers like the uncontrolled rectifiers can be single-phase or three-phase. The controlled rectifier configurations are identical to the uncontrolled rectifiers, however, in order to control the output dc voltage, SCRs are used in place of the power diodes. The output dc voltage can be controlled at any desired level by changing the firing angle α as discussed in paragraph 2-1f(2). Control by changing the firing angle α is termed “phase control." The voltage is controlled by a feedback loop which senses the output voltage and adjusts the SCRs firing angles to maintain the output at the desired level. The configurations of single-phase and three-phase controlled bridge rectifiers and their wave forms are shown in figures 2-12 and 2-13 respectively. The output dc voltage of rectifiers with resistive-inductive or non-linear loads and the effect of the firing angle α can be determined by circuit analysis techniques for each specific load. The effect of the firing angle α on the magnitude of the output dc voltage is as follows.

(a) Single-phase bridge rectifier with a resistive load. The following equation models the voltage output of the single-phase bridge rectifier with a resistive load.

$$E_{do}(\alpha) = E_{do}\,\frac{(1+\cos\alpha)}{2}$$

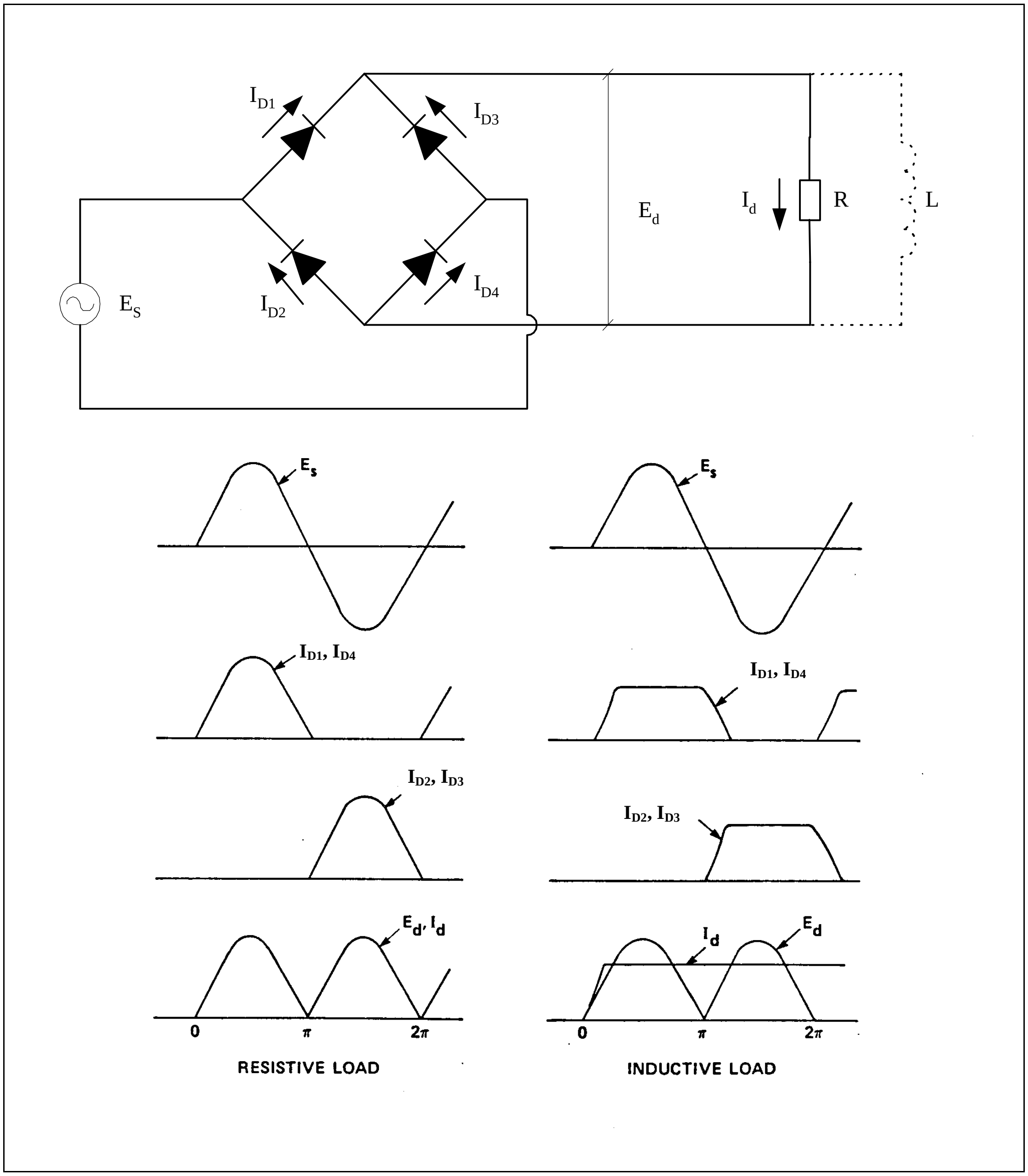

Figure 2-9. Full-wave bridge uncontrolled rectifier

(b) Single-phase bridge rectifier with an inductive load. The following equation models the voltage output of the single-phase bridge rectifier with an inductive load.

$$E_{do}(\alpha) = E_{do} \cos\alpha$$

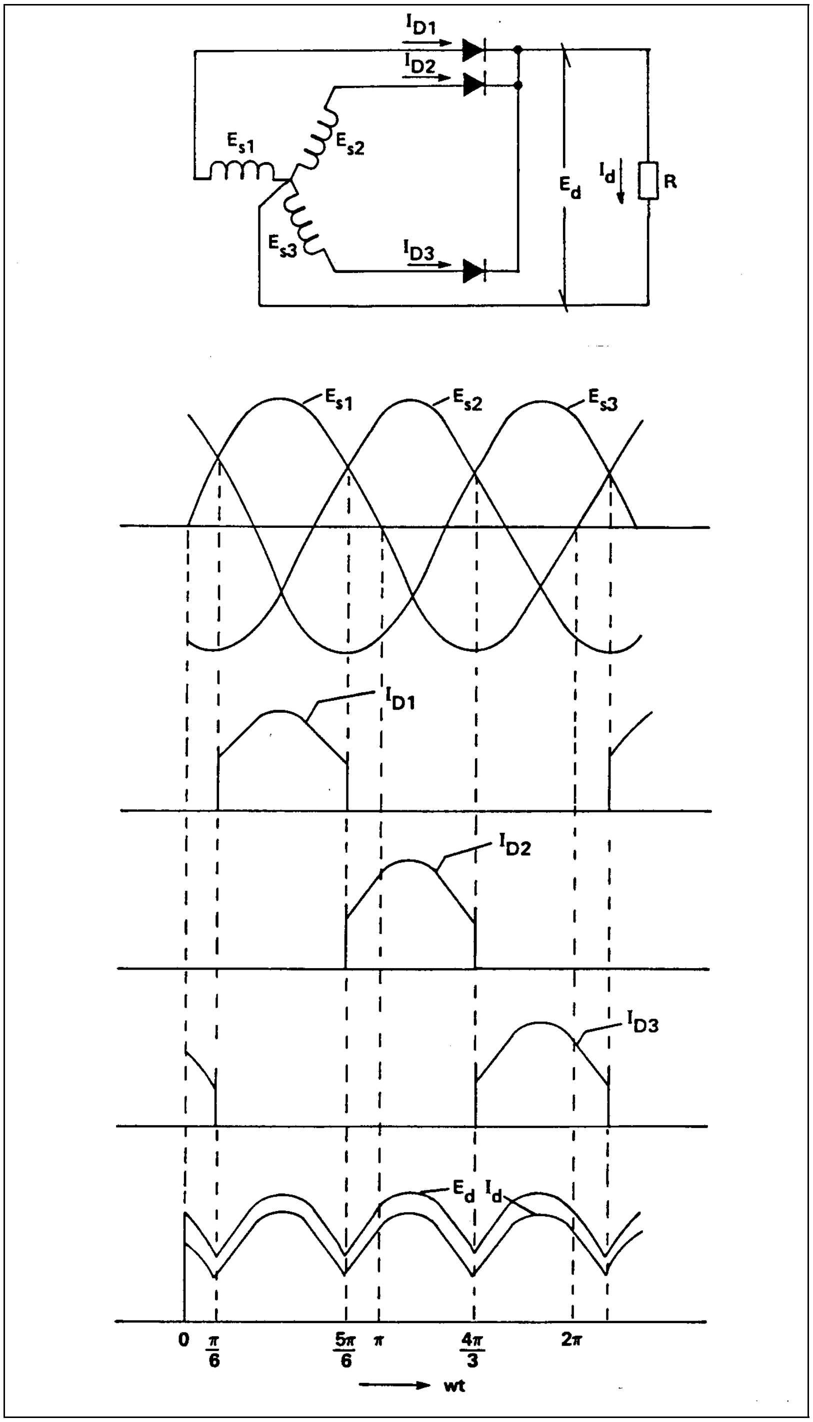

Figure 2-10. Three-phase uncontrolled single-way rectifier

(c) Three-phase bridge rectifier with a resistive load. The following equation models the voltage output of the three-phase bridge rectifier with a resistive load.

$$E_{do}\,(\alpha) = E_{do}\;1 - \sin\,(\alpha - \frac{\Pi}{6})$$

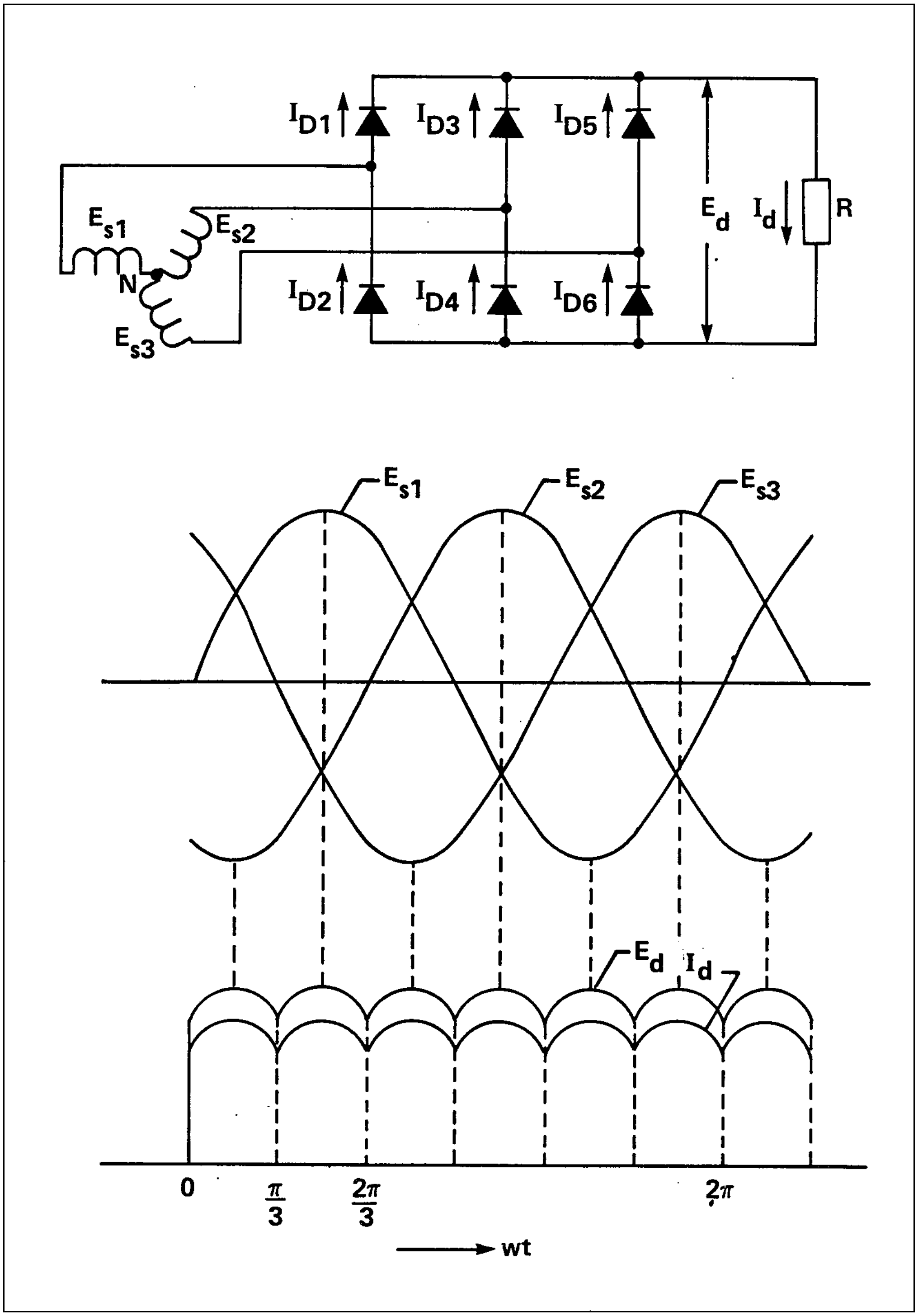

Figure 2-11. Three-phase uncontrolled bridge rectifier

(d) Three-phase bridge rectifier with an inductive load. The following equation models the voltage output of the three-phase bridge rectifier with an inductive load.

$$E_{do}(\alpha) = E_{do}\cos\alpha$$

where: E_{do} = average dc voltage at no load without phase control (neglecting the voltage drop in the circuit elements)

$E_{do}(\alpha)$ = average dc voltage at no load with phase control at firing angle α (neglecting the voltage drop in the circuit elements).

