Uninterruptible Power Supply Systems Provide Protection

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UPS Systems Are a Reliable Source of Continuous Electric Power During Outages or Line Problems

JOSEP M. GUERRERO, LUIS GARCÍA DE VICUÑA, and JAVIER UCEDA

NOWADAYS, UNINTERRUPTIBLE power supply (UPS) systems are in use throughout the world, helping to supply a wide variety of critical loads, such as telecommunication systems, computer sets, and hospital equipment, in situations of power outage or anomalies of the mains. In the last few years, an increasing number of publications about UPS systems research have appeared, and, at the same time, different kinds of industrial UPS units have been introduced in the market. Furthermore, the development of novel storage systems, power electronic topologies, fast electrical devices, high-performance digital processors, and other technological advances yield new opportunities for UPS systems.

A UPS is a device that maintains a continuous supply of electric power to the connected equipment by supplying power from a separate source when the utility mains are not available. The UPS is normally inserted between the commercial utility mains and the critical loads. When a power failure or abnormality occurs, the UPS will effectively switch from utility power to its own power source almost instantaneously. There is a large variety of power-rated UPS units: from units that will backup a single computer without a monitor of around 300 VA, to units that will power entire data centers or buildings of several megawatts, which typically work together with generators.

This article describes the most common line problems and the relationship between these and the different existing kinds of UPS, showing their operation modes as well as the existent energy storage systems. It also addresses an overview of the control schemes applied to different distributed UPS configurations. Finally, it points out the applicability of such systems in distributed generation, microgrids, and renewable energy systems.

Common Power Line Problems

Public utility grids have many types of power line problems that encompass a wide range of different phenomena. The typical power quality problems that UPS systems correct can be seen in Table 1. The line problems considered here are the following: failures, sags, under-voltages, surges, brownouts, swells, spikes, frequency variations, noise, and harmonic distortions [1]. UPS systems should be able to protect critical loads from these issues. Hence, UPSs are divided into categories depending on which of the above problems their units address [2].

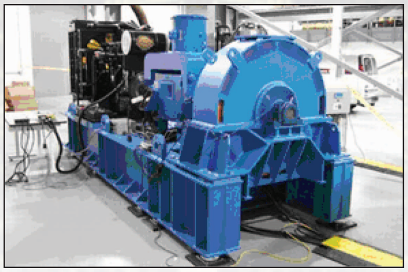


FIGURE 1 — Rotary UPS from SatCon Power Systems. (Courtesy of SatCaon Technology Corporation.)

Types of UPS Systems

UPS systems are generally classified as static, which use power electronic converters with semiconductor devices, and rotary (or dynamic), which use electromechanical engines such as motors and generators. The combination of both static and rotary UPS systems is often called a hybrid UPS system [3].

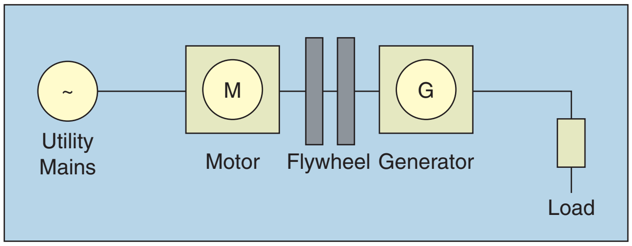
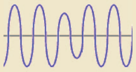
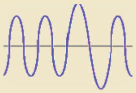
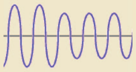
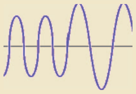
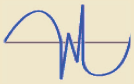
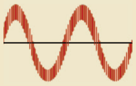
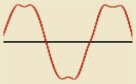


FIGURE 2 – Block diagram of a rotary UPS consisting of an M-G set with flywheel.

Rotary UPS systems have been around for a long time and their power rating reaches several megawatts [4]. Figures 1 and 2 show a picture and a configuration, respectively, of a rotary UPS consisting of a motor-generator set with heavy flywheels and engines. The concept is very simple: a motor powered by the utility drives a generator that powers the critical load. The flywheels located on the shaft provide greater inertia in order to increase the ride-through time. In the case of line disturbances, the inertia of the machines and the flywheels maintain the power supply for several seconds. These systems, due to their high reliability, are still in use and new ones are being installed in industrial settings. Although this kind of UPS is simple in concept, it has some drawbacks such as the losses associated with the motor-generation set, the noise of the overall system, and the need for maintenance. In order to reduce such losses, an offline configuration is often proposed, as shown in Figure 3. Under normal operation, the synchronous machine is used to compensate reactive power. When the utility fails, the static switch opens and the synchronous machine starts to operate as a generator, injecting both active and reactive power. While the flywheel provides the stored energy, the diesel engine has time to start.

TABLE 1—CLASSIFICATION OF THE POWER QUALITY PROBLEMS TO BE SOLVED BY THE UPS SYSTEMS.

