J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

UNINTERRUPTIBLE POWER SUPPLIES

There are several uses of electric energy for which the continuous availability of electricity is critical. Examples of such applications include medical equipment, air and ground traffic control systems, electronic data-processing systems, telecommunication equipment, and process plant instrumentation. An uninterruptible power supply (*UPS*) operates in conjunction with the utility power supply to ensure a continuous supply of electric energy to critical loads. The critical loads normally use the utility as their energy source. However, in the event of utility-supply interruptions, the UPS provides the energy to those loads.

Closely related to, but distinct from, the UPS is the standby power supply (*SPS*). While the UPS ensures that the proper voltage is supplied to the load without break in the event of a power failure, the SPS permits a break during load transfer from the utility supply to the SPS.

The essential components of an UPS are (1) a means of energy storage and (2) a means of converting the stored energy to a form usable by the load. The most common energy-storage devices that are used in typical UPS applications are batteries and mechanical flywheels. Under normal conditions, when the utility supply is available, the storage device is charged up from the utility. The UPS delivers this energy to the critical load during abnormal conditions, when supply from the utility is interrupted.

Flywheels usually store mechanical energy to supply the critical load for a few seconds. UPS batteries are usually sized to be able to supply the critical load for several minutes (typically, 15 min). This permits a standby power supply, such as a diesel generator, to be started in order to supply the critical load during sustained utility-supply interruptions. In some cases, the protected equipment can be shut down gradually during the time that the UPS supply is available.

When the UPS delivers energy to the critical load, it does so through an energy-conversion circuit. The conversion circuit, or converter, ensures that the voltage provided to the load has the correct frequency and amplitude that the load needs. The converter functions as an interface between the energy-storage device and the critical load. In this way, energy is stored for emergency use in a form convenient for storage and is delivered in a form that the load needs.

In addition to their main task of providing uninterrupted energy to critical loads, UPS units are also often used to isolate the loads from other utility disturbances such as short-duration overvoltages and undervoltages, utility voltage harmonic distortion, and resonances.

This article begins with a review of the power-supply requirements of critical loads. It then discusses the various UPS types that are in common use and the power electronic inverters that make up these UPS systems. Typical UPS system configurations are considered, followed by UPS system control methods. The article also includes a section on batteries meant for UPS use.

Power-Supply Requirements of Critical Loads

Typically, utilities provide power to a large area that has a mix of various types of load. It is often difficult for utilities to meet the stringent power-quality requirements of individual critical loads economically. Often, the causes of power-supply disturbances are not in the utility's control. For example, the utility power supply may be interrupted by a tree falling on a power-supply line. In regions where the demand for electric power exceeds supply, the utility may even resort to practices such as supply-voltage reduction or load shedding to maintain the balance between supply and demand. Power supply to an installation may even be interrupted by the opening of circuit breakers as the result of a short circuit within the installation itself. In these and similar situations, critical loads need to be supplied from an UPS.

Different critical loads have different tolerances to power-supply interruptions. For example, data-processing systems, such as safety and life support systems, and communication systems have different requirements with respect to power-supply interruptions. These requirements are often governed by specific standards. References 1,2,3,4 present these requirements in detail. This article provides only an overview of these requirements.

The IEEE Standard 1159-1995, Ref. 5, describes interruptions based on the duration for which power supply is interrupted. In *short-duration* interruptions, the power-supply voltage magnitude falls to less than 10% of its nominal value. Short-duration interruptions lasting between 0.5 cycles and 3 s are termed *momentary*. Those lasting between 3 s and 1 min are termed *temporary*. (The IEEE Standard 1159-1995 also refers to instantantaneous voltage *sags*. These events have typical durations between 0.5 cycles and 30 cycles. The voltage magnitude typically falls to between 90% and 10% of its nominal value.) Long-duration, or *sustained*, interruptions last longer than 1 min, and the power-supply voltage falls to 0 V during the interruption.

The IEEE Standard 446-1995, Ref. 2, contains descriptions of power-supply requirements for various types of critical load. By way of illustration, the requirements for data-processing equipment are presented briefly in the following.

Data-processing systems are often classified as being either *on-line* or *off-line*, depending on their function. On-line data-processing systems are required to process and act on data immediately, as they arrive at the processing equipment. Off-line systems typically process data that have been stored previously. Examples of on-line data-processing systems include automatic teller machines (*ATMs*), passenger reservation systems, industrial process control systems, and web servers. Off-line systems include applications such as the handling of employee records, engineering design on workstations, scientific simulations, and word processing and typesetting.

Power-supply interruptions affect on-line and off-line data-processing systems differently. As can be expected, interruptions affect on-line systems more severely than off-line systems. The shutdown of a web server due to power failure can have severe adverse consequences to remote users connected to the server. The shutdown of a computer controlling a kiln in a cement plant would similarly have a severe impact in terms of production loss and possibly damaged equipment.

The effect of power-supply interruptions on off-line systems is generally less severe but can still be serious enough to warrant the use of an UPS. The interruption of power to a workstation executing a long simulation, for example, may make it necessary to rerun the entire simulation, resulting in the loss of hours or even days of computing time.

Data-processing equipment is sensitive not only to sustained power-supply interruptions, but also to short-duration deviations in input voltage magnitude from the nominal value. Often, magnitude deviations manifest themselves as voltage dips (sags) and voltage increases (swells). In order to be effective, an UPS system should be capable of compensating for short-duration voltage magnitude deviations as well as for sustained power-supply interruptions.

The tolerance of data-processing equipment to interruptions and voltage sags is often presented graphically by curves similar to Fig. 1, which illustrates the low-voltage part of the tolerance curve detailed in Refs. 2 and 6. This tolerance depends largely on the amount of energy stored in the internal power supplies of the data-processing equipment. In Fig. 1, the curves a and b represent equipment with different amounts of stored energy. Curve a signifies more stored energy than curve b. Note that the complete loss of voltage for more than half a cycle results in a malfunction of the data-processing equipment.

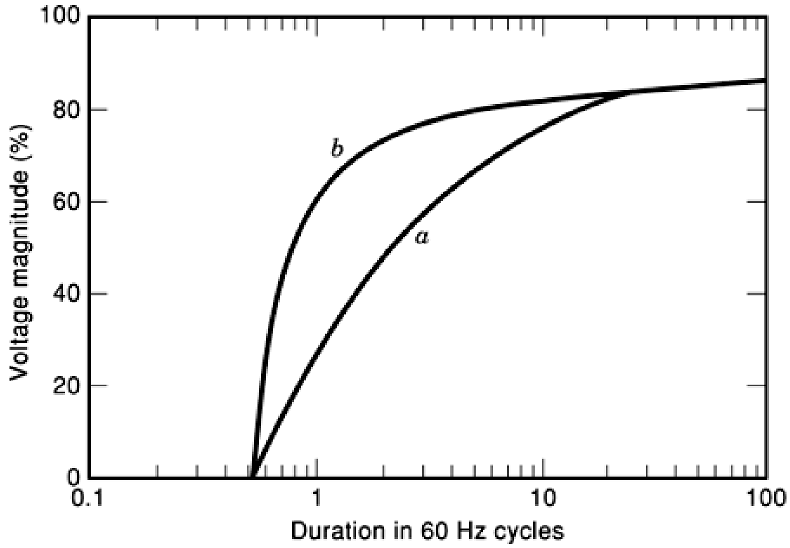

Fig. 1. Example of low-voltage tolerance of data-processing equipment. Curve a signifies more tolerance than curve b.

In the United States, the Information Technology Industry Council (*ITIC*) has published a curve that represents boundaries on the input ac voltage magnitude for information technology equipment. Known as the ITI [Computer and Business Equipment Manufacturer's Association (*CBEMA*)] curve, it is meant specifically for use with information technology equipment that has a nominal input voltage of 120 V, 60 Hz, single phase. Similarly to Fig. 1, the ITI (CBEMA) curve provides tolerance boundaries for the input voltage magnitude against time of overvoltage or undervoltage that the equipment can typically withstand. Details of the ITI (CBEMA) curve can be found in Ref. 7.