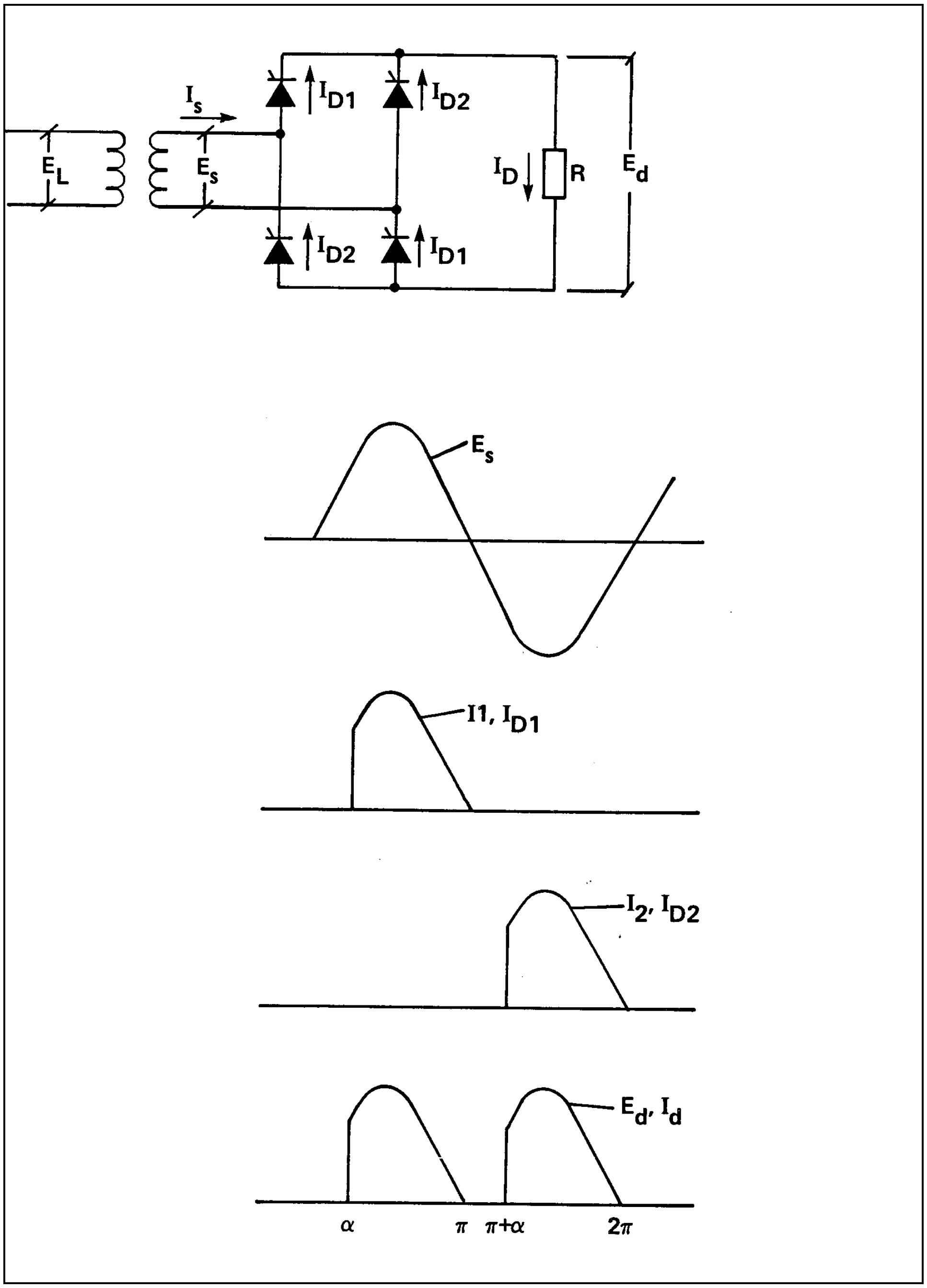

Figure 2-12. Single-phase controlled bridge rectifier

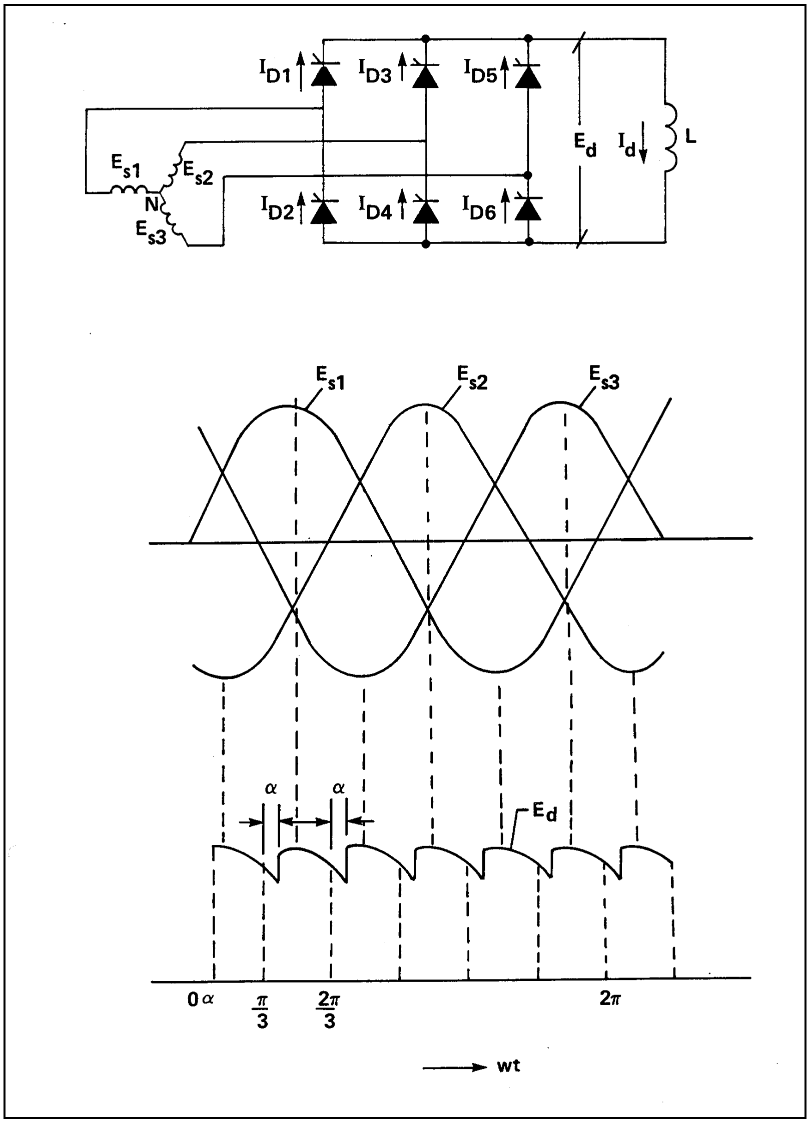

Figure 2-13. Three-phase controlled bridge rectifier

h. Inversion. Inversion is the conversion of dc power to ac power. Inversion can be accomplished using SCRs or IGBTs. In high power applications, IGBTs have been used. Inverters for static UPS systems can be single-phase or three-phase. Single-phase inverters are used in ratings up to approximately 75 kVA; at higher ratings three-phase inverters are used.

(1) Inverter principles. The basic elements of a single-phase inverter are shown in figure 2-14. When SCRs 1 and 4 are turned on while SCRs 2 and 3 are off, a dc voltage appears across the load with the polarity shown in figure 2-14a. After some time interval, if SCRs 1 and 4 are turned off and SCRs 2 and 3 are turned on, a dc voltage appears across the load with opposite polarity as shown in figure 2-14b. If SCRs 2 and 3 are allowed to conduct for the same time interval as SCRs 1 and 4 and then turned off while SCRs 1 and 4 are turned on and the process is

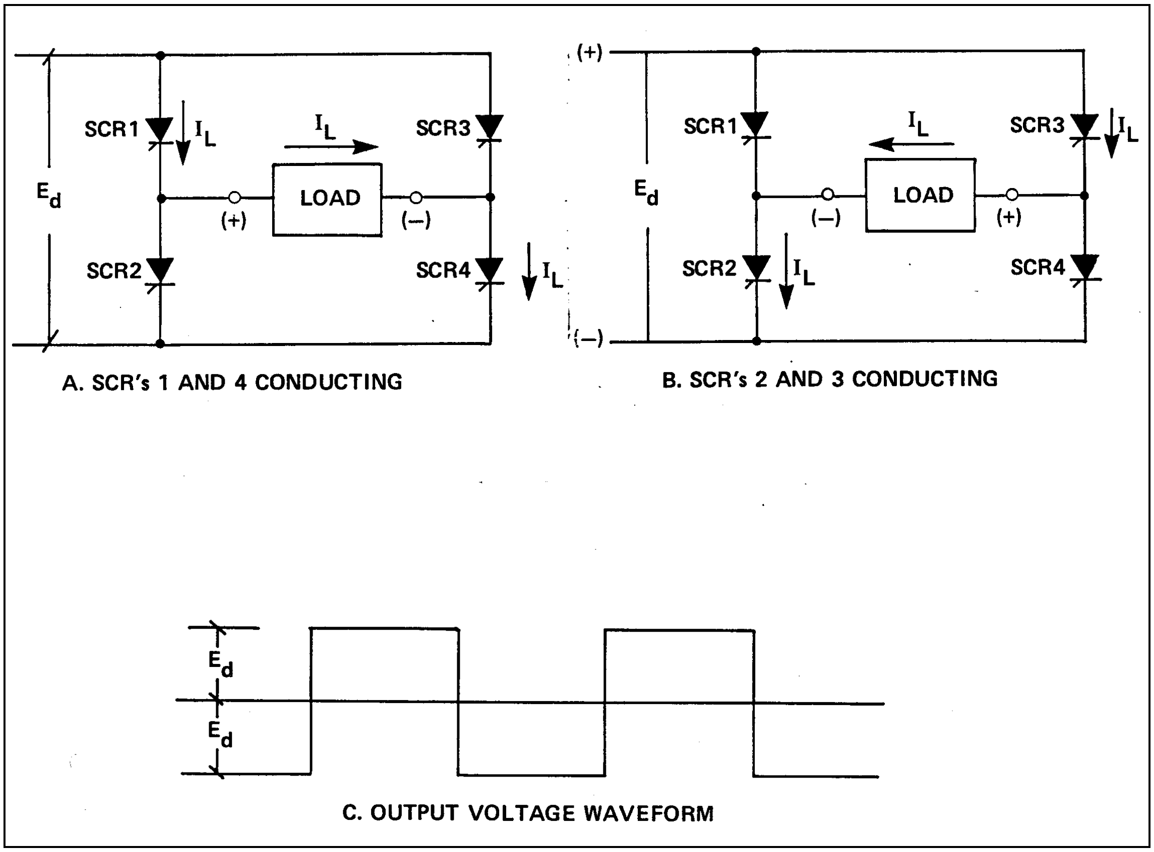

Figure 2-14. Simple single-phase inverter

repeated, an alternating voltage will appear across the load. The wave form of this alternating voltage is as shown in figure 2-14c. Two points must be taken into consideration to make the simple circuit in figure 2-14 of practical importance. As discussed before, once a SCR is turned on it remains conducting until the current drops to nearly zero. In the circuit shown in figure 2-14, once the SCR is turned on, load current flows with magnitude larger than zero. Therefore, some external means are required to cause the current to drop to near zero in order to turn off the SCR. Such means is called a commutating circuit. Generally, all inverters with SCRs require commutation means and normally charged capacitors are used to effect the commutation process. However, when gate turn off (GTO) SCRs or power transistors are used, no commutation circuits are required. GTO SCRs and power transistors can be turned off by gate pulses supplied by low power gating circuits. Commutation circuits are relatively complex and their principles of operation are beyond the scope of this manual. The second point is that in the circuit shown, the load is directly connected to the dc source through the SCRs. This subjects the load to transients generated within the dc system. For this reason, the load is normally isolated from the dc source through the use of an output transformer. Also, the inverter output wave shape is a square wave. This wave shape is not suitable for supplying power sensitive equipment. Therefore, some means are required to condition the inverter output to a sinusoidal waveform.

(2) Inverter voltage control. The common methods of inverter output voltage control are pulse width control, PWM, and use of a ferroresonant transformer. Any of these methods may be used for output voltage control. In some designs a combination of pulse width control and modulation is used. However, a ferroresonant transformer is never used in combination with either of the other two methods. The pulse width control technique has become less common

than the PWM technique and the use of ferroresonant transformers. Also, some manufacturers advocate the use of PWM while others favor the use of ferroresonant transformers. Although each method may have some advantages over the others, the voltage control method is normally not specified when specifying UPS systems. Either type may be used provided it meets the performance requirements.