Comprehensive power-quality studies conducted in the United States (8) have found that the majority of voltage sags have a magnitude of about 80%, lasting for 4 to 10 cycles. About 40% of voltage sags fall outside the tolerance curves of Fig. 1. UPS equipment is designed to ensure that even if the utility voltage falls outside of the tolerance curves, the voltage supplied to the protected equipment is still within these curves. Furthermore, for sustained utility-supply interruptions, the UPS supplies the critical load until a backup energy source, such as a diesel generator, can be started and connected to the load bus.

Types of ups Systems

UPS systems can be either *rotary* or *static*. As the name implies, rotary UPS systems consist essentially of an ac generator at the output. The generator is driven by a dc or ac motor that is normally powered by the utility. In the event of utility-supply failure, the motor is powered from a source of stored energy. The energy is usually stored either mechanically in a flywheel or electrically in a battery. Flywheels can store sufficient energy to supply the critical load for several seconds. Batteries are used for protection against longer-duration utility-voltage interruptions. In this case the UPS design features a dc motor to drive an ac generator, and the battery is used to drive the dc motor. If an ac motor is used to drive the generator, then the battery is connected to an inverter, which powers the ac motor.

Rotary UPS systems have several attractive features. The rotating ac generator has a sinusoidal voltage output, having low harmonic content. It also effectively isolates the critical load from utility-system

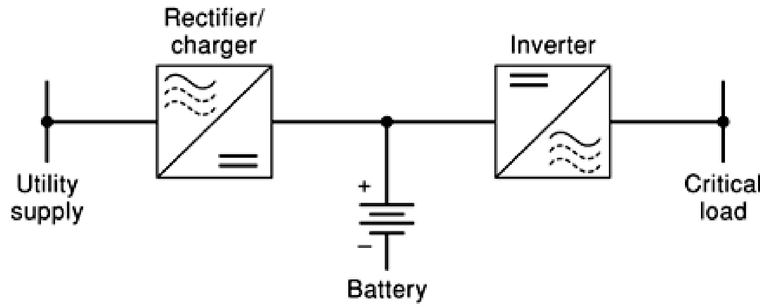

Fig. 2. Schematic diagram of a double-conversion UPS system. The input utility ac supply is rectified to dc by the rectifier or charger, and converted to output ac by the inverter.

disturbances. Furthermore, the motor and generator have predictable failure modes, making them suitable for testing and preventive maintenance. The entire UPS system is robust and tolerant of internal and external faults.

Rotary UPS systems tend to occupy more space than static UPS systems of similar rating. Because of their rotating parts, they also require stronger foundations to prevent vibrations. They also emit more acoustic noise than static UPS systems.

The majority of modern UPS systems are of the static type and have no moving parts. For these systems, electric energy is most commonly stored in batteries. This article concentrates on static UPS systems.

The basic components of a typical static UPS are the following.

(1) Battery charger
(2) Battery
(3) Inverter and filter

UPS systems can have either single- or three-phase outputs. UPS systems with three-phase outputs often provide a neutral conductor to enable the connecting of single-phase loads to the UPS output. In this situation, the load on the three-phase UPS can be unbalanced. As a result, the UPS output voltage will also be unbalanced. For different load-imbalance conditions, UPS manufacturers specify limits on the amount of output-voltage imbalance for their equipment.

The loads on UPS systems are often nonlinear—when supplied with a fundamental frequency sinusoidal voltage, they draw currents that contain harmonic frequency current components in addition to the fundamental frequency component. These harmonic current components also distort the UPS output voltage. Manufacturers usually provide the limits on the harmonic voltage distortion that appears on the output voltage of their UPS systems.

Static UPS systems are of two main types: *double conversion* and *single conversion*. This classification is based on the manner in which the UPS delivers power to the critical load. These two basic UPS types are discussed in the following.

Double-conversion UPS. In a double-conversion UPS, the utility voltage is first converted to dc by the battery charger. The dc voltage is next converted to an ac sine wave by the combination of the inverter and the filter. Figure 2 shows the schematic diagram of a basic double-conversion UPS. The input supply to the UPS can be either single phase or three phase. Similarly, the output of the UPS can be either single phase or three phase.

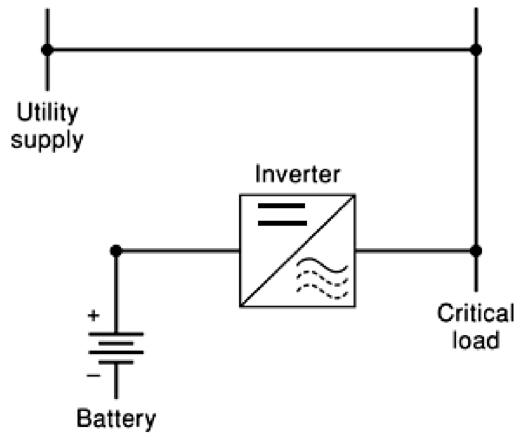

Fig. 3. Schematic diagram of a single-conversion UPS system. The inverter rectifies the utility supply to charge the battery. If the utility supply fails, the inverter takes energy from the battery to power the critical ac load.

The inverter of a double-conversion UPS is in continuous operation and supplies the load in both normal and emergency situations. Under normal operation, with the utility supply avaliable, the dc circuit of the UPS is fed from the utility through the rectifier. If the utility voltage is interrupted, the inverter automatically draws load power from the battery, and the load experiences no break in its terminal voltage.

The length of backup time during which the critical load can be supplied from the battery essentially depends on the battery capacity. For long-duration utility-voltage interruptions, an auxiliary power source, such as a diesel-generator set, can be started and brought on line to feed the load. The UPS is required to provide load power for the time it takes to bring the auxiliary power source on line.

The double-conversion UPS configuration permits an auxiliary power source to be connected to its dc circuit. For example, the dc output of a rectifier fed from a diesel-generator set can be connected in parallel to the battery. The battery can supply the load power without break until the diesel-generator set can be started. Before the battery backup time is exceeded, the set can start up and provide the load power through the UPS dc circuit.

Note that the UPS inverter essentially determines the critical load voltage in both normal and emergency operations. Since the inverter output can be controlled very accurately, the frequency and voltage stability of the load voltage are very good. The dc circuit of the UPS isolates the load from utility-supply voltage and frequency variations. However, since the inverter always carries the load power, losses in the inverter reduce the overall UPS efficiency.

Single-conversion UPS. A single-conversion UPS system does not have a separate charger for the battery. Rather, the inverter of a single-conversion UPS has bidirectional power-handling capability. When utility voltage is available, the inverter draws power from the utility to charge the battery, if needed. If the utility voltage is interrupted, the battery provides power to the load through the inverter. Figure 3 shows the schematic diagram of the basic single-conversion UPS system.

Note that unlike double-conversion UPS systems, single-conversion systems do not carry the load power when the utility voltage is available. Because of this, single-conversion systems typically have better efficiency figures than double-conversion systems. However, the critical load on a single-conversion system is more susceptible to utility-supply voltage deviations than a load on a double-conversion system.

The single-conversion UPS system shown in Fig. 3 is also often called a *line-interactive* UPS. It is always connected to the load in parallel with the utility supply. In addition to feeding the load with no break in case of utility failure, it can also provide buck or boost functionality, so that the load-voltage magnitude remains constant in the face of utility-voltage magnitude variations.

Unlike the system of Fig. 3, some versions of a line-interactive UPS system may introduce a short break in load power, as the load is transferred from the utility to the UPS or vice versa. In such systems, a transfer switch effects the transfer of the load from the utility to the UPS and back. Such systems are more appropriately termed as SPSs.

Two important variations of the line interactive UPS are the triport UPS and the ferroresonant UPS. In a triport UPS, the load, the utility, and the UPS inverter are each respectively connected to one winding of a three-winding transformer. The UPS inverter operates continuously. The phase of the inverter output voltage is adjusted so that it supplies no power. It may even take battery-charging power from the utility. When the utility-voltage fails, the utility is disconnected from the three-winding transformer, and the UPS inverter supplies the load through the transformer.