(a) Pulse width control. To illustrate this technique, the circuit in figure 2-14 is redrawn in figure 2-15. Referring to this figure, when each of the two SCR pairs (1, 4 and 2, 3) is gated for a time interval equal to a half cycle without the two pairs conducting simultaneously, the output voltage waveform is as in figure 2-15b. If the gating of SCR pair 2, 3 is retarded by a

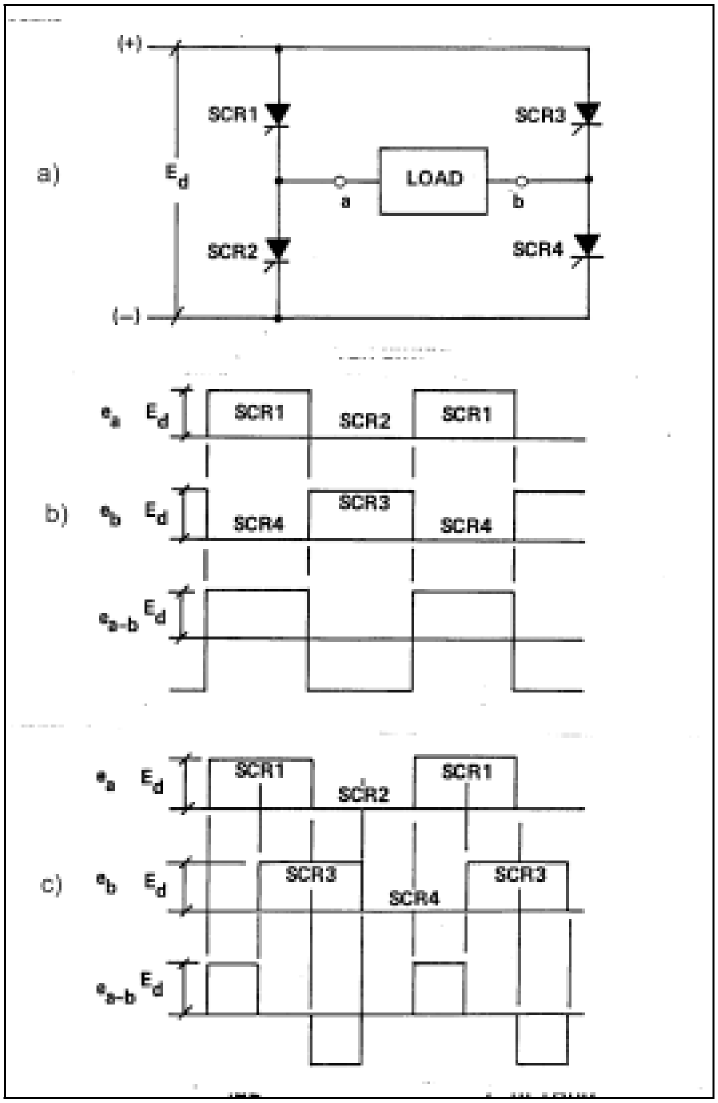

Figure 2-15. Voltage control using pulse width control

quarter of a cycle, the output voltage waveform is as in figure 2-15c. Therefore, the inverter output voltage can be continuously adjusted by retarding the firing signal of one pair of SCRs with respect to the other. The magnitude of the fundamental component of the output voltage depends on the pulse width and is higher for a wider pulse. The maximum output voltage is obtained with no retard; zero voltage is obtained when the firing signal is retarded by a half cycle. The voltage control is accomplished by a feedback control loop which senses the output voltage and adjusts the SCRs' firing angles to increase or reduce the output voltage level. With the pulse width control technique, the output voltage harmonic content is high and a harmonic filtering means is required.

(b) PWM. In this technique, the inverter SCR pairs are switched on and off many times every half cycle to provide a train of pulses of constant amplitude and different widths. The output voltage is synthesized from this train of pulses as shown in figure 2-16. The output voltage level can be controlled by varying the width of the pulses. By this technique the output voltage wave shape can be made to closely approximate a sine wave. Also, it is feasible to eliminate all harmonics by the use of this technique. This eliminates the use of output filters. Inverters using this technique have lower impedance and faster transient response. The control is accomplished by feedback control as in the pulse width control technique.

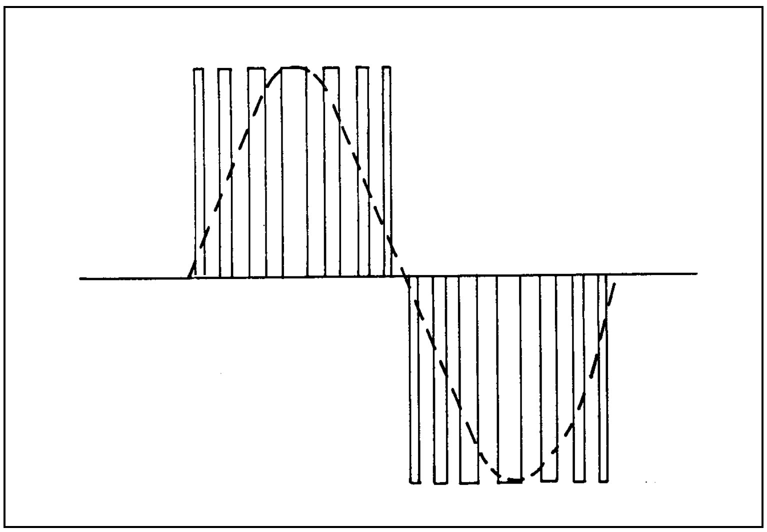

Figure 2-16. Pulse width modulation (PWM)

(c) Use of a ferroresonant transformer. A ferroresonant transformer connected across the inverter's output can be used to regulate the output voltage and reduce its harmonic content. The ferroresonant transformer is basically a two-winding transformer with an additional small secondary compensating winding and a series low pass filter connected across part of the main secondary winding as shown in figure 2-17. The filter presents a low impedance to the lower order harmonics and reduces their amplitude in the output to a low acceptable value. The compensating winding voltage is added to the secondary output voltage 180° out-of-phase thus maintaining the output voltage within a narrow regulation band. However, with the use of a ferroresonant transformer, the output voltage is not continuously adjustable as in the previous techniques.

(3) Three-phase inverters. Three-phase inverters are commonly made up of three single-phase inverters connected to the same dc supply, as shown in figure 2-18. The secondaries of the three single-phase inverter output transformers are connected in wye configuration. To generate a three-phase output, the firing signals for phase B inverter SCRs are delayed 120° from those of phase A inverter. Similarly the firing signals for phase C inverter SCRs are delayed 120° from

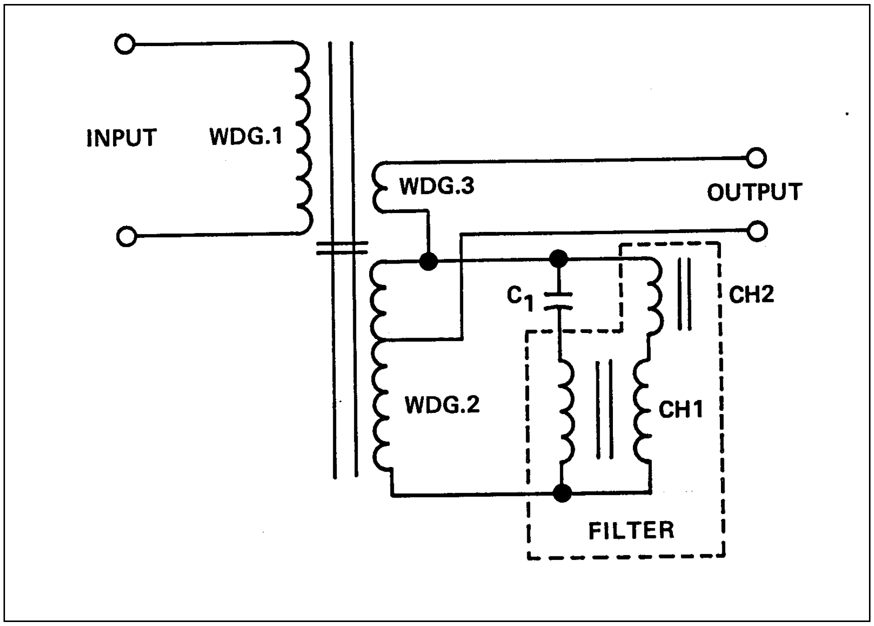

Figure 2 -17. Ferroresonant transformer

those of phase B inverter. The resulting phase-to-neutral voltages for 180° pulses and the line-to-line secondary voltages are shown in figure 2-18, where:

$$E_{A-B} = E_{A-N} - E_{B-N}$$
$$E_{B-C} = E_{B-N} - E_{C-N}$$
$$E_{C-A} = E_{C-N} - E_{A-N}$$

In this case as with the single-phase inverter, the output wave shape is a square wave and means for conditioning the output to a sinusoidal waveform is required. The three-phase inverter output voltage control can be accomplished by the same techniques used for single-phase inverters. However, the use of ferroresonant transformers is not feasible in many three-phase applications. This is due to the fact that a slight load current unbalance can cause substantial phase shifts in the ferroresonant transformers output voltages. With substantial voltage phase shift, the three line to neutral voltages may have the same magnitude but the line-to-line voltages may be extremely unbalanced. However, PWM technique can also be used as in the case of single-phase inverters.

i. Static transfer switch. A static transfer switch, like an electromechanical transfer switch, is used to transfer loads from one power source to another, manually or automatically. However, unlike an electromechanical transfer switch, the static transfer switch total transfer time is in the order of one fourth of a cycle which will provide power to the loads without interruption.

(1) Design. As shown in figure 2-19, a single-phase static transfer switch consists of two pairs of SCRs. Each pair is connected in antiparallel arrangement, i.e., the anode of one SCR is connected to the cathode of the other. By this arrangement, each SCR in the pair can be made to conduct every other half cycle. One pair of SCRs is connected between the load and each of the two sources. The logic circuit applies firing signals to either pair of SCRs.

(a) Operation. Applying a firing signal to source No. 1 SCRs causes them to conduct and power flows from source No. 1 through the SCRs to the load. To transfer the load to source

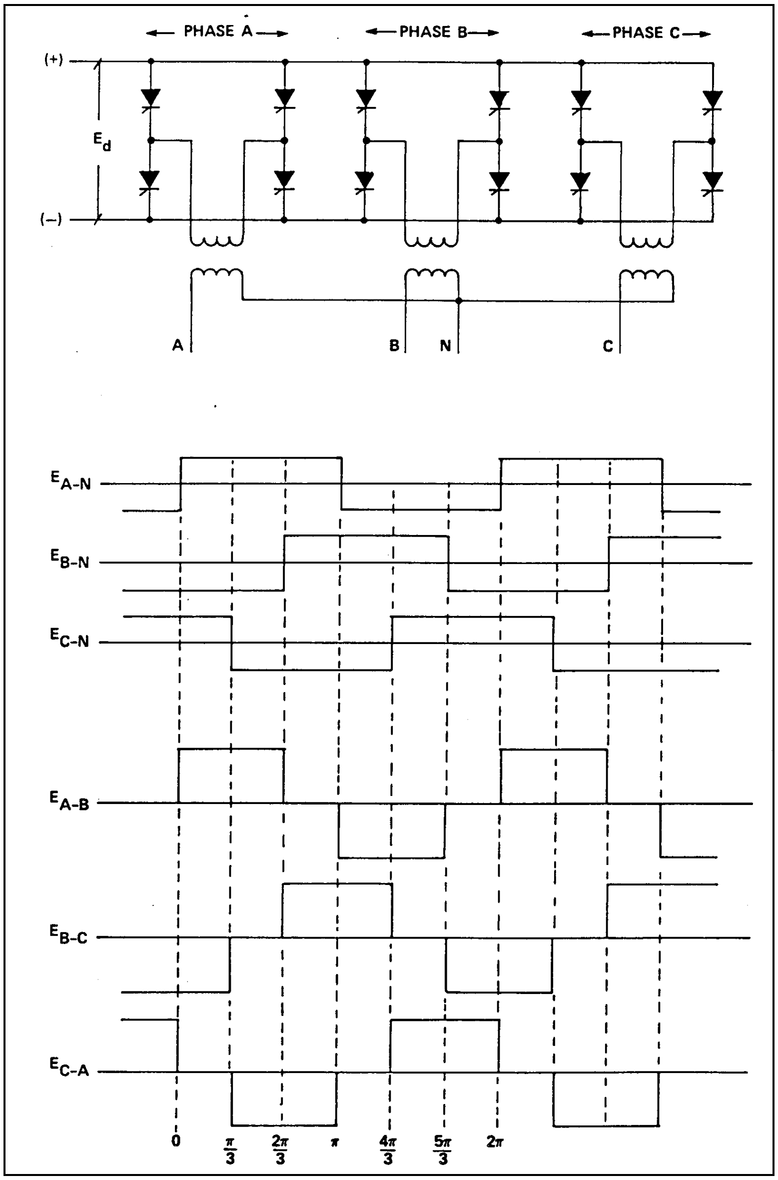

Figure 2-18. Three-phase inverter

No. 2, the firing signals are transferred from source No. 1 SCRs to source No. 2 SCRs. This causes source No. 2 SCRs to conduct and source No. 1 SCRs to block when the SCR anode voltage reaches zero. By causing source No. 2 SCRs to conduct and source No. 1 SCRs to block, power flows from source No. 2 through the SCRs to the load during the transfer, the two sources are paralleled momentarily until source No. 1 SCRs reach the blocking state and the transfer is in a "make-before-break" mode.

(b) Initiation. The transfer process can be initiated manually or automatically through the sensing and logic circuit. This circuit senses the voltage and frequency of both sources and checks their synchronism. When the connected source voltage and/or frequency deviate from the required level, the sensing and logic circuit initiates transfer to the other source provided its voltage and frequency are within allowable tolerances. The transfer is normally initiated after a short time delay to avoid unnecessary transfers during transients.

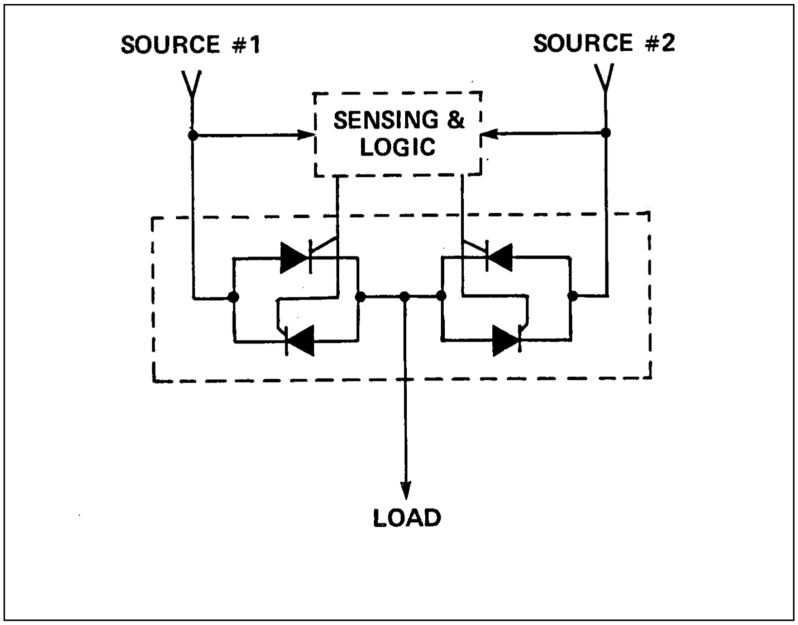

Figure 2-19. Single-phase static transfer switch

(c) Three-phase static switch. A three-phase static transfer switch consists of three single-phase switches. However, only one common sensing and logic circuit is used to monitor the frequency and voltages of the three phases. A voltage deviation in any phase initiates the transfer. Otherwise, operation is the same as the single-phase switch operation.