The ferroresonant UPS also connects the load to the utility through a transformer, as does a triport UPS. However, the inverter of a ferroresonant UPS is normally not in continuous operation. Rather, it is brought into operation only when the utility power fails and is disconnected from the transformer. In the interval during which the load power is transferred to the inverter, the load is fed from the energy stored in the tank circuit of the ferroresonant transformer.

The ferroresonant transformer isolates the load from distrubances on the utility supply. It also provides good regulation of the load-voltage magnitude, without having to switch on the inverter even if the utility-voltage magnitude drops by about 10%. The inverter of a ferroresonant UPS, when turned on, operates at line frequency. The transformer design provides a sinusoidal voltage to the load without the need for additional filters. Line-frequency operation of the inverter, as opposed to pulse-width-modulated (*PWM*) operation, implies that the inverter switching losses are low and overall efficiency is high.

Power Electronic Inverters for UPS Systems

A modern UPS system interfaces its battery with the critical load by means of an inverter made up of semiconductor power switches. The inverter input voltage is dc, and its output voltage is single- or three-phase ac.

The dc to ac conversion is achieved by appropriate control of the semiconductor switches of the inverter. Several families of semiconductor switches are available for general inverter applications. However, for UPS applications, the preferred switch is the insulated gate bipolar transistor (IGBT). Reference 9 contains a comprehensive discussion of the various power semiconductor switch technologies, including the IGBT.

Figure 4 shows the basic schematic diagram of an inverter with constant dc voltage and a single-phase ac output. The inverter power circuit is made up with four semiconductor power switches. Each switch is made up with an IGBT and a diode, as shown in Fig. 4. The terminal marked E is the *emitter*, C is the *collector*, and G is the *gate*. Usually, the diode and the IGBT are both internally connected in the same package. Only the terminals C, E, and G are brought out of the package for external circuit connections.

Depending upon the current-carrying capacity of the switch, a package may contain different numbers of switches. For high current ratings, a package may contain only one switch made up of an IGBT and a diode. Medium current rated packages may contain two switches, for example, switches 1 and 3 in Fig. 4, which form a *phase leg* that spans the dc bus of the inverter. For small current ratings, all the switches that make up the inverter circuit (four for single-phase inverters and six for three-phase inverters) are included in one package.

The IGBT is turned on by applying a positive voltage at the gate relative to the emitter. In the absence of this voltage, the switch is off and cannot conduct current from the collector to the emitter. Note, however, that the diode ensures that current can always flow in the opposite direction. All inverter circuits are essentially

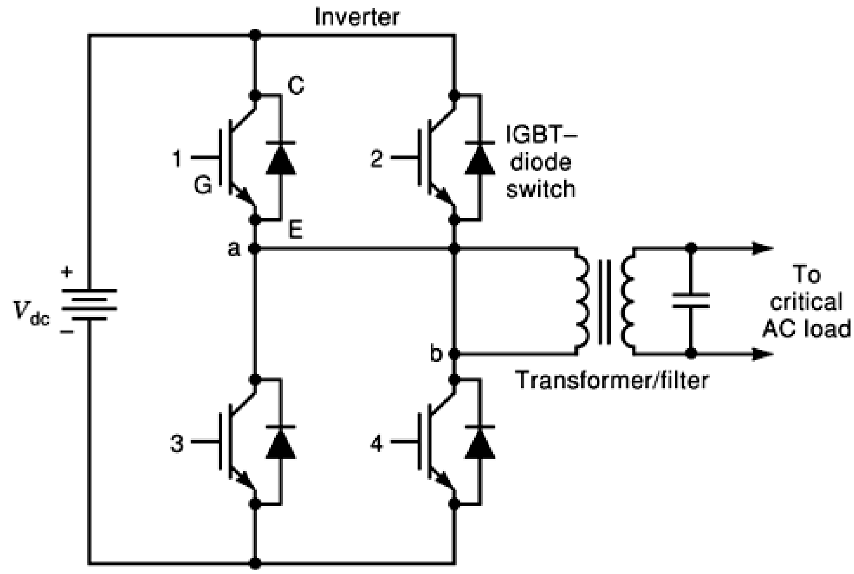

Fig. 4. A single-phase UPS inverter powers the critical load through an output transformer and filter.

switching circuits in that they synthesize the output ac voltage by appropriately turning their semiconductor switches on and off.

This section describes single- and three-phase inverter circuits and those aspects of their control concepts that are relevant to UPS applications. Further information on single-phase and three-phase inverter power circuits and their control methods can be obtained from Ref. 9.

The inverter circuits described below are used with both double- and single-conversion UPS systems. The inverters are capable of *four-quadrant* operation by which they can source or sink both active and reactive power. Their ability to function as bidirectional real-power sources makes them suitable for use with single-conversion UPS systems.

Single-phase inverters. Figure 4 shows the schematic diagram of a single-phase inverter. The battery forms the dc bus of the inverter. The inverter ac output terminals, marked a and b in Fig. 4, are connected to a transformer. The critical ac load is connected across the capacitor on the transformer secondary winding. The capacitor and the leakage inductance of the transformer form a filter that provides sinusoidal ac voltage to the critical load.

The transformer at the inverter output (Fig. 4) serves to match the inverter fundamental output voltage magnitude with the voltage magnitude required by the load. The maximum value of the inverter fundamental output-voltage magnitude is limited by the available battery dc voltage. The transformer boosts up the inverter output voltage to the required load voltage. In addition to voltage matching, the transformer also serves to isolate the load from the inverter.

In the simplest switching strategy, the IGBT switch 1 and 4 pair is turned on and off complementary to the switch 2 and 3 pair. This produces an alternating square wave at the inverter output with an amplitude equal to the dc battery voltage and a frequency equal to the desired output frequency (50 Hz or 60 Hz). UPS systems that employ inverters that follow this square-wave switching method are usually low-cost, low-power systems. Sometimes, the output filter is also omitted, and the square-wave voltage is applied directly to the load. These UPS systems may be used with loads that can withstand a square voltage wave shape and poor

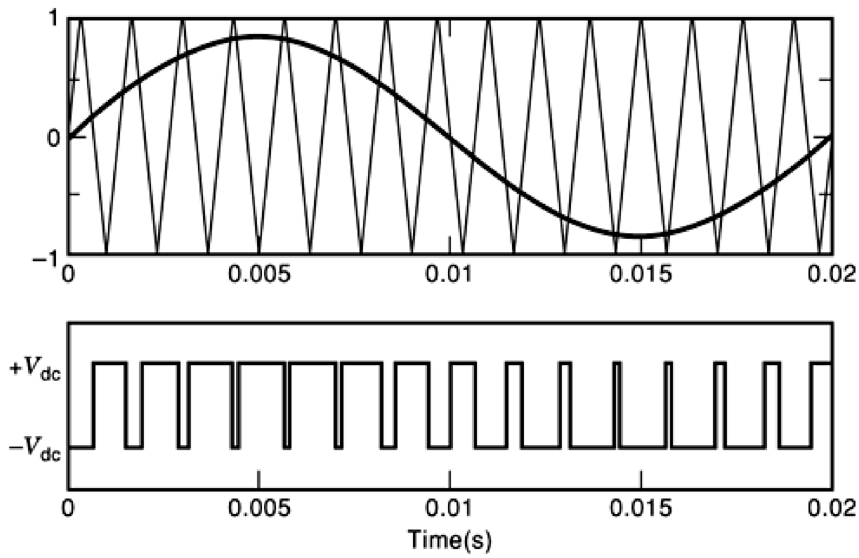

Fig. 5. Single-phase PWM by sine-triangle comparison. The upper trace shows the sine and triangle waves. The lower trace shows the inverter output voltage.

voltage-magnitude regulation, but in general, for critical loads that are sensitive to voltage waveform distortion, these are better avoided.

The preferred method of controlling the inverter switches is PWM. In this method, the output voltage of the inverter is switched in pulses of appropriate duration. The output filter acts on these pulses to produce a sinusoidal voltage at the critical load terminals.