(2) Static transfer switches with short time rating. The static transfer switch discussed in paragraph 2-1i. above is capable of transferring and carrying the full load current continuously. In some designs, particularly larger ratings, a static transfer switch with short time rating is used in conjunction with a circuit breaker connected in parallel at the bypass source. In this arrangement the static transfer switch is not rated to carry the load current continuously; it can carry the full load current for a duration of less than one second. The static switch is used to affect fast transfer and to carry the load current for the duration required to close the motor operated circuit breaker which is in the order of several cycles. Once the circuit breaker closes, it carries the load current and relieves the static transfer switch. This configuration is comparable to the fully rated static transfer switch. However, it has a lower reliability due to the higher failure rate of motor operated circuit breakers. It is used mainly for economic reasons in lower cost systems.

j. Batteries. A battery is used in a static UPS system to provide reliable emergency dc power instantaneously to the inverter when the normal power fails or degrades. Of the many available battery types, the following two basic types are generally used in static UPS systems, namely, the lead-acid and the nickel-cadmium (ni-cad) batteries.

(1) Lead-acid batteries. A lead-acid battery cell consists basically of a sponge lead negative electrode, a lead dioxide positive electrode, and a sulfuric acid solution as an electrolyte. As the cell discharges, the active materials of both positive and negative electrodes are converted to lead sulphate and the electrolyte produces water. On charge, the reverse action takes place. At the end of the charging process, water electrolysis occurs producing hydrogen at the negative electrode and oxygen at the positive electrode.

(a) Lead-acid design. The most common design of lead-acid batteries is the lead-calcium cell construction where the active material for each electrode is prepared as a paste spread onto a lead-calcium alloy grid. The grid provides the electrical conductivity and structure to hold the active materials. The resultant plates are soldered to connecting straps to form positive and negative groups which are interleaved. Separators are placed between the plates and the assembly is placed in a container or jar. These batteries can survive more short duration, shallow cycles than long duration, deep discharge cycles.

(b) Voltage. The nominal voltage of a lead-acid cell is 2 volts while the open circuit voltage is approximately 2.05 volts. A commonly used end or discharged voltage is 1.75 volts. However, lower end voltages are also possible. The electrolyte specific gravity with the cell fully charged can range from a nominal 1.210 to 1.300 at a temperature of 25°C (77°F).

(c) Rate design. The batteries may be of the high rate, medium rate, or low rate design. The high rate batteries are designed to deliver a large amount of current over a short amount of time of approximately 15 minutes. This is achieved by designing the batteries with thin plates. This design is most common for UPS applications. The medium rate batteries are designed for general use. They deliver a medium amount of current over a medium amount of time of approximately 1 to 3 hours. The design consists of medium width plates. This design is most common with switchgear and control applications. The low rate batteries are designed for delivery of power over a long amount of time of approximately 8 hours. The battery design consists of thicker plates. This design is most common for applications such as emergency lighting and telecommunications.

(d) Vented (flooded) lead-acid battery. Vented (flooded) lead-acid cells are constructed with the liquid electrolyte completely covering the closely spaced plates. The electrolyte maintains uniform contact with the plates. These batteries require regular maintenance of checking the specific gravity of the electrolyte and adding water. These batteries are well suited for industrial applications due to the long lifetime (20 years) and high reliability with the proper maintenance. Without the proper maintenance, the lifetime of the battery could be greatly reduced. These batteries are approximately half the cost of ni-cad batteries. These are the most commonly used batteries for industrial application UPSs.

(e) Valve regulated lead-acid (VRLA) batteries. The VRLA batteries are sealed with a valve allowing venting on excessive internal pressure. These cells provide a means for recombination of the internally generated oxygen and suppression of hydrogen gas evolution to reduce the need for adding water. This design does not require the maintenance of checking the specific gravity and adding electrolyte as does the flooded lead-acid batteries. These batteries have a lifetime of approximately 5 to 6 years. This is substantially shorter than the 20 year lifetime of the flooded lead-acid and the ni-cad designs. These batteries would need to replaced 3 to 4 times to provide the same service of the flooded lead-acid and ni-cad designs. These units sometimes experience failures called “sudden death failures” where deposits form on the plates causing a short. This type of failure is difficult to detect and makes this battery less reliable than the flooded lead-acid design and the ni-cad design. The VRLA batteries cost approximately half of the price of the flooded lead-acid batteries and one fourth of the price of the ni-cad batteries. These units are well suited for UPS systems providing back up to computer systems because of their low maintenance, low cost, and low emissions. For industrial applications requiring greater reliability and longer life the flooded lead-acid and ni-cad designs are preferred.

(2) Ni-cad batteries. Stationary ni-cad batteries designed for emergency power applications are being used in static UPS systems. These batteries have a long lifetime of 25

years. However, because of their initial cost their use is not as common as the flooded lead-acid type.

(a) Ni-cad design. The ni-cad battery cell consists basically of a nickel hydroxide positive electrode, a cadmium hydroxide negative electrode, and a potassium hydroxide solution as an electrolyte. As the cell discharges, the nickel oxide of the negative electrode is changed to a different form of oxide and the nickel of the positive electrode is oxidized. On charge the reverse action takes place. Also, hydrogen and oxygen are evolved by the positive and negative electrodes, respectively, as the cell reaches full charge. However there is little or no change in the electrolyte's specific gravity.

(b) Ni-cad voltage. The nominal voltage of a ni-cad cell is 1.2 volts while the open circuit voltage is 1.4 volts. The electrolyte specific gravity is approximately 1.180 at a temperature of 25°C (77°F).

(c) Ni-cad rate design. Ni-cad batteries are also available in one of three designs of high, medium, or low rate power delivery. The high rate batteries are the most commonly used in the application of UPS systems.

(d) Advantages. These batteries are resistant to mechanical and electrical abuse. They operate well over a wide temperature range of –20°C to 50°C. Also, they can tolerate a complete discharge with little damage to the capacity of the battery.

(3) Lead-acid vs. ni-cad batteries. Lead-acid batteries are about 50 percent less expensive than an equivalent ni-cad battery; the ni-cad batteries exhibit a longer life and a more rugged construction. Also the ni-cad battery requires less maintenance than a lead-calcium battery. However, a ni-cad battery requires approximately 53 percent more cells than a lead-acid battery at the same voltage. Lead-acid batteries are more susceptible to high temperature than ni-cad batteries. The life of a lead-acid battery is reduced by 50 percent for every 15°F increase in electrolyte temperature while a ni-cad battery loses approximately 15 percent of its life. It should also be noted that lead-acid batteries release more hydrogen during recharging than ni-cad batteries.

k. Battery charging. During initial operation, the battery requires charging. During normal operation, local chemical reactions within the cell plates cause losses that reduce the battery capacity if not replenished. Also, these local chemical reactions within the different cells occur at varying rates. In lead-acid batteries these local reactions over long periods of time cause unequal state-of-charge at the different cells. In addition, it is required to recharge the battery following a discharge. Therefore, the battery charger should provide the initial charge, replenish the local losses to maintain the battery capacity, equalize the individual (lead-acid) cells state-of-charge, and recharge the battery following discharge. In stationary applications such as static UPS systems, the battery is continually connected to the charger and the load and the battery is float charged. During float charging the battery charger maintains a constant dc voltage that feeds enough current through the battery cells (while supplying the continuous load) to replenish local losses and to replace discharge losses taken by load pulses exceeding the charger's current rating. Periodically the charger voltage is set at a level 10 percent higher than the floating voltage to restore equal state-of-charge at the individual (lead-acid) cells. This mode of charging is called “equalizing charge” and the charger voltage level during this mode is the equalizing voltage. Following the battery discharge, the charger is set at the equalizing voltage to recharge the battery. The charger is set at this higher voltage to drive a higher charging current to recharge the battery in a reasonably short time and to restore it to the fully charged state. Although a periodic equalizing charge is not required for equalizing ni-cad cells, a charger with float/equalize mode is required. At the floating voltage level, the ni-cad cell cannot be charged over 85 percent of its full capacity. Therefore, the equalizing voltage level is required to fully recharge the cell after successive discharges.

l. Service life influences. Service life as reported by battery manufacturers is greatly influenced by temperature considerations. Battery manufacturers are finding that the type and number of discharge cycles can reduce life expectancy when installed for the high-current, short period, full discharges of UPS applications. Characteristics of expected life and full discharge capabilities of various types of UPS batteries are given in table 2-1. An explanation of the relationship of battery life to battery capacity, of the basis for battery sizing, and of the effects of battery cycling is considered necessary to impress on maintenance personnel why continual maintenance, data reporting is so important in fulfilling warranty policy requirements. Operating characteristics of the overall system such as charging/discharging considerations, ripple current contribution, and memory effect also can lead to a diminishment in expected battery performance.

Table 2-1. Characteristics of UPS battery types

Battery Type	Typical Warranty Period	Typical Expected Life	Approximate Number of Full Discharges
Lead-acid antimony, flooded electrolyte	15 years	15 years	1,000-12,000
Lead-acid calcium, flooded electrolyte	20 years	20 years	100
Lead-acid/calcium gelled electrolyte, valve-regulated	2 years	5 years	100
Lead-acid/calcium suspended electrolyte, valve-regulated	1 - 10 years	5 - 12 years	100-200
Lead-acid special alloy suspended electrolyte, valve-regulated	14 years	14 years	200-300
Lead-acid/pure starved electrolyte, valve-regulated	1 year	5 - 20 years	150
Ni-cad, flooded electrolyte	20 - 25 years	25 years	1,000-1,200

(1) Voltage tapping. Sometimes the UPS system will require one dc voltage level while electrical operation of circuit breakers will require another dc voltage level. Tapping off of the higher-voltage battery is not permitted. Unequal loads on the battery will reduce the battery's life since it causes one portion of the battery to be undercharged while the other portion is overcharged. Battery and UPS manufacturers both often indicate that such practices invalidate their warranties.

(2) Cycling effects. A cycle service is defined as a battery discharge followed by a complete recharge. A deep or full cycle discharge/recharge consists of the removal and replacement of 80 percent or more of the cell's design capacity. Cycling itself is the repeated charge/discharge actions of the battery. A momentary loss of power can transfer the UPS to the battery system and impose a discharge on the battery for the time period needed by the UPS to determine whether the ac power input has returned to acceptability. As we see an increase in non-linear loads, we may expect to see more frequent cycling. As indicated in table 2-1, the ability of flooded lead-acid batteries utilizing a lead-antimony alloy to provide the greatest number of full discharges. Ni-cad batteries have a good cycle life, but their increased cost does not encourage their use in large installations. Valve-regulated batteries have low-cycle capabilities because each recharge means a possibility of some gassing, resulting in the ultimate failure of the cell when it eventually dries out.

(3) Charging/discharging considerations. A battery cannot function without a charger to provide its original and replacement energy. A well designed charger will act to charge a discharged battery by maintaining the correct balance between overcharging and undercharging so as not to damage the battery. Additionally, the charger must assure that battery discharging is limited to the point where the cells approach exhaustion or where the voltage falls below a useful level (usually about 80 percent of the battery's rated capacity). Overcharging results in increased water use, and over discharging tends to raise the temperature, which may cause permanent damage if done frequently.

(a) Current flow. Batteries are connected to the charger so that the two voltages oppose each other, positive of battery to positive of charger and negative to negative. Battery current flow is the result of the difference between the battery and the charger voltages and the battery's extremely low opposing resistance. The voltage of the battery rises during charging, further opposing current flow. Chargers are designed to limit starting charging currents to values that keep equipment within a reasonable size and cost. They must also maintain a sufficiently high current throughout charging so that at least 95 percent of the complete storage capacity is replaced within an acceptable time period. This recharge time may range from 5 to 24 times the reserve period (for a 15 minute reserve period with a 10 times recharge capability the recharge period would be 2.5 hours).

(b) Voltage action. Providing the precise amount of charge on each and every cell for each and every recharge is impracticable for a continuously floating battery operation. The float-voltage point should just overcome the battery's self-discharge rate and cause the least amount of corrosion and gassing. Ambient temperature differences will affect the charging ability of the selected float-voltage level. Overcharge, undercharge, and float voltage levels differ, depending upon the type of cell used.

(c) Lead-acid cells. The usual recommended float voltage for UPS applications is 2.20 to 2.30 volts per cell depending upon the electrolyte's specific gravity. The excess energy of higher float voltages results in loss of water, cell gassing, accelerated corrosion, and shorter cell life. To eliminate such actions, the charge is stopped slightly short of a fully-charged condition on daily or frequent discharges. However, permissible cell manufacturing tolerances and ambient temperature effects will cause individual cell-charge variations. Sulphation will take place and not be reconverted upon recharge, since the charge is insufficient to draw all the acid from the plates. The sulphate may start to crystallize and be shed from the plate. To prevent this, an "equalizing" charge is given for a selected time period to provide a complete recharge on all cells. However, excessive equalizing charges will have an adverse effect on battery life. Automatic equalizing after a discharge may require less maintenance time but may affect battery life. Equalizing charges on a periodic basis are not recommended but should follow the manufacturer's guidelines. Equalizing charging should be considered a corrective action rather than routine maintenance. Periodic equalizing charges can be considered as treating a possible problem before determining that there is a problem.

(d) Ni-cad cells. The usual recommended float voltage for UPS applications is 1.38 to 1.47 volts per cell depending upon the manufacturer's recommendation. Overcharge, as such, may cause no harm to the battery although there will be water loss. The current rate used for charging, though, could produce a damaging heating effect during any appreciable overcharge. Equalizing is not as important for this type of battery, but may be recommended to assist in electrolyte mixing after addition of water.