With PWM, the width and position of each individual pulse of the inverter output voltage can be controlled so as to produce a load voltage of the desired magnitude and frequency. The ability to control the load-voltage magnitude means that it can be kept within tight tolerances in the face of changing load-current and utility-voltage magnitude. The ability to control the frequency also means that the load-voltage frequency can be kept within tight tolerances.

It is the task of the inverter control circuit to generate the PWM pattern that controls the switching on and off of the inverter switches. The control circuit does this such that the PWM voltage pattern at the output has the desired fundamental component amplitude and frequency.

A common way to generate the PWM switching pattern at the inverter ac terminals is the *sine-triangle comparison* method. In this method, the control circuit compares a reference sine wave having the desired output frequency with a higher-frequency triangle wave, as shown in Fig. 5. If the value of the sine signal is greater than that of the triangle signal, switches 1 and 4 are turned on. Otherwise, switches 2 and 3 are turned on. This strategy to control the switches results in the pulse pattern shown in Fig. 5. This pattern appears across the inverter ac output terminals a and b.

The frequency of the triangle wave determines the inverter *switching frequency*, which is the frequency at which the inverter switches operate. The filter formed by the transformer leakage inductance and the capacitor, shown in Fig. 4, serves to ensure that only the sinusoidal fundamental component of the pulse pattern at the inverter output is applied to the load.

The amplitude of the triangle wave is fixed, and the amplitude of the reference sine wave can be changed by the controller. As the amplitude of the reference sine wave is increased from zero, the amplitude of the fundamental component of the pulse pattern appearing at the inverter output increases proportionately. This

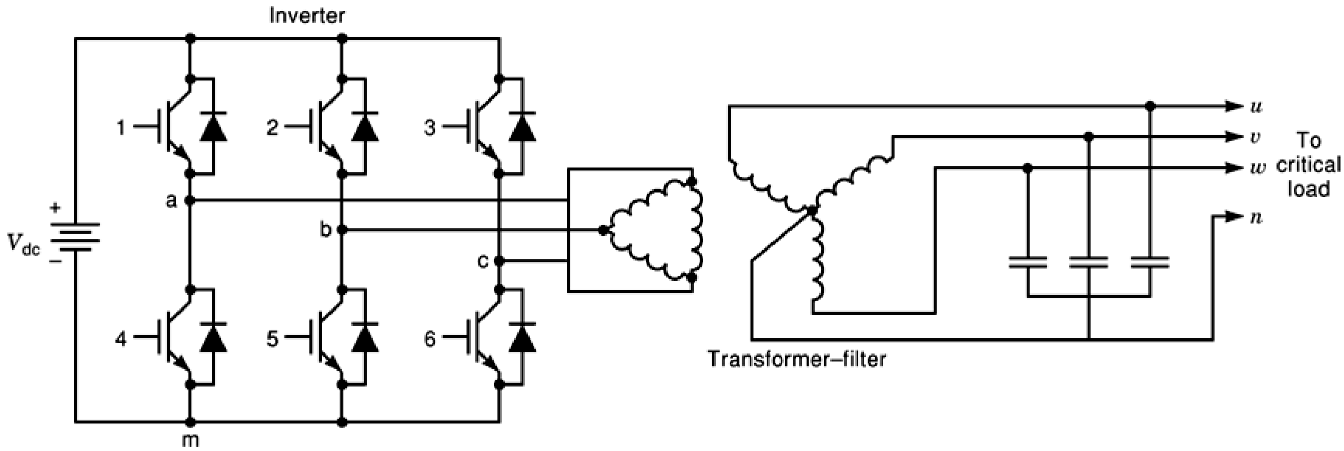

Fig. 6. A three-phase UPS inverter with an output transformer and filter.

proportionality is maintained until the amplitudes of the sine wave and the triangle wave are equal. As the sine-wave amplitude is increased beyond the triangle-wave amplitude, the amplitude of the fundamental of the inverter output pulse pattern is no longer proportional to the reference sine-wave amplitude.

In addition to controlling the output-voltage amplitude, the UPS controller also needs to control the frequency and phase of the output voltage. Often, control of frequency and phase may be more critical than control of the amplitude. For example, errors in the frequency and phase of the inverter output voltage may result in loss of synchronization between the filtered inverter output voltage and an alternate bypass source. In this situation, it may not be possible to effect a no-break transfer of the load from the UPS to the bypass source and vice versa.

Three-phase inverters. UPS systems with a three-phase output voltage incorporate a three-phase inverter. The most commonly used three-phase inverter power circuit is an extension of the single-phase inverter, and is shown in Fig. 6. This three-phase circuit has one more leg of IGBT switches than the single-phase inverter of Fig. 4. The inverter output is usually given to a three-phase filter to produce a balanced sinusoidal voltage supply for the critical load.

Figure 6 also shows the filter capacitors on the transformer load side winding. These capacitors, along with the transformer leakage inductance, form a filter that allows only the fundamental component voltage to appear across the load terminals. An external three-phase inductance may also be used to form the filter, especially if there is no transformer at the inverter output.

As with the single-phase circuit, the three-phase UPS inverter is also often connected to an output transformer for voltage matching and isolation. In this case, the load side of the three-phase transformer is wye-connected, and the output to the load is a three-phase, four-wire output in which the transformer star point provides the neutral conductor. In this arrangement, single-phase loads can also be connected to the UPS output between a phase and the neutral conductor.

Three-phase inverters for UPS applications typically use PWM to control the turning on and off of their semiconductor switches. A common method to generate the PWM pattern is the sine-triangle comparison method, similar to the method described in the previous section for single-phase inverter control.

The sine-triangle comparison method for three-phase inverters uses three reference sine waves and one higher-frequency triangle wave. The reference sine waves form a balanced set, having the same amplitude, and a relative phase shift of 120° between each other. However, the UPS controller may cause deliberate unbalances in the three-phase reference in order to compensate for unbalanced load on the UPS output.

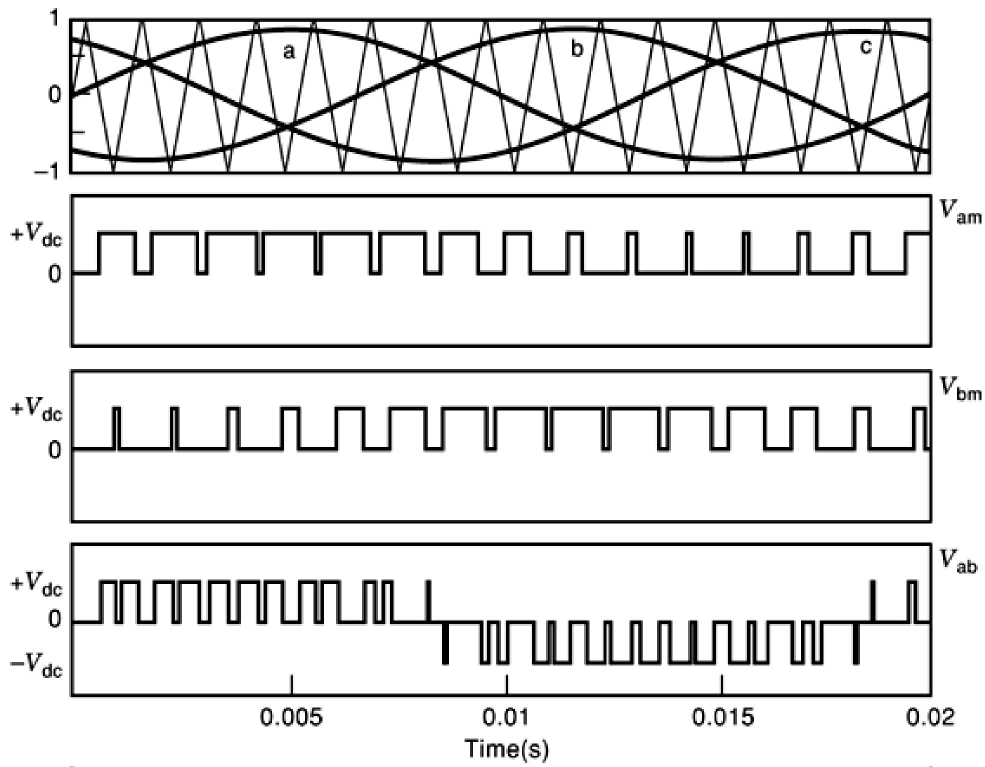

Fig. 7. Three-phase PWM by sine-triangle comparison. The uppermost trace shows the three-phase reference sine waves and the triangle wave. The lower traces show the inverter a phase voltage (V_{am}), the b phase voltage (V_{bm}), and the phase-to-phase voltage (V_{ab}).

Figure 7 shows the sine-triangle comparison method for controlling three-phase inverters. The uppermost section of Fig. 7 shows the three-phase reference sine waves and the triangle wave. The reference sine waves are marked as a, b, and c. The lower sections show the inverter voltages V_{am}, V_{bm}, and V_{ab}. V_{am} is the voltage of inverter output terminal a with respect to the negative dc bus terminal (Fig. 6). Similarly, V_{bm} is the voltage of terminal b with respect to the negative dc bus terminal. $V_{ab} = V_{am} - V_{bm}$ is the voltage across the inverter output terminals a and b.

As with sine-triangle PWM for single-phase inverters, the inverter fundamental output-voltage magnitude is proportional to the amplitude of the reference signals as long as the reference amplitude is less than the triangle amplitude. For larger reference amplitudes, proportionality is lost.

The sine-triangle comparison method described here for single- and three-phase inverters is one of several methods in use to control the switching of the inverter switches in UPS applications. Details of the characteristics of the sine-triangle comparison method can be found in Ref. 9.

There are numerous variations of the basic sine-triangle comparison method described here. In addition, there are many PWM methods that do not make use of sine-triangle comparions at all. A review of various PWM methods and their relative comparison can be found in Ref. 10.

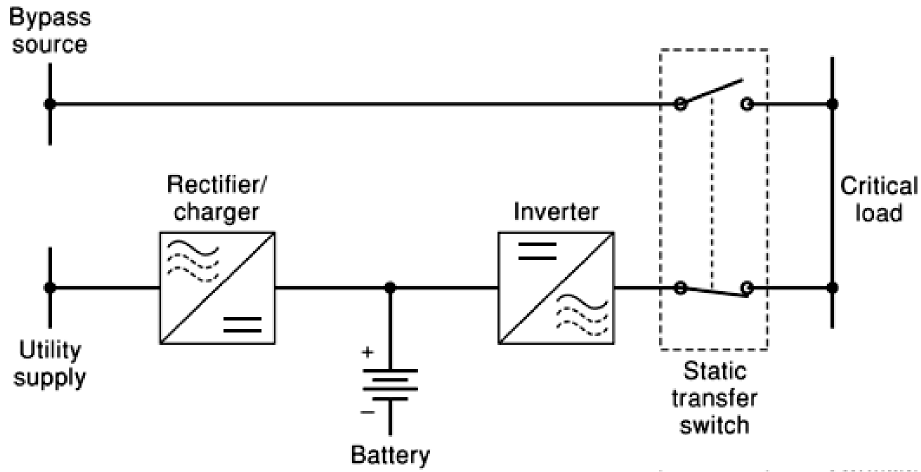

Fig. 8. A double-conversion UPS configuration with a bypass source and a static transfer switch. The switch connects the critical load to either the UPS output or to the bypass source.

UPS System Configurations

Both the basic UPS types—double and single conversion—can be used in a variety of larger system configurations. Many of these configurations are discussed in Refs. 2, 11, and 1.

The motivations behind different UPS system configuration designs are (1) increasing the power rating of the system and (2) increasing the overall system reliability. The total power rating of the UPS system can be increased by connecting more units in parallel. This provides a measure of flexibility in the UPS system design, as the system can grow to accommodate increases in installed load.

Often, an extra UPS unit is included in the system configuration for the purpose of redundancy. This practice increases the reliability of the overall configuration, as the failure of one UPS unit in the overall system does not cause a system shutdown. The failed unit is rapidly disconnected from the system, which still has sufficient capacity to supply the entire critical load. Interested readers will find a discussion on the issues relating to UPS system reliability calculations in Ref. 12.

Of the several possible UPS system configurations, the two most commmon are (1) static transfer switch connection to a bypass source and (2) parallel redundant configuration.

Bypass source connection. A common UPS system configuration, involving a static transfer switch, is shown in Fig. 8. The static transfer switch makes it possible to connect the critical load either to the UPS output or to a bypass source. Apart from increasing the reliability of the overall configuration, the bypass connection makes it possible to supply the critical load when the UPS is disconnected for maintenance and repair. If the UPS output voltage and the bypass source voltage are synchronized, the transfer from one source to the other can take place without a break in the critical load supply.

The bypass source may either be independent of the main utility voltage, or be derived from it. The transfer switch can be in either of two positions for normal operation. In the *UPS preferred* scheme, the transfer switch connects the critical load to the UPS output during normal operation. In the *bypass preferred* scheme, the transfer switch normally connects the critical load to the bypass source.

Figure 8 shows the bypass configuration for a double-conversion UPS system. A similar configuration is possible for a single-conversion system as well. An example of a bypass configuration with a single-conversion UPS system can be found in Ref. 13 and is illustrated in Fig. 9. For UPS preferred operation, switch S1 is open

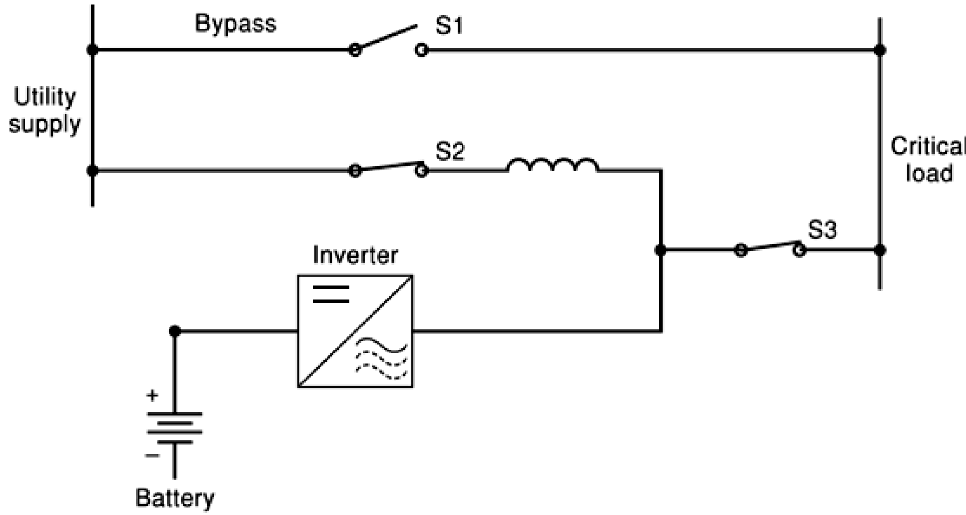

Fig. 9. A single-conversion UPS configuration with a bypass source and a static transfer switch. The switch either bypasses the UPS or permits it to operate in parallel with the utility, while supplying the critical load.

and switches S2 and S3 are closed. Similarly, for bypass operation, switch S1 is closed and switches S2 and S3 are open.

Parallel redundant configuration. The reliability of a UPS system configuration can be substantially improved if extra UPS modules are connected in parallel. Usually, this redundancy is obtained by connecting one more than the number of UPS modules needed to supply the entire critical load, a practice often called $n + 1$ redundancy. In case a particular UPS module fails, it is rapidly removed from the configuration by a solid-state disconnect switch. The remaining UPS configuration continues to supply the critical load up to its rated capacity. The failed UPS module can then be repaired and connected back to the configuration.

Figure 10 shows a $1 + 1$ parallel redundant UPS configuration with double-conversion UPS units. In addition to redundancy, the configuration shown in Fig. 10 also incorporates a bypass source and a static transfer switch. A similar configuration can be constructed with single-conversion UPS units as well.