(4) Ripple currents. UPS applications can place unusual load conditions on a battery, and one condition that increases the rate of battery breakdown is ripple current. Ripple current is caused by the ripple voltage of the battery charger output and by the pulsating current requirements of the inverter. The UPS battery design strives for excellent short-term, high-rate, current characteristics and this demands the lowest possible internal cell resistance. This low resistance can serve as a better short circuit path for the ripple voltages coming out of the rectifier stage of the UPS than can the filter capacitors in the output rectifier. Also, the inverter stage of the UPS demands large instantaneous dc currents as it builds ac power from the parallel rectifier/battery combination. If the UPS is located some distance from the commercial ac power source, the short-term instantaneous currents must then come from the battery. These factors can result in a relatively high ac component in the UPS battery. The relative detrimental effects of ripple current on the battery are mainly a function of the design of the UPS, the comparative size of the battery as compared to the UPS rating, and the battery type. Ripple current tends to heat the batteries and is equivalent to constantly discharging and recharging the battery a tiny amount. Ni-cad cells can be adversely affected by ripple currents although they provide a very good filtering capability. Lead, being much softer than nickel, requires different plate construction techniques which make lead-acid batteries even more susceptible to harmful effects from ripple currents. Usually ripple currents of less than 5 percent over the allowable continuous input range of the battery will not be harmful to lead-acid batteries. A lead-acid battery operated on a high-ripple current input at an elevated temperature can have its operating life reduced to one quarter of what would normally be expected.

(5) Memory effect. Ni-cad cells charged at very low rates are subject to a condition known as a "memory effect." Shallow cycling repeated to approximately the same depth of discharge leads to continual low-rate charging. The result is a battery action which has reduced the effective reserve time of the UPS system. An affected cell can have the memory effect erased by providing a complete discharge followed by a full charge with constant current which breaks up the crystalline growth on the plates.

m. Effects of loads on static UPS systems. Linear loads present a constant load impedance to the power source. This type of load results in a constant voltage drop. However, non-linear loads draw non-sinusoidal current resulting in a non-sinusoidal voltage drop. Non-linear loads and loads with high inrush current demand could adversely affect the static UPS system performance.

(1) Non-linear loads. Non-linear loads are loads whose current is not proportional to the supply voltage such as loads with ferroresonant transformers or regulating transformers and solid-state power supplies. Non-linear loads distort the inverter output voltage wave shape and cause the output voltage to contain high harmonic content. This effect can be more pronounced in inverters with high impedance such as inverters with pulse width control technique and inverters with a ferroresonant output transformer.

(2) Loads with high inrush current. Loads such as motors, transformers, incandescent lamps, etc., draw a high initial current when energized. The high initial current for such loads could be as high as 10 times the normal full load current. Therefore, loads with high inrush current requirements should not be energized simultaneously otherwise the inverter may reach the current limit point.

n. Effect of static UPS system on power supply system. The battery charger within the static UPS is a controlled rectifier which draws non-sinusoidal currents from the power source. The ac line current drawn is basically a square wave or a stepped wave depending on the charger design. This square or stepped wave can be analyzed into an equivalent sinusoidal wave of the power frequency (i.e., the fundamental component) plus other sinusoidal waves of higher frequencies or harmonics. These harmonic currents cause harmonic voltage drops in the power source impedance. This results in power source voltage distortion and the flow of harmonic currents in the power system components and loads. The degree of power source voltage distortion increases with the static UPS system capacity as well as the power source equivalent impedance. The flow of harmonic currents in the power system can cause resonance and additional losses and heating in the power source's components and loads. Normally, a static UPS system does not have detrimental effects on the power supply system. However, when the static UPS system capacity is close to 20 percent of the supply system capacity, the harmonic effects should be analyzed. The effect of the UPS generated harmonics on the power source and other supplied equipment can be minimized when necessary. The use of a 12- (or more) pulse rectifier reduces the harmonic currents generated. The harmonic currents present in input current to a typical rectifier in per-unit of the fundamental current are as shown in table 2-2. However, the rectifier number of pulses is an equipment specific design parameter that is not normally specified by the user. Should the UPS generated harmonics become a problem and affect other loads supplied from the same bus as the UPS, harmonic filters at the UPS input may be used. Harmonic filters filter out the harmonic currents and minimize the voltage distortion and its effects on harmonic susceptible equipment.

Table 2-2. Harmonic currents present in input current to a typical rectifier in per-unit of the fundamental current

Converter	**Harmonic Order**							
Pulses	**5**	**7**	**11**	**13**	**17**	**19**	**23**	**25**
6	0.175	0.11	0.045	0.029	0.015	0.010	0.009	0.008
12	0.026	0.016	0.045	0.029	0.002	0.001	0.009	0.008
18	0.026	0.016	0.007	0.004	0.015	0.010	0.001	0.001
24	0.026	0.016	0.007	0.004	0.002	0.001	0.009	0.008

(1) Magnitude of harmonic effects. Systems with low impedances such as a large power system will be less sensitive to the harmonic distortion from the non-linear UPS load than an engine-generator source whose rating is close to that of the UPS. Sources with a high impedance in relation to the load are known as "soft" power sources when they are unable to absorb the generated distortion of their critical load; that is, the source voltage waveform can be greatly deformed by the critical load waveform. It is difficult for the UPS to attenuate load produced noise. A very noisy or extremely non-linear load may reflect current distortions via the UPS input onto the source. Any interposed soft source may interact with this load to increase rather than reduce critical load power disturbances. So non-linear loads on the UPS can actually distort the "clean" power the UPS is designed to provide by their load-induced current harmonics. Most UPSs provide an input current distortion which meets or is less than the Information Technology Industry Council (ITIC) [formerly called Computer Business Equipment Manufacturers Association (CBEMA)] recommendations. To maintain required power quality to other loads served by the UPS source, ITIC advocates an input having a total reflected current harmonic distortion (THD) of 5 percent or less of line-to-line distortion with a maximum of 3 percent for any one harmonic order. Total distortion is the vector sum of individual harmonic frequency distortions. UPS manufacturers typically guarantee that this distortion holds when the UPS supplies linear loads. A UPS sized for the addition of future loads may be in trouble if the future loads have high harmonic contents. All manufacturers of electronic equipment install line filters

to meet the Federal Communications Commission's (FCC) requirements for radio frequency limits. They do not necessarily provide them for reducing power-line harmonics since this adds to equipment costs. Electronic load-induced distortion beyond the UPS limitations can be deduced if adverse effects occur under maximum loads but not under lesser loads. As the UPS impedance increases in relation to the lower loads, this may reduce the distortion to limits which can be handled by the UPS. Experience has shown that while distortion in excess of the UPS manufacturer's specified limits may not operate protective circuitry, such excess distortion will probably result in increased heating and possible reduction in equipment life.

(2) Problems from harmonics. Harmonic voltages and currents resulting from non-linear loads have caused operating problems, equipment failures, and fires. Harmonics cause increased heating, lower the power factor, change crest factors, increase zero crossing points, provide noise feedback, and influence inductive and capacitive reactance. An understanding of harmonic behavior helps to recognize actions which adversely influence the overall electrical systems.

(3) Neutral harmonic behavior. Harmonics are integral multiples of the fundamental power [60 hertz (Hz)] frequency. Odd-order harmonics are additive in the common neutral of a three-phase system. For pulsed loads, even-order harmonics may be additive if the pulses occur in each phase at a different time so that they do not cancel in the neutral. This results in overloaded neutrals and becomes a fire safety concern. ITIC recommends providing double-capacity neutrals. Section 310-4 of the National Electrical Code (NEC) suggests installing parallel conductors to alleviate overheating of the neutral in existing installations where there is high harmonic content. Balanced neutral current buildup due to harmonics can be as high as 1.73 times the phase current. Under unbalanced conditions, neutral current can be as much as three times the phase current for worst case, pulsed loads. Oversized (that is per normal linear-load applications) neutrals should be a requirement wherever solid-state equipment is installed.

(4) Harmonics and equipment ratings. Transformers, motors, and generators are rated on the heating effects of an undistorted 60-Hz sine wave. At higher frequencies, hysteresis and eddy current losses are increased, and the conductor's skin effect decreases its ampacity. Substantial harmonic currents therefore will result in substantial heating effects, which means that the equipment loads must be decreased to prevent overheating. Equipment loaded to less than 70 percent of its nameplate rating has been shut down because of harmonic overheating. Unfortunately, there is only one standard on how to derate equipment. American National Standards Institute (ANSI) C57.110 covers transformers, but a measured harmonic distribution of the load current is probably not available to most users. Equipment capability must be checked then by observation based on the temperature rise of the affected equipment.

(5) Lower power factor. Many non-linear loads have an uncorrected low power factor because expensive power factor and harmonic line distortion correction has not been provided. Any decrease in system power factor may indicate a load change has been made, which has increased harmonic distortion.

(6) Crest value changes. Measurements for currents and voltages are based on average or peak values, which are calibrated to read root-mean-square () or effective values. For a sine wave, the crest factor or ratio of the peak to the root mean square (RMS) value is 1.414. Crest values of non-sinusoidal waveforms can be greater than this value, so that normal measuring instruments do not provide correct readings. It is the effective value which is a measure of the true amount of heat from a resistance. Inaccurate measurements (low for average-sensing and high for peak-sensing instruments) can lead to protective device actions such as premature tripping or failure to trip. Induction-disc watt-hour meters, when used for billing, may result in

bills which are usually too high rather than too low. True RMS sensing is practical but requires microprocessor based technology. The use of other than true RMS sensing meters, relays, and circuit breaker trip units may contribute to system operating problems.

(7) Zero crossing increases. Controls such as generator voltage regulators which use the zero crossing point of a voltage or current wave can start hunting where harmonic contents result in more zero crossings than there are naturally in a 60-Hz system. Instability in speed and frequency can result, causing generator paralleling problems. An inaccurate measurement of RMS values can prevent proper load sharing of paralleled units. These are important considerations when generating-capacity requirements are changed. Generator manufacturers should be contacted when existing units are used to supply non-linear loads in order to ensure compatible interfacing.

(8) Noise feedback. Power-line harmonics at audio and even radio frequencies can be interposed on telephone, communication, and data systems by inductive or capacitive coupling and by radiation. FCC has set maximum power line conduction and radiation standards for many types of electric equipment. Unfortunately, not all harmonic-generating non-linear loads come under FCC standards, and improperly shielded and filtered equipment can conduct or radiate noise, which may cause problems even many miles from their source.

(9) Inductive and capacitive influences. High harmonic content can cause resonant circuits at one or more of the harmonic frequencies, resulting in voltages and currents that are higher than equipment ratings. Insulation breakdown, overheated equipment, and eventually equipment failure will result. Additionally, capacitors added for surge suppression or power factor correction may have such a low reactance at higher harmonic frequencies as to cause a short circuit and failure of the capacitor.

(10) Harmonic correction techniques. The measurements of harmonic currents and voltages require special techniques. The inductive and capacitive impedance is variable because of harmonic variations; therefore, its effects are usually unpredictable. More and more the power system is becoming susceptible to the operation of the sensitive electronic equipment, as much as or more than the sensitive electronic device is susceptible to the power source. If harmonic problems have been identified as causing problems, certain procedures are recommended. The following are some of the procedures. Provide oversized neutral conductors. Derate transformers, generators, motors, and UPS if necessary. Insure all controls, especially those involving generator speed and paralleling, are properly shielded and filtered and are designed to respond as quickly as is necessary. Use of unfiltered voltage regulators and non-electronic governors will probably cause problems, especially for generators supplying more than a 25-percent non-linear load. Provide line filters to suppress the harmonics emanating from the power source. Increase power source capacities so as to lower output impedance and minimize voltage distortion. Use UPS outputs which have no neutrals. Where neutral voltages are required, provide isolation transformers as close to their loads as possible to shorten oversized neutral installations. Use true RMS sensing for circuit breaker trip units, relays, meters, and instruments.

o. Advantages and disadvantages of static UPS systems. Static UPS systems have several advantages. They provide disturbance free uninterrupted power, operate at low sound levels, have high reliability and short repair times, require minimal maintenance, simple installation, and lend themselves to future expansion and reconfiguration. However, they also have some disadvantages. Some of the disadvantages are that they introduce harmonics into the power supply system, have a high initial cost to purchase, require large space, require regulated environment, require skilled technicians for trouble shooting and repairs, and have a somewhat low efficiency.

2-2. Principles of rotary UPS systems

The most basic UPS system is the inertia-driven ride-through system. This system consists of a synchronous motor driving a synchronous generator with a large flywheel as shown in figure 2-20. During normal operation the motor drives the flywheel and the synchronous generator at constant speed proportional to the power supply frequency. The generator output voltage is regulated by the voltage regulator and the frequency is constant and proportional to the motor power supply frequency. When input power is momentarily lost or degrades, the flywheel supplies its stored energy to the generator and the frequency is maintained within the required tolerance for a duration depending on the flywheel inertia. The time interval for which the frequency can be maintained within tolerance is proportional to the ratio of flywheel inertia to the

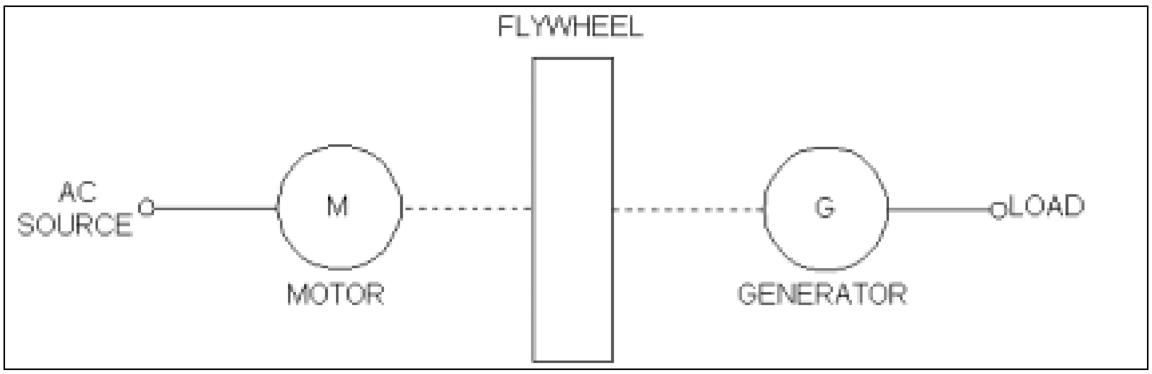

Figure 2-20. Inertia-driven ride-through system

load for a given speed. To keep the system weight low, high speed is required. However, to keep the noise level low, low speed is desirable. Therefore, the system is commonly operated at a speed of 1800 revolutions per minute (rpm) as a trade-off. In this system, a synchronous motor is used to maintain a constant speed independent of the load level. However, an induction motor with very low slip may also be used as discussed in paragraph 2-2a(1). In newer designs an asynchronous motor is coupled with a synchronous generator. This technology uses induction coupling rather than a flywheel for the ride-through inertia. Other designs use a battery. The battery-supported inertia rotary UPS system consists of a synchronous motor driving a synchronous generator, with a rectifier, inverter, and storage battery added. The system configuration is shown in figure 2-21. During normal operation, the synchronous motor drives the synchronous generator and provides filtered power. Upon loss of the ac input power to the motor, the battery supplies power to the motor through the inverter which drives the generator. The batteries provide energy to the system during the transition from normal to emergency operation. This system may also use a kinetic battery in place of the standard lead-acid and ni-cad batteries [see paragraph 2-2b(6)].