The configuration shown in Fig. 10 incorporates redundancy in all UPS components. It is also possible, at the expense of reliability, to incorporate partial redundancy in some of the UPS components. For example, a partially redundant UPS configuration may include a single battery bank instead of individual battery banks.

Manufacturers of parallel redundant UPS systems have to address the issue of power balance between the parallel connected units. Since all UPS units in a parallel redundant configuration have equal ratings, the total load power should be distributed equally among all the parallel connected units. However, inequalities in filter components, output transformer ratios, and battery voltages cause unequal power sharing. The control systems of the UPS units are designed to compensate for these effects and to ensure both real- and reactive-power balance among the units.

Real- and reactive-power balance between the parallel connected UPS units is achieved by controlling the phase and the magnitude of the fundamental component of the inverter output voltage in each unit. In a frequently used load-sharing control strategy, each UPS unit measures its own output current and also makes it available to every other unit connected in parallel. Each unit also measures its own output voltage. On the basis of the voltage and current measurements, each unit calculates the phase and magnitude of its voltage reference, so as to achieve real- and reactive-power sharing.

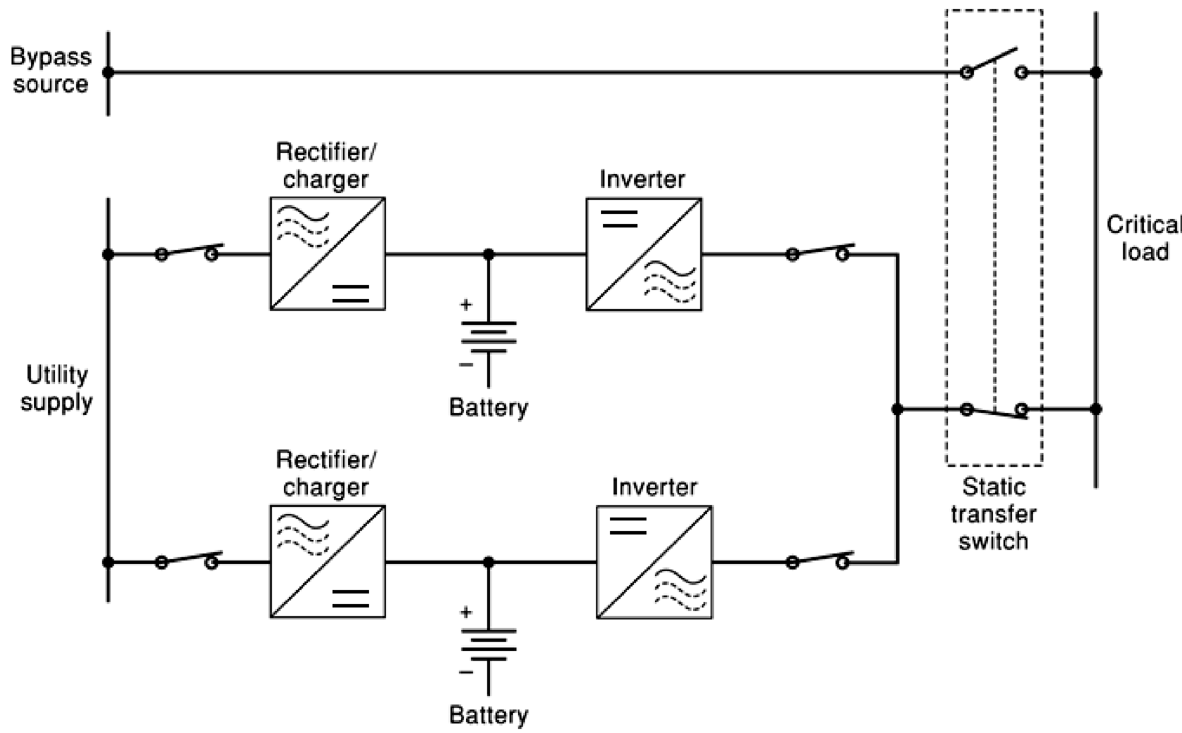

Fig. 10. A parallel redundant UPS configuration with a bypass source and a static transfer switch. The two UPS units share the critical load power. The configuration provides redundancy and ensures that the load is powered even if one of the two UPS units were to fail. The static transfer switch can be used to bypass the UPS configuration.

Another control concern of parallel redundant system design is the synchronization of the UPS units with each other and with the main supply or the bypass source. UPS units need to be synchronized with each other to ensure that they all operate at the same frequency and that their output voltages have the same relative phase angles at the point of the parallel interconnection. In addition, the output voltage of the parallel connected unit ensemble needs to be synchronized with the main supply or bypass source to ensure a no-break transfer between the bypass and UPS systems.

A frequently used method to achieve synchronization is the so-called *master-slave* approach, in which one UPS unit is the *master* and all other units are *slaves*. The master unit sets the frequency and phase reference, synchronous with the main supply or the bypass source. The other units synchronize their output voltages with the master reference. In this strategy, it is very important to implement a protocol to decide which unit should be the master. If the master should fail and be disconnected from the configuration, the protocol assigns the role of the master to another unit.

Examples of power sharing and synchronization control methods for parallel redundant UPS configurations can be found in Refs. 14,15,16.

Control Methods for UPS Systems

Pulse-width modulation control of the UPS inverter is at the lower control level—it directly controls the turning on and off of the inverter semiconductor switches. The reference signals to the pulse-width modulator are provided from higher control levels. These control levels essentially determine the instantaneous amplitude and frequency of the reference sine waves and provide these as references to the pulse-width modulator. Modern UPS control systems are implemented digitally via control hardware built around one or more digital processors.

The UPS control produces the reference signals for the modulator to achieve various tasks. The basic tasks include the following.

(1) Load-voltage magnitude and frequency regulation
(2) Damping of output filter oscillations
(3) Maintaining a sinusoidal voltage waveform at the load
(4) Maintaining phase-voltage balance (for three-phase UPS)
(5) Ensuring power sharing (for parallel redundant UPS systems)

Apart from these basic tasks, the UPS control system should also provide for battery functions: charging and float operations. At a higher level, the controller also often provides features for battery monitoring during normal operation and during battery discharge and charge. Communication between the UPS and the protected equipment permits the gradual shutdown of the equipment when the battery voltage falls below the specified minimum value during long-duration utility failures. These control system requirements are common to both UPS types—double and single conversion.

Load-voltage magnitude and frequency regulation. Load-voltage magnitude and frequency have to be regulated in the face of load changes, utility-voltage changes, and changes in the battery voltage during discharge. Essentially, this is done by changing the amplitude and frequency of the sine-wave reference shown in Figs. 5 and 7.

For no-break transfer of the critical load between utility and UPS, the UPS output voltage should be synchronized with the utility voltage. The use of a phase-locked loop (*PLL*) is a very effective way of achieving this synchronization. The PLL ensures that the sinusoidal references that are provided to the pulse-width modulator have a desired phase relative to the utility voltage. Thus, the sinusoidal references track the phase of the utility voltage. Any change in the phase or frequency of the utility voltage is also tracked by the references.

There are several ways for UPS controllers to generate sinusoidal references of variable amplitude and frequency, all suitable for use with a PLL to enable synchronization with the utility voltage. A common method, used with digital processors, is the use of a table of precomputed sine values stored in memory on the digital hardware. The rate at which the values are accessed by the controller determines the frequency of the reference sine wave. The amplitude of the reference sine wave is set by the digital processor by appropriately scaling the sine values read from the table.

Another way to generate the reference sine waves digitally is to use the mathematical processing power of the digital processor to solve the equations of a simple harmonic oscillator. These equations are as follows:

$$\frac{d}{dt}x = \omega y$$
$$\frac{d}{dt}y = -\omega x$$

In these equations, ω is the desired angular frequency for the sine waves. With the initial conditions $x(0) = 0$ and $y(0) = 1$, the preceding equations, when solved for the digital processor, result in $x(t) = \sin \omega t$ and $y(t) = \cos \omega t$.

The digital generation of sine waves by using the preceding equations is especially suitable for UPS applications, since the required frequency range is small for such applications. Moreover, it facilitates implementing the phase-locked loop synchronization fully digitally.

Damping of output filter oscillations. The UPS schematic diagrams in Figs. 4 and 6 show the filter formed by the filter capacitor and either the transformer leakage inductance or an externally connected filter inductance. This filter attenuates the harmonic components in the PWM voltage waveform at the UPS inverter output and thus ensures that the load voltage is sinusoidal. The filter has a natural angular frequency of oscillation given by

$$\omega_{\mathrm{f}} = \frac{1}{\sqrt{L_{\mathrm{f}} C_{\mathrm{f}}}},$$

where C_{f} is the filter capacitance value and L_{f} is the sum of the transformer leakage inductance and the externally connected filter inductance.

The presence of a load on the UPS system would modify the frequency of oscillation slightly. However, in most cases, the filter oscillations are underdamped. Unless actively damped by the inverter controller, these oscillations would be superimposed on the desired sinusoidal output voltage.

Filter-oscillation damping is achieved by appropriately modifying the references that the controller provides to the pulse-width modulator. Often, this modification takes the form of adding a damping signal to the original sinusoidal signal before providing it to the pulse width modulator. A common method to generate the damping signal is to make it proportional to the time derivative of the voltage across the filter capacitor. It can be shown that this practice is effective in damping the filter oscillations, for example, in Ref. 17.

Since the filter capacitor current is proportional to the time derivative of the voltage, many practical implementations use capacitor current measurement and feedback to achieve filter-oscillation damping. More information on this approach to damp the filter oscillations can be obtained in Refs. 17 and 18.

Maintaining a sinusoidal load-voltage waveform. UPS systems are often required to feed nonlinear loads. These loads, when excited by the UPS sinusoidal voltage at fundamental frequency, also draw harmonic currents from the UPS, in addition to a fundamental current. An example of a nonlinear load is the diode rectifier bridge, found in the input stage of most computer power supplies.

The harmonic currents drawn by such loads tend to distort the UPS output-voltage waveform. Achieving a sinusoidal waveform in the presence of harmonic load currents is accomplished by a combination of filter design and the UPS control system. Deviations of the UPS output voltage waveform from the sinusoidal are quantified by total harmonic distortion (*THD*), which is the ratio of the root-mean-square (*rms*) value of the harmonic voltages to the rms value of the fundamental voltage component.

The current drawn by a diode rectifier bridge has a peak value that can be substantially higher than the peak value of its fundamental component. The ratio of the peak value of the load current to the rms value is called the *crest factor*. Manufacturers of UPS systems that are designed to supply nonlinear loads provide information on the maximum load-current crest factor that the UPS system can tolerate so that the output-voltage waveform distortion is within specifications. For example, a particular UPS manufacturer of three-phase UPS systems designed for nonlinear loads specifies a THD of 5% when the UPS supplies a load that draws a current with a 3:1 crest factor.

Maintaining UPS phase-voltage balance. When a three-phase UPS system supplies an unbalanced three-phase load, the UPS should regulate its output voltage so that the imbalance between the phase voltages is within specifications. A set of unbalanced three-phase UPS output voltages can be written in the following form:

$$
\begin{aligned}
v_a &= V_a \cos(\omega t) \\
v_b &= k_b V_a \cos\left(\omega t - \frac{2\pi}{3} + \delta_b\right) \\
v_c &= k_c V_a \cos\left(\omega t + \frac{2\pi}{3} + \delta_c\right)
\end{aligned}
$$

In the above equations, ω is the angular frequency of the UPS output voltage. The constants k_b and k_c represent amplitude deviations from the perfectly balanced case, and the constants δ_b and δ_c represent phase deviations. For the perfectly balanced case, $k_b = k_c = 1$ and $\delta_b = \delta_c = 0$.

Unbalanced conditions in three-phase networks are analyzed by the *theory of symmetrical components*, in which unbalanced three-phase quantities are represented by their balanced symmetrical component sets: (1) the positive sequence set, (2) the negative sequence set, and (3) the zero sequence set. Within each set, all the phase components have equal amplitude. All components have the same frequency as the original unbalanced three-phase quantities. The three-phase components of the positive sequence set are represented as

$$
\begin{aligned}
v_{a+} &= V_+ \sin(\omega t + \phi_+) \\
v_{b+} &= V_+ \sin\left(\omega t - \frac{2\pi}{3} + \phi_+\right) \\
v_{c+} &= V_+ \sin\left(\omega t + \frac{2\pi}{3} + \phi_+\right)
\end{aligned}
$$

The negative sequence set is as follows:

$$
\begin{aligned}
v_{a-} &= V_- \sin(\omega t + \phi_-) \\
v_{b-} &= V_- \sin\left(\omega t + \frac{2\pi}{3} + \phi_-\right) \\
v_{c-} &= V_- \sin\left(\omega t - \frac{2\pi}{3} + \phi_-\right)
\end{aligned}
$$

The zero sequence set is as follows:

$$
v_{a0} = v_{b0} = v_{c0} = V_0 \sin(\omega t + \phi_0)
$$

The individual phase quantities are the sum of the corresponding sequence components. For example, the phase voltage v_b is given by the following equation:

$$
v_b = v_{b+} + v_{b-} + v_{b0}
$$

In these equations, the quantities V_+, V_-, V_0, ϕ_+, ϕ_-, and ϕ_0 are determined by the extent of voltage imbalance. Interested readers can obtain more information on unbalanced three-phase system analysis from Refs. 19 and 20.

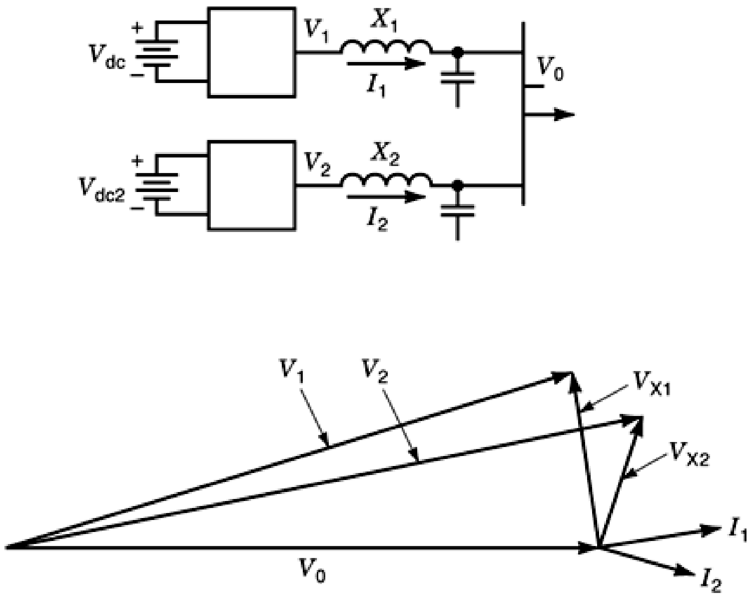

Fig. 11. Power sharing between two parallel connected UPS units. The two units are expected to share the load power equally. Differences in their dc bus voltages and output filter components make it necessary to incorporate power-sharing functionality in the UPS unit control systems.

While the equations given above consider UPS output voltages, the same analysis is valid for unbalanced load currents. Manufacturers of three-phase UPS systems meant to supply unbalanced loads specify the amount of imbalance that occurs on the UPS output voltage for a given amount of imbalance in the output load current. Load-current imbalance can be measured as the ratio of the magnitude of the negative or zero sequence current component to the magnitude of the positive sequence component. The ratio is often expressed as a percentage. Thus, in a three-phase four-wire system, a single-phase load connected between any one phase and the neutral conductor, with no load on the other two phases, results in a current imbalance of 100%.

UPS manufacturers often provide a figure for output-voltage imbalance for 100% load-current imbalance. For example, a UPS system designed for unbalanced-load operation may be specified to maintain its output voltage imbalance to less than 2% for a load current imbalance of 100%.