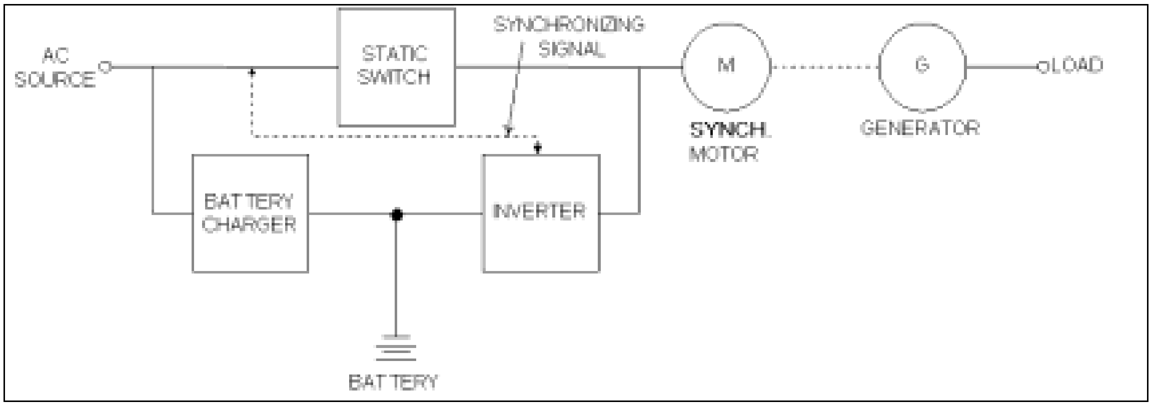

Figure 2-21. Battery supported motor-generator (M-G) set

a. Motor types and characteristics. In a rotary UPS system an ac motor is used to convert electrical energy to mechanical energy for driving an ac generator and a flywheel. Both synchronous and induction motor types may be used. DC motors are also used in rotary systems with a storage battery for back-up power. In the following paragraphs, only the motor characteristics relevant to rotary UPS applications are addressed.

(1) Induction motors. Induction motors are of the squirrel cage or the wound rotor type. It is the three-phase cage motor type that is used in rotary UPS applications. The relevant characteristics of a cage motor are as follows. The motor speed is essentially proportional to the power supply frequency. The motor speed is dependent on the load level. For a motor with 5 percent slip, the speed may increase by up to 5 percent of the rated speed from rated load to no load. The speed variations are lower for low slip motors. When energized, the motor draws a starting current as high as 6.5 times the rated current for a duration of 2 to 10 seconds or longer depending on the load inertia. The induction motor power factor is approximately 0.8 lagging.

(2) Synchronous motors. The relevant characteristics of a three-phase synchronous motor are as follows. The motor speed is independent of the load and is directly proportional to the power supply frequency. The starting current and starting duration of a synchronous motor are slightly less than those of a comparable induction motor. A synchronous motor can be either self-excited or externally excited (see paragraph 2-2b(3) for exciter types). The synchronous motor power factor can be changed from lagging to unity to leading by adjusting the field or exciting current.

(3) DC motors. DC motors are classified according to the method of excitation used as shunt excited, series excited, and compound excited. The shunt excited dc motor is the most suitable in rotary UPS applications and has the following characteristics. The motor speed is dependent on the load level. The speed may decrease by up to 5 percent of the rated speed from no load to rated load. The motor speed can be easily adjusted by varying the shunt field current through the use of a rheostat. The motor can be operated as a generator by applying mechanical input to the shaft.

b. Generator types and characteristics. In a rotary UPS system a synchronous generator is used to convert the motor mechanical energy or the mechanical energy stored in a flywheel to ac electrical energy with regulated voltage. In rotary systems with a storage battery a dc motor or inverter is provided for driving the generator during a loss of ac power. When ac power is available, the dc motor is operated as a dc generator to charge the battery. Newer rotary system designs may also utilize a back-up inverter and a dc battery to supply the driving motor upon loss of the normal ac power. In the following paragraphs, only the generator characteristics relevant to rotary UPS applications will be discussed.

(1) Synchronous generators. The relevant characteristics of a three-phase synchronous generator are as follows. The generator frequency is directly proportional to the prime mover speed. Controlling the output frequency is accomplished by controlling the prime mover speed. The output voltage can be regulated by varying the field current, i.e., excitation level. The generator rated power factor is normally 0.8 lagging. The generator has a limited load unbalance capability; severe unbalance can result in overheating. The generator can supply a maximum current of 6 to 7 times rated RMS current for a few cycles and 3 to 4 times rated RMS current for a few seconds. The output voltage harmonic content is typically less than 5 percent.

(2) DC generators. Similar to dc motors, dc generators are classified as shunt excited, series excited, and compound excited. The relevant characteristics of dc generators are as follows. The generator output is essentially ripple free power. The output voltage can be precisely held at any desired value from zero to rated by controlling the excitation level. The generator can be operated as a motor by applying dc power to its armature.

(3) Exciters. Exciters are used to create the magnetic field on the generator. They can be broadly classified as static and rotary. In a static exciter all components are stationary and are mounted outside of the machine frame. The synchronous machine field coils are connected to commutator rings, and brushes are used to connect the field coils to the excitation power source. In a rotary exciter, some of the components are rotating and are mounted either on the synchronous machine shaft or externally. Also, in a rotary exciter a commutator ring and brushes may be required or the system may be brushless. Brushless type exciters are more commonly used now due to their lower maintenance requirements. However, selection of the exciter type is largely up to the manufacturer to meet the performance requirements.

(4) Flywheel. A flywheel is used in a rotary UPS system as an energy storage device. The flywheel is coupled to the M-G shaft and supplies stored energy to drive the generator upon momentary loss of the motor output. In addition, it acts to stabilize the generator frequency by maintaining the rotational speed following transient frequency variations at the motor power supply or sudden load changes. The flywheel may be considered an analog to a storage battery (with a very short protection time) in static UPS systems.

(5) Induction coupling. Induction coupling occurs when using an asynchronous motor and a synchronous generator. The induction coupling provides kinetic energy lasting approximately 2 seconds after loss of normal ac power to allow transfer to backup power. During this time a backup diesel generator may be brought on-line to provide power. This kinetic energy is supplied from the rotor. Energy storage is achieved when the rotor of a three-phase, two-pole asynchronous machine is accelerated to 3600 rpm. The stator of the same machine is mechanically connected with the rotor of the synchronous machine, running at 1800 rpm. The squirrel cage rotor of the asynchronous machine will run at 5400 rpm (1800 plus 3600 rpm). To retrieve energy from the squirrel cage, at the moment of power interruption, a controlled dc field is provided through an additional dc stator winding in the asynchronous machine. The magnetic field created in this way brakes the speed of the free running inner rotor, so that energy is released. This energy is used to keep the rotor running at 1800 rpm, while the generator comes on line.

(6) Kinetic battery. The kinetic battery may be used in place of regular flooded lead-acid or ni-cad batteries in the battery backed M-G configuration as shown in figure 2-21. The energy for the kinetic battery comes from a flywheel coupled with a M-G set. The energy from the flywheel is driven by a small pony motor using normal ac power. Upon loss of normal power, the flywheel continues to put out energy through the generator which provides input ac power to the rectifier. The rectifier and inverter filters the ac power and provides ac power to the primary M-G set. The ac power must be filtered to prevent the load from seeing the degradation of the frequency as received from the flywheel-generator source. This system allows for approximately 15 to 30 seconds of ride-through while waiting for the diesel generator to start.

c. Affect of loads on rotary UPS systems. Various types of loads may affect the UPSs ability to perform. Some of these load types are non-linear loads, loads with high inrush current, and unbalanced loads.

(1) Non-linear loads. Non-linear loads as discussed in paragraph 2-1m(1) will distort the synchronous generator output voltage wave shape and cause the output voltage to contain high harmonic content. The harmonic currents generated can also cause additional losses and heating in the generator. This may require derating the generator if the harmonic content of the load current is excessive. The generator manufacturer should provide the derating recommendations which are based on the nature as well as the level of the non-linear loads.

(2) Loads with high inrush current. Unlike a static UPS system, a rotary UPS system is capable of supplying high inrush currents at reduced voltages. The level of voltage reduction is more gradual than for the static inverter and depends on the generator transient reactance.

(3) Unbalanced loads. The unbalanced load capability of a rotary system is less than that of a comparable static UPS system. A synchronous generator has a very limited negative sequence current capability. Highly unbalanced loads produce high negative sequence currents which cause severe overheating.

d. Affect of the rotary UPS system on the power supply system. Due to the high starting current required by ac motors, a rotary UPS system may cause the reduction of the power supply system voltage during startup. The duration of the voltage reduction is dependent on the motor type and the system inertia. It could be as long as 10 or 15 seconds. The power factor of a system with a synchronous motor can be made leading by adjusting the motor excitation level. This means that the motor can be made to supply reactive power to the power supply system and improve its overall power factor. Improving the overall power factor can improve the supply system voltage regulation. On the other hand, systems with an induction motor have a power factor of approximately 0.8 lagging. Such a system requires reactive kVA from the power supply system which may cause a voltage reduction on the supply system. AC motors contribute currents during system faults. A large rotary UPS system may appreciably increase the system short circuit capability.

e. Advantages and disadvantages of rotary UPS systems. The rotary UPS system has both advantages and disadvantages that should be considered at the time of selection.

(1) Rotary advantages. There are many advantages to a rotary UPS system. The rotary system low output impedance makes it able to supply higher fault currents to operate a circuit breaker during fault conditions. They provide total isolation of sensitive loads from power supply system transients. They provide disturbance free uninterrupted power. Systems without storage batteries have a low initial cost. Efficiency is higher than comparable static UPS systems. The

rotary UPS systems have higher tolerance to adverse environments. Some require small space, especially systems without a storage battery. They do not cause power supply system voltage distortion. High ratings, e.g., above 1000 kVA can be built in the rotary UPS design. A rotary system has a lower number of components than a comparable static system and hence has a lower failure rate. It has a low output impedance which makes its output voltage less susceptible to harmonic distortion as may be caused by non-linear loads.

(2) Disadvantages. While there are several advantages to the rotary UPS, it does have some short comings. Some of them are that they operate at high sound levels unless equipped with special silencing enclosures. They require more maintenance and long repair times. Also, they require special foundations. Their installation is more complex. They do not easily lend themselves to future expansion, paralleling, or reconfiguration. Their performance requirements and configurations are not commonly standardized. Fewer manufacturers produce rotary UPS systems as compared to static UPS systems. The rotary UPS has a short backup time and requires either a battery or backup diesel generator for longer backup power.

2-3. Common static UPS system configurations

The building blocks of a static UPS system are rectifier/charger, inverter, battery, and static switch. These building blocks can be assembled in many configurations as required to meet reliability and/or economic considerations. However, some specific configurations have been in common use and are standardized in Institute of Electrical and Electronic Engineers (IEEE) 446. The most common of these configurations in ascending order of reliability are a non-redundant system, a system with static bypass switch, a redundant system, a cold standby redundant system, and a dual redundant system with static transfer switches.

a. Non-redundant system. The non-redundant static UPS system shown in figure 2-22 is the basic system described in paragraph 2-1. One major limitation in this configuration is that failure of the inverter leads to the loss of power to the supplied loads. This limitation makes this configuration undesirable except for supplying redundant loads where the loss of one load group does not impact operation. Another limitation is that due to the limited overload capability of the inverter elements, it is not suitable for supplying loads with high inrush current requirements.