Often, loads on three-phase UPS systems are nonlinear as well as unbalanced. Such loads draw unbalanced harmonic currents in addition to unbalanced fundamental currents. Reference 21 provides information on UPS control under nonlinear unbalanced-load conditions.

Ensuring power sharing. In a parallel redundant UPS system, it is important to ensure that the load power is shared equally by all the parallel connected UPS units. The issues governing power sharing between two parallel connected UPS units are illustrated by the phasor diagram of Fig. 11.

In Fig. 11, V_0 is the load voltage, and V_1 and V_2 are the fundamental component output voltages of the two inverters. The voltages across the filter inductances are V_{X_1} and V_{X_2}. The fundamental component inverter output currents are I_1 and I_2. The impedance magnitudes of the filter inductances L_1 and L_2 are $X_1 = \omega L_1$ and $X_2 = \omega L_2$.

The angles δ_{10} and δ_{20}, measured counterclockwise from V_0 to V_1 and from V_0 to V_2, respectively, have a crucial influence on the real power supplied by each UPS unit to the common load. The two UPS units supply real-power values to the load as follows:

$$P_1 = \frac{V_1 V_0}{X_1} \sin \delta_{10}$$
$$P_2 = \frac{V_2 V_0}{X_2} \sin \delta_{20}$$

Likewise, the reactive-power values supplied by the two units are as follows:

$$Q_1 = \frac{V_0}{X_1}(V_1 \cos \delta_{10} - V_0)$$
$$Q_2 = \frac{V_0}{X_2}(V_2 \cos \delta_{20} - V_0)$$

Normally, during parallel redundant operation, the two UPS units should share the load real and reactive power equally, such that $P_1 = P_2$ and $Q_1 = Q_2$. Differences in the dc voltages and filter inductance values of the two units require that, to ensure real- and reactive-power balance, the sine-wave reference signals of the two pulse-width modulators should have different amplitudes and different phase shifts relative to the load voltage V_0.

Appropriate sine-wave references to ensure power sharing are usually generated by measuring the total load current as well as the current of each UPS unit. This measurement is used to calculate the real and reactive powers supplied by the individual units and thus the power-sharing mismatch. Each UPS unit controller generates its references to eliminate the mismatch.

Batteries for UPS Systems

Battery designs are usually tailored for the needs of particular applications. UPS applications are characterized by the following features:

(1) UPS applications are usually stationary.
(2) UPS batteries undergo discharge and charge cycles infrequently.

Because of these features, batteries for UPS applications are of two main types: (1) lead-acid batteries and (2) nickel-cadmium batteries. Of these, lead-acid batteries find more widespread use than nickel-cadmium batteries. Lead-acid batteries are cheaper than equivalent nickel-cadmium batteries. Further, lead-acid batteries are available in larger capacities than nickel-cadmium batteries.

Batteries meant for use with UPS systems are designed for short-duration use, with high discharge rates. A typical figure for the UPS backup time is 15 min, after which either an alternative source is used to supply the critical load or the load is shut down in a predetermined manner.

As a battery discharges its stored energy into the load, its terminal voltage decreases. In UPS applications, the battery is allowed to discharge down to a specified end-of-discharge voltage. The energy-storage capacity of a battery is given in ampere-hours, and is specified by the battery manufacturer for a given discharge rate, electrolyte temperature, specific gravity, and end-of-discharge voltage.

When a utility supply is available, the UPS battery does not supply the load. Instead, the charger keeps the battery in *float service* by keeping the battery terminal voltage slightly higher than the normal battery voltage. This compensates for battery internal losses, and keeps the battery fully charged.

The battery needs to be recharged after a temporary utility-supply failure. The charger may apply the normal float-service voltage to the battery terminals to recharge the battery. The recharging process can be accelerated by applying at the battery terminals a *boost voltage* that is higher than the float voltage. UPS manufacturers using boost recharging in their equipment need to ensure that the boost voltage is always less than the maximum voltage specified by the battery manufacturer and also less than the maximum dc voltage specified for the equipment connected to the battery terminals. Excessive boost charging may shorten battery life. Some battery types, for example, valve-regulated lead-acid batteries, do not permit boost charging.

UPS manufacturers also need to design their equipment so that battery-discharge and -recharge cycles are mimimized during normal operation. In a double-conversion UPS system, the battery may be discharged by a load change that may be beyond the rectifier rating. A drop in the utility-supply voltage magnitude may also cause load power to be drawn from the battery.

The following two sections discuss the two commonly used batteries in UPS applications. Further information on batteries for UPS applications can be found in Refs. 2, 22, and 23.

Lead-acid batteries. Lead-acid batteries use a solution of sulfuric acid and water as the electrolyte, lead dioxide for the positive plate, and lead for the negative plate. When the battery is under discharge, sulfate ions in the electrolyte are used up, and lead sulfate is formed at both electrodes. Water is also generated in the process. When the battery is recharged, lead sulfate is converted to lead dioxide at the positive plate and lead at the negative plate, and oxygen and hydrogen are released.

In a lead-acid cell, the specific gravity of the electrolyte is an indicator of the ratio of sulfuric acid to water. The specific gravity figure for lead-acid batteries typically ranges between 1.17 and 1.3, depending on battery design and intended usage. Batteries meant to be operated in high ambient temperature environments (about 30°C) usually have lower figures of specific gravity. Higher specific gravity figures result in cells with higher storage capacity. However, battery life is reduced, and internal losses are higher. A higher float-service voltage is needed to compensate for the higher losses.

Lead-acid cells have a nominal dc open circuit voltage of 2 V, and a battery is made up of a series connection of several cells. There are two types of lead-acid batteries: (1) vented batteries and (2) valve-regulated batteries.

Vented lead-acid batteries. Also called *flooded batteries*, these batteries are constructed with the electrolyte completely flooding the cell plates. The battery is equipped with flame-arrestor vents, which permit oxygen and hydrogen—generated during charging—to escape from the battery. Regular maintenance of vented lead-acid batteries includes monitoring the level and specific gravity of the electrolyte.

These batteries have low internal resistance and can provide high currents to the load during discharge. These batteries are often used in large stationary battery banks with high storage capacity.

Valve-regulated lead-acid batteries. In a valve-regulated lead-acid (*VRLA*) battery, the electrolyte is immobilized. The battery is sealed, except for a vent that releases internal gases periodically to regulate internal pressure.

The generation of gases during charging is limited by a recombination process. Oxygen, which is generated at the anode during charging, is directed to the cathode instead of being vented out. This results in a reaction that essentially limits the loss of water from the battery. Since the battery needs no addition of water, it is often called a *maintenance-free* battery.

However, improper usage of a VRLA battery will result in a loss of water. The sealed construction of the battery does not permit the water to be replaced, and the battery dries out and becomes unusable. This can happen when the battery is overcharged or charged at a higher voltage than recommended. Boost charging is usually not recommended for VRLA batteries.

Nickel-cadmium batteries. Unlike the lead-acid battery, the nickel-cadmium battery uses an alkaline electrolyte, potassium hydroxide, which does not participate in the reaction. Nickel hydroxide at the anode and cadmium hydroxide at the cathode form the active reagents.

A nickel-cadmium cell has an open circuit voltage of about 1.3 V, and batteries are made up of several series-connected cells. Batteries can operate over wide temperature ranges and can tolerate deep discharges better than lead-acid batteries. However, nickel-cadmium batteries are costlier than equivalent lead-acid batteries.

The most common constructions for nickel-cadmium batteries use a vented design, although sealed batteries are also available with limited capacity. Nickel-cadmium batteries can sustain high charging rates without damage and can also be boost charged after a discharge cycle.

Conclusion

UPS systems play an important role in ensuring the proper functioning of critical electric equipment. Working together with the main utility power supply, these systems ensure that electric voltage with the appropriate specifications is available at all times to power the critical equipment. UPS systems protect their critical loads not only from utility-power-supply interruptions but also from problems such as utility-voltage sags and surges. It is often difficult for large power utilities, with their mix of loads having different power-quality requirements, to meet the needs of individual critical loads economically. The use of UPS systems is often the most economical solution for providing high-quality power to critical electric loads.

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