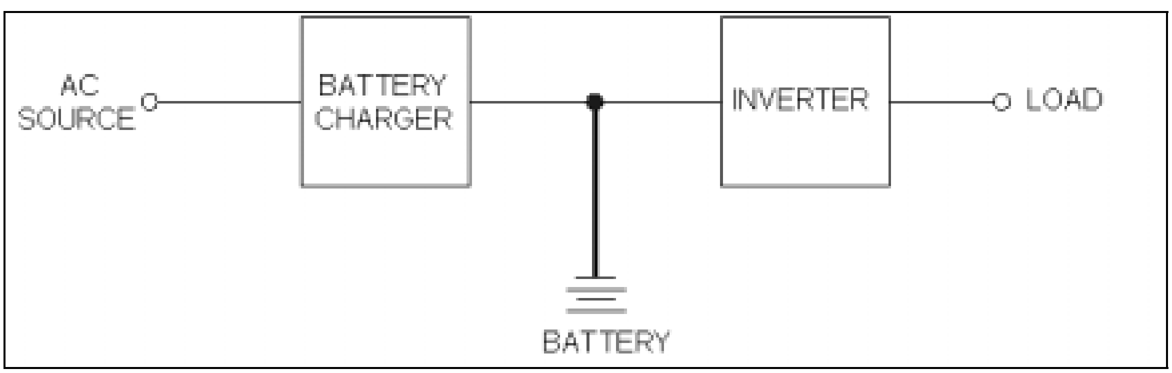

Figure 2-22. Non-redundant static UPS system

b. System with static bypass switch. The static UPS system with a static transfer switch is shown in figure 2-23. It is made up of the basic system with the addition of a static transfer switch to transfer to an alternate ac source. Normal operation of this system is basically the same as the basic system as described in paragraph 2-1. In addition, the static transfer switch sensing and logic circuit continuously monitors the inverter output voltage and initiates a load transfer to

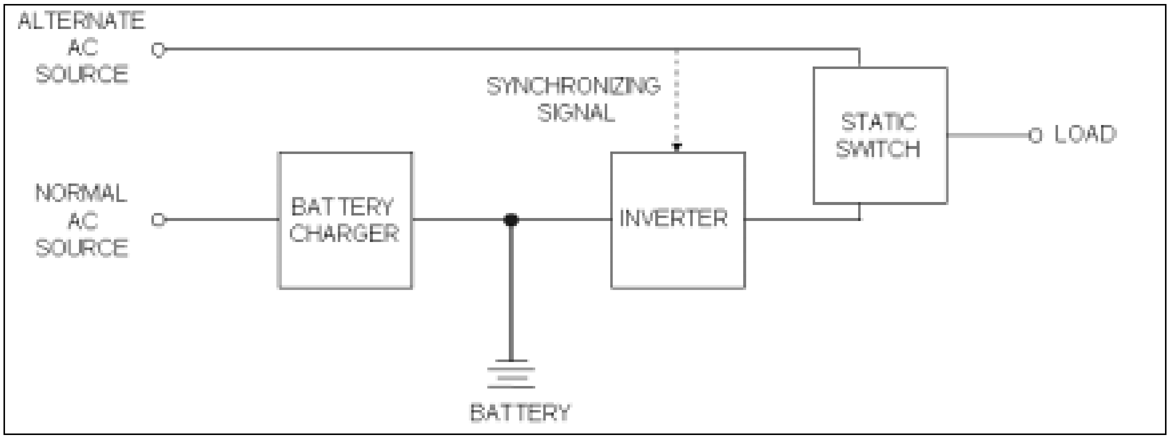

Figure 2-23. Static UPS system with static transfer switch

the alternate source during a loss of inverter output or a deviation of the inverter output voltage beyond the allowable tolerance due to malfunctions, high inrush demand, or a load branch circuit fault. In order to minimize disturbances to the connected loads during transfers, the inverter is synchronized to the alternate ac source. During normal operation the inverter frequency is controlled by the alternate source's frequency. In this mode, the inverter's internal oscillator provided for controlling the inverter frequency is bypassed. However, should the alternate source frequency deviate beyond the allowable tolerance, the inverter automatically reverts to its internal oscillator for frequency control and maintains the frequency within tolerance. The static transfer switch is commonly designed to automatically retransfer the loads back to the inverter when its output voltage recovers to within tolerance. However, the automatic retransfer feature can be inhibited if desired to allow for manual retransfer only. The addition of the static transfer switch to the basic system configuration increases the system reliability by connecting the loads to an alternate source upon loss of the inverter output. In addition, this configuration facilitates supplying loads with high inrush demands. One common improvement to this system is the addition of a regulating transformer as shown in figure 2-24. A regulating transformer is a specially designed transformer which can maintain its output voltage with limited deviations in input voltage. In addition, it can attenuate voltage surges and spikes originating in the power supply source.

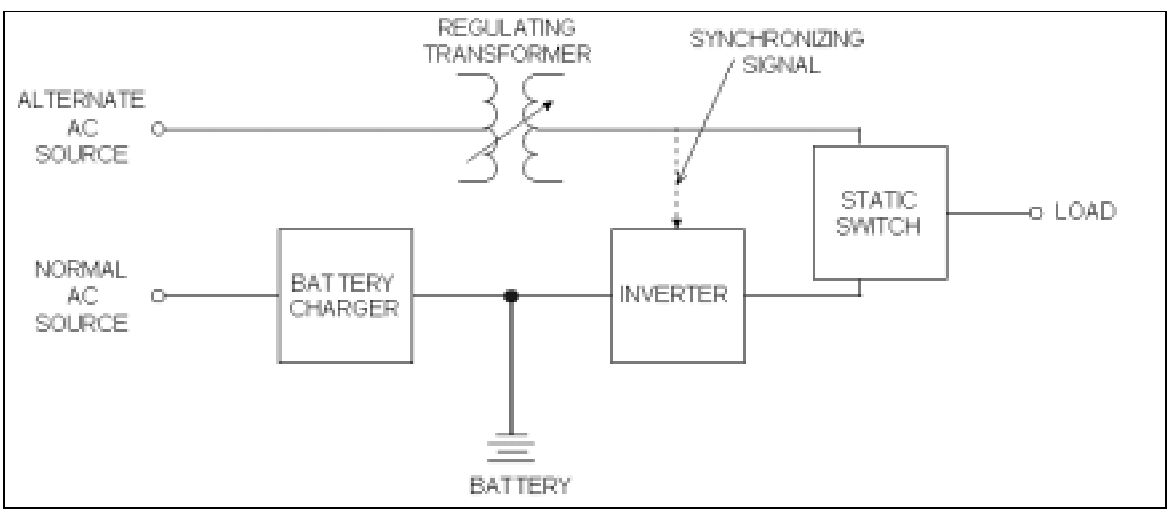

Figure 2-24. Static UPS system with static transfer switch and an alternate source regulating transformer

c. Redundant system. The redundant static UPS system configuration is shown in figure 2-25. This configuration is made up of two or more normally energized basic systems connected in parallel and synchronized with one another. The static interrupters used in this configuration are solid-state devices which serve to isolate a faulty inverter from the connected loads and to prevent the other inverters from supplying high fault currents to the faulted inverter. In this configuration, although the rectifier/inverter combinations are duplicated for higher reliability, only one common battery is used. This is due to the extremely high reliability of batteries. The rating of each of the parallel basic systems should be such that if one system fails, the remaining systems are capable of supplying the connected load. Therefore, for a two-parallel system, each system should be rated for 100 percent capacity and for a three-parallel system, each system should be rated for 50 percent capacity, etc. In this configuration, all the parallel systems are normally energized and share the load equally. It is also used where very high reliability is required. Should one system fail, the remaining systems supply the load without interruption. installations (400 kVA and larger) where the load exceeds the rating of available systems. This configuration is also commonly used in very large configuration is more costly than other configurations to purchase and install. In addition, it has a lower overall efficiency since all the parallel systems have to be operated continuously at part load where the efficiency is lower than at full load. However, this configuration is desirable where very high reliability is essential and the reliability of the ac power supply is questionable. It should be noted that C4ISR facilities require a system reliability level of 99.9999 percent.

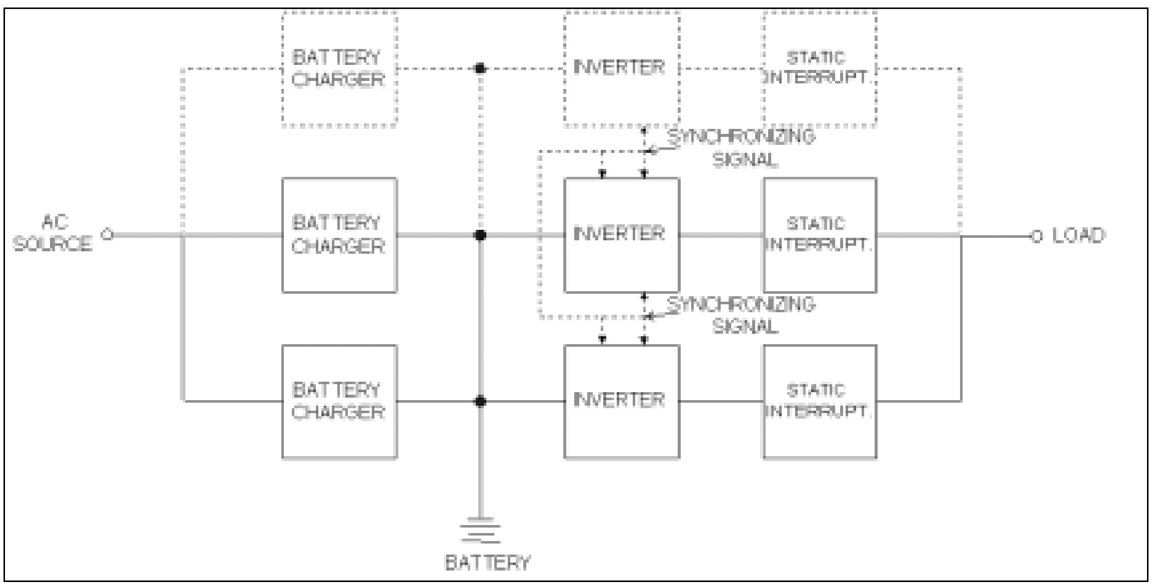

Figure 2-25. Redundant static UPS system

d. Cold standby redundant system. The cold standby redundant static UPS system configuration is shown in figure 2-26. It is made up of two basic systems with one common battery. Each of the two basic systems is rated at 100 percent capacity. During normal operation one system is de-energized and the other system is energized to supply the load through a manually operated circuit breaker. Upon loss of the inverter output, the static switch automatically connects the load to the alternate source without interruption. The second system's static switch is then closed manually, also connecting the load to the alternate source. To transfer the load to the second system, the static switch of the failed system is manually opened. Next the second system's breaker is manually closed, its static switch is opened, and the load is supplied from the system's inverter. During the transfer operations, the load is continuously supplied from the alternate source without interruption until it is switched to the second system. In this configuration the two inverters are not intended for operation in parallel and their output circuit breakers are interlocked to prevent this condition. One disadvantage of this configuration, when compared to the redundant system, is that the load is supplied from the unregulated alternate source for a short duration before the transfer is completed. Also, the transfer from one system to the other is manually accomplished and requires an operator's action. This makes the use of this configuration undesirable in locations where the alternate power source has a low reliability. However, this configuration has a higher efficiency than a comparable two-parallel redundant configuration. The higher efficiency is due to operating the energized system at 100 percent capacity as compared to operating each of the systems of a two-parallel redundant configuration at 50 percent capacity. Another advantage of this configuration over the redundant system is that the two basic systems are not susceptible to a single failure.

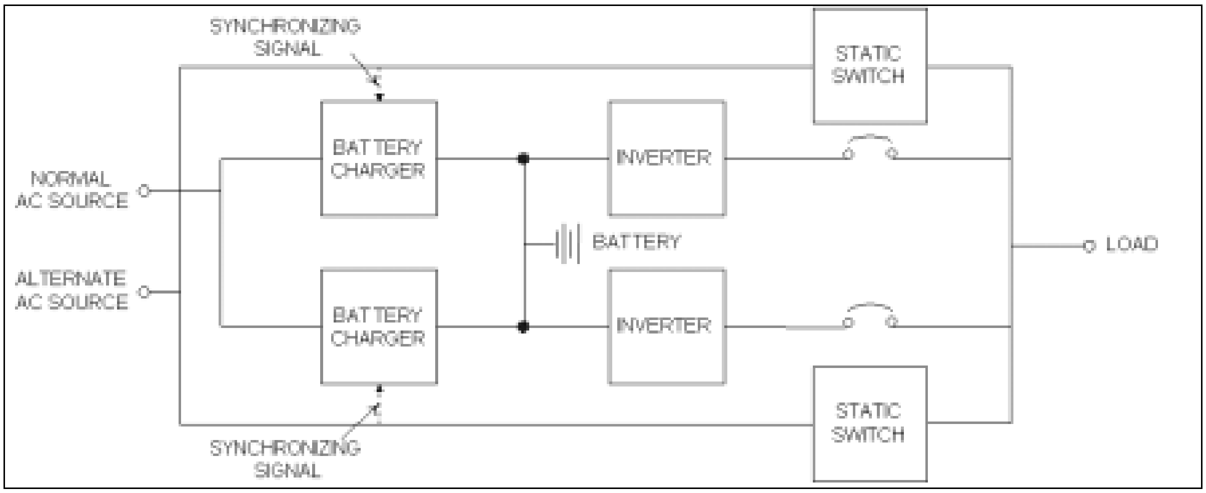

Figure 2-26. Cold standby redundant static UPS system

e. Dual redundant system with static transfer switches. The configuration of the dual redundant static UPS system with static transfer switches is shown in figure 2-27. Like the redundant system configuration, it is made up of two normally energized 100 percent capacity basic systems connected in parallel with one common battery. Each of the two basic systems is synchronized to the alternate source. The static switch provided at the output of each system serves the functions of a static interrupter as in the redundant system configuration, and a switch. Operation of this configuration is similar to the redundant system. In addition, upon loss of both systems or deviation of the output voltage beyond acceptable limits, the static switches disconnect the load from the inverters and connect it to the alternate source in a make-before-break transfer. The addition of the alternate source increases the reliability of this configuration over the comparable redundant system. In addition, the static switches make this configuration capable of supplying high in-rush currents by transferring to the alternate source. As with all systems with a static transfer switch to an alternate ac source, a regulating transformer connected to the alternate ac source is commonly used.

2-4. Rotary UPS system configurations

The main building blocks of rotary UPS systems are the synchronous motor, ac generator, and flywheel. In addition to the main building blocks, induction motors, eddy current clutches, batteries, dc M-Gs, and static rectifier/inverters are also used in rotary UPS systems. The building blocks can be assembled in numerous configurations to meet reliability and/or economic considerations. The most common rotary UPS configurations are the inertia-driven ride-through system with a synchronous motor, the inertia-driven ride- through system with an induction motor, inertia-driven ride-through system with an induction motor and an eddy current clutch, battery supported inertia system with a dc motor, and battery supported inertia system with a backup inverter.

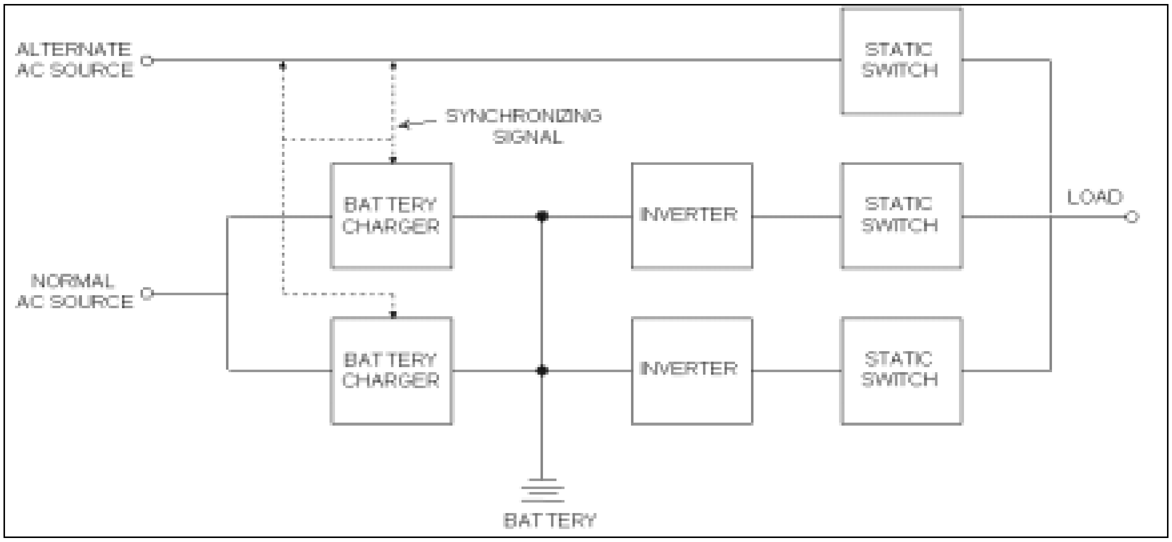

Figure 2-27. Dual redundant static UPS system with static transfer switches

a. Inertia-driven ride-through system with a synchronous motor. The inertia-driven ride-through system with a synchronous motor shown in figure 2-28 is the basic inertia-driven ride-through system described in paragraph 2-2. The main limitation in this configuration is that the ride-through time is normally limited to 0.5 seconds. This makes this configuration suitable only at locations where the power supply has a high reliability and long term interruptions are unlikely as in large metropolitan areas. This configuration is also widely used in frequency changer applications to convert the power supply frequency to another frequency such as 420 Hz. In this application the synchronous motor drives the generator at a constant speed proportional to the power supply frequency. The ratio of the generator number of poles to the motor number of poles should be the same as the ratio of the desired frequency to the power supply frequency. This configuration is becoming less common and it is not available from many manufacturers. However, newer technologies provide an induction coupling system for the inertia ride-through rather than the flywheel as discussed in paragraph 2-2b(5). This system is used with an asynchronous motor and a synchronous diesel generator. The induction coupling allows for approximately 2 seconds of ride-through while the diesel generator comes on line.

b. Inertia-driven ride-through system with an induction motor. The inertia-driven ride-through system with an induction motor is the same as shown in figure 2-28 except for replacing the synchronous motor with an induction motor. In this configuration, the induction motor must be with low-slip characteristics - typically less than 0.5 percent slip. With 0.5 percent slip characteristic, the generator output frequency (for a 60 Hz system) can vary from 59.7 Hz at rated load to near 60 Hz at no load. This configuration has the same limitation as the configuration with a synchronous motor. In addition, it is mostly suitable for supplying loads with higher tolerance to frequency variations. However, due to the lower cost of an induction motor as compared to a comparable synchronous motor, this configuration is less costly.

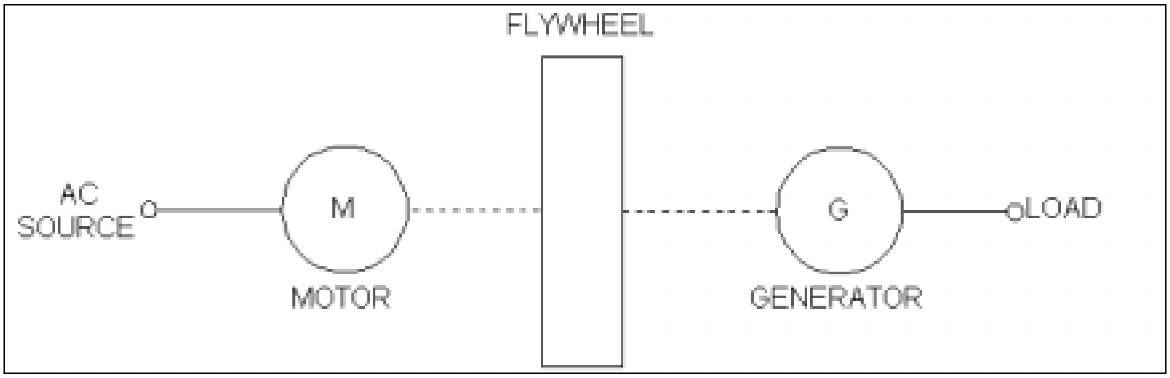

Figure 2-28. Inertia-driven ride-through system with a synchronous motor

c. Inertia-driven ride-through system with an induction motor and an eddy current clutch. This configuration shown in figure 2-29 consists of an induction motor which drives a flywheel and an eddy current clutch at a speed essentially proportional to the supply frequency. The generator rotates at a constant speed lower than the motor speed by controlling the slip of the eddy current clutch. The generator output frequency can be maintained at 60 hertz ±0.25 hertz. On loss of the ac input power, the generator receives energy stored in the flywheel. As the flywheel slows down, the slip of the eddy current clutch is reduced so as to maintain the generator frequency at 60 Hz. The generator frequency can be maintained above 59.5 Hz for up to 15 seconds after loss of ac input power. This configuration is most suitable where a backup power source such as a diesel generator or gas turbine is available. The rotary system can supply the loads until the backup source is started and operated to supply the motor. However, the use of this configuration is becoming less common and it is not available from many manufacturers.

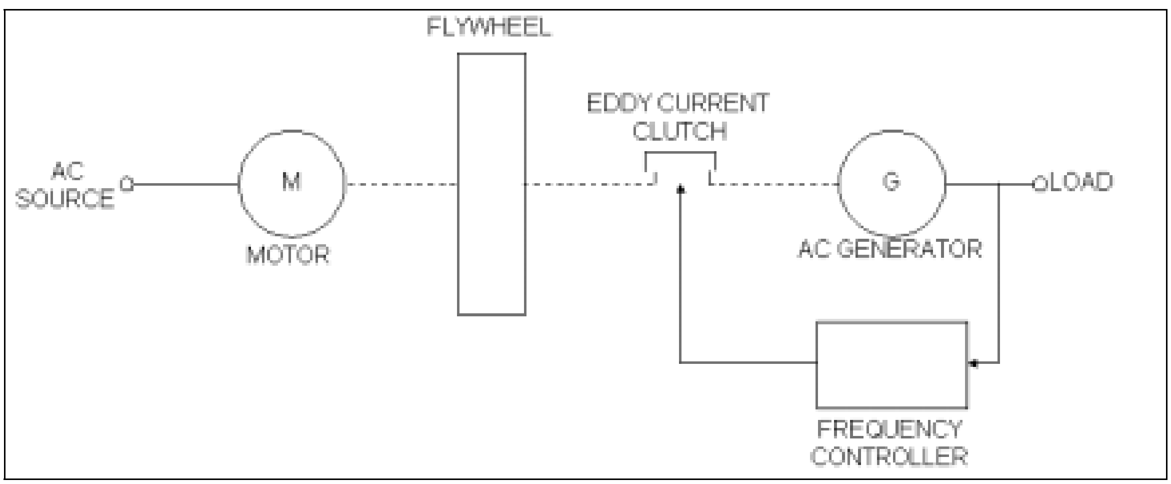

Figure 2-29. Inertia-driven ride-through system with an induction motor and an eddy current clutch

d. Battery supported inertia system with a dc motor. The battery supported inertia system with a dc motor is shown in figure 2-30. The ac motor may be a synchronous or a low slip induction motor. The frequency regulation of systems using an induction motor is the same as the inertia-driven ride-through system described in paragraph 2-2. This configuration is required at installations where the power supply is of low reliability and long term interruptions are common. This type is no longer manufactured, however, there may be some still in use.

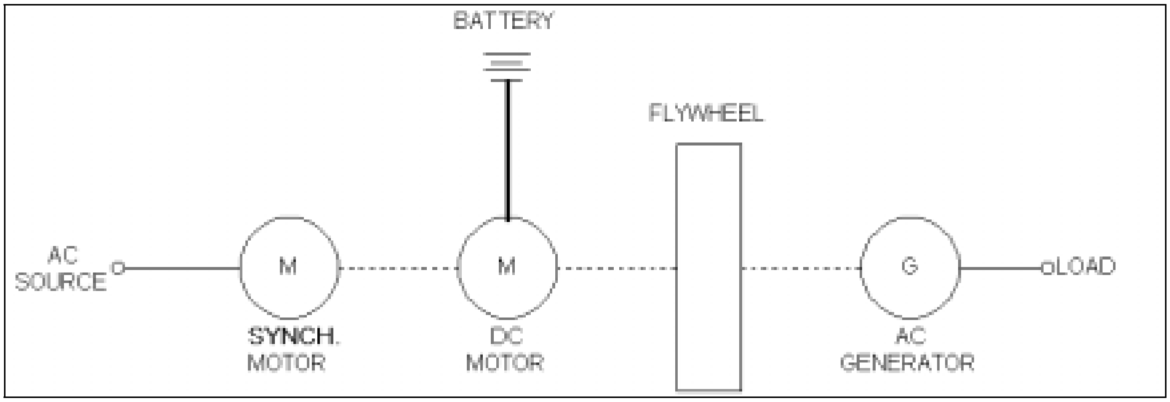

Figure 2-30. Battery supported inertia system

e. Battery supported M-G set. The battery supported M-G system with a backup inverter is shown in figure 2-31. It is made up of a synchronous M-G set with the addition of a rectifier/inverter, batteries, and a static switch. During normal operation, the static switch is conducting and 95 percent of the required power is supplied to the motor from the ac source. The remaining 5 percent power is supplied through the rectifier/inverter while the battery is float charged. The inverter is kept operational at this low power level to ensure that it remains operational and can supply full power in the event of degradation or loss of the ac source. Upon loss of the ac source or deviation of its frequency and/or voltage from acceptable limits required to maintain the generator output, the static switch is automatically blocked and power is supplied from the battery to the motor through the inverter. Upon restoration of the ac source, the static switch automatically conducts and the system reverts to normal operation. This configuration provides conditioned, isolated, and uninterrupted power. In addition, it has a higher reliability and requires less maintenance than a comparable rotary system with a dc motor. DC machines in general require more frequent maintenance due to wear in brushes and wear and pitting in the commutator ring.

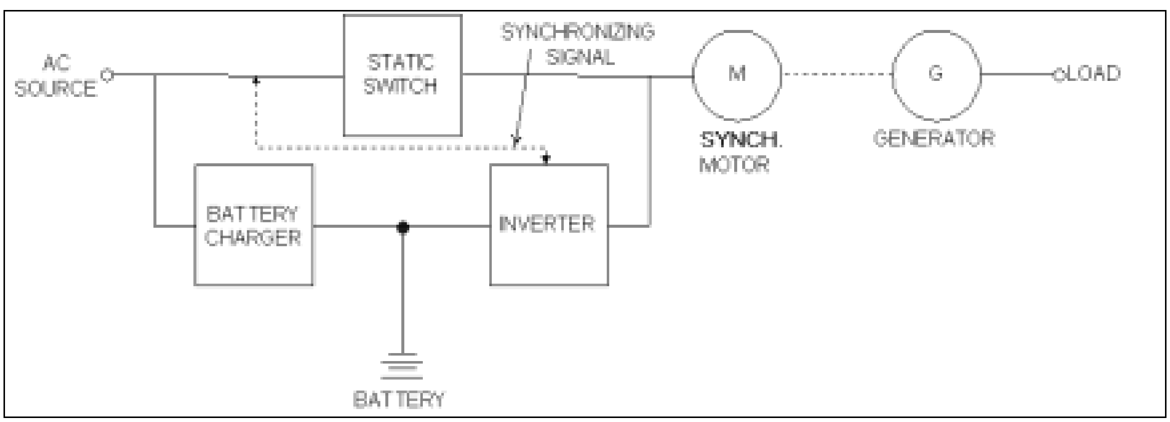

Figure 2-31. Battery supported M-G set

f. Rotary systems with a transfer switch to a bypass source. Like static UPS systems, rotary systems can be provided with a transfer switch to transfer the load to an alternate source upon loss of the generator output. However, unlike the static UPS inverter, it is not practical or economical to synchronize the generator to the alternate source. Therefore, the transfer may occur in "out-of-synch" mode and may subject the connected loads to undesirable transient overvoltages. Therefore, although the addition of a transfer switch can increase the availability of power supply, live transfer is not recommended in rotary systems. Also, less costly electromechanical switches may be adequate for this purpose.

g. Paralleling of redundant rotary systems. Redundant rotary systems may be connected in parallel to provide higher capacity and/or to increase the reliability as was discussed in paragraph 2-3c for static UPS systems. However, due to the difficulty of synchronizing the generators to one another, switching the individual generators for parallel operation should be performed without the loads being connected to avoid subjecting sensitive equipment to high voltage transients during switching.