POWER LINE PROBLEMS	WAVEFORM	IEC62040-3	UPS SOLUTION
1) Line failure (outage, blackouts) Total loss of utility line (>10 ms)		Voltage + frequency dependent	Off-line UPS
2) Sag or dip Short under-voltage (<16 ms)			
3) Surge Quick burst of over-voltage (<16 ms)			
4) Under-voltage or brownout Low line voltages for an extended period of time		Voltage independent	Line-interactive UPS
5) Over-voltage or swell Increased voltages for an extended period of time			
6) Transient, impulse, or spike under-voltage or over-voltage for up to a few nanoseconds		Voltage + frequency independent	On-line UPS
7) Frequency variation of the line voltage waveform			
8) Noise Distortions superimposed on the voltage waveform			
9) Harmonic distortion Multiples of line frequency superimposed on the voltage waveform			

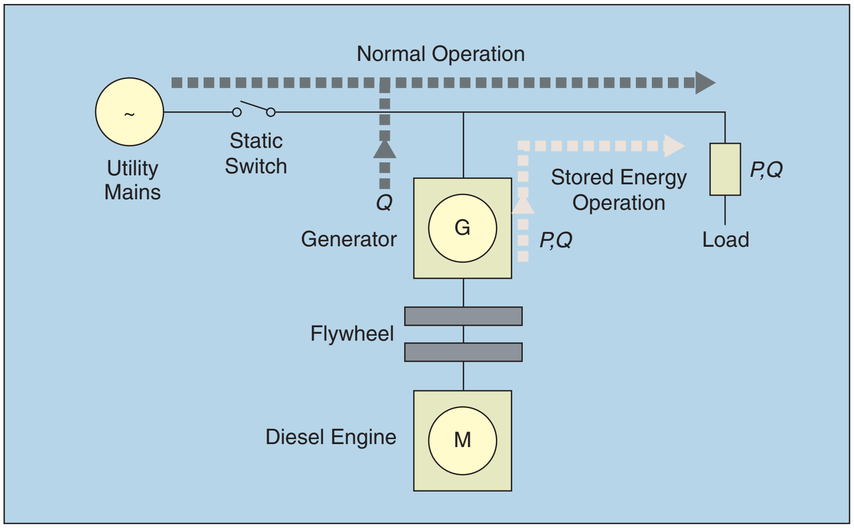


FIGURE 3 – Offline UPS with diesel engine backup.

Further, the combination of rotary UPS systems with power electronic converters results in hybrid systems, as shown in Figure 4. The variable speed drive, consisting of an ac/ac converter, regulates the optimum speed of the flywheel associated with the motor. The written-pole generator produces a constant line frequency as the machine slows down, provided that the rotor is spinning at speeds between 3,150 and 3,600 rev/min. Flywheel inertia allows the generator rotor to keep spinning above 3,150 rev/min when the utility fails [5].

Static UPS systems are based on power electronic devices. The continuous development of devices such as insulated gate bipolar transistors allows high frequency operation, which results in a fast transient response and low total harmonic distortion (THD) in the output voltage. According to the international standards IEC 62040-3 and

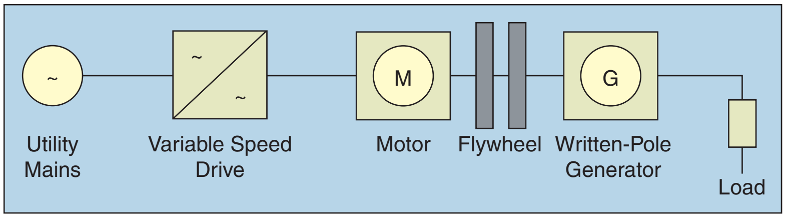


FIGURE 4 — Hybrid UPS system.

ENV 500091-3, UPS systems can be classified into three main categories [6], [7]:

- offline (passive standby or line-preferred), for line disturbances 1–3
- line-interactive, for line disturbances 1–5
- online (double conversion or inverter-preferred), for line disturbances 1–9.

Figure 5(a) shows the configuration of an offline UPS, also known as line-preferred UPS or passive standby. It consists of a battery set, a charger, and a switch, which normally connects the mains to the load and to the batteries so that these remain charged (normal operation). However, when the utility power fails or under abnormal function, the static switch connects the load to the inverter in order to supply the energy from the batteries (stored energy operation). The transfer time from the normal operation to the stored energy operation is generally less than 10 ms, which does not affect typical computer loads. With this configuration, the UPS simply transfers utility power through to the load until either a power failure, sag, or spike occurs, at which point the UPS switches the load onto battery power and disconnects the utility power until it returns to an acceptable level. Offline UPS systems completely solve problems 1–3. However, when power problems 4–9 occur they only can be solved by switching to stored energy operation. In this situation, the batteries will be discharged even though line voltage is present [8]. Offline UPSs are commonly rated at 600 VA for small personal computers or home applications.

Figure 5(b) depicts the configuration of an online UPS, also known as double conversion UPS [9]–[12]. During normal or even abnormal line conditions, the inverter supplies energy from the mains through the rectifier, which charges the batteries continuously and can also provide power factor correction. When the line fails, the inverter still supplies energy to the loads but from the batteries. As a consequence, no transfer time exists during the transition from normal to stored energy modes. In general, this is the most reliable UPS configuration due to its simplicity (only three elements), and the continuous charge of the batteries, which means that they are always ready for the next power outage. This kind of UPS provides total independence between input and output voltage amplitude and frequency, and, thus, high output voltage quality can be obtained. When an overload occurs, the bypass switch connects the load directly to the utility mains, in order to guarantee the continuous supply of the load, avoiding damage to the UPS module (bypass operation). In this situation, the output voltage must be synchronized with the utility phase, otherwise the bypass operation will not be allowed. Typical efficiency is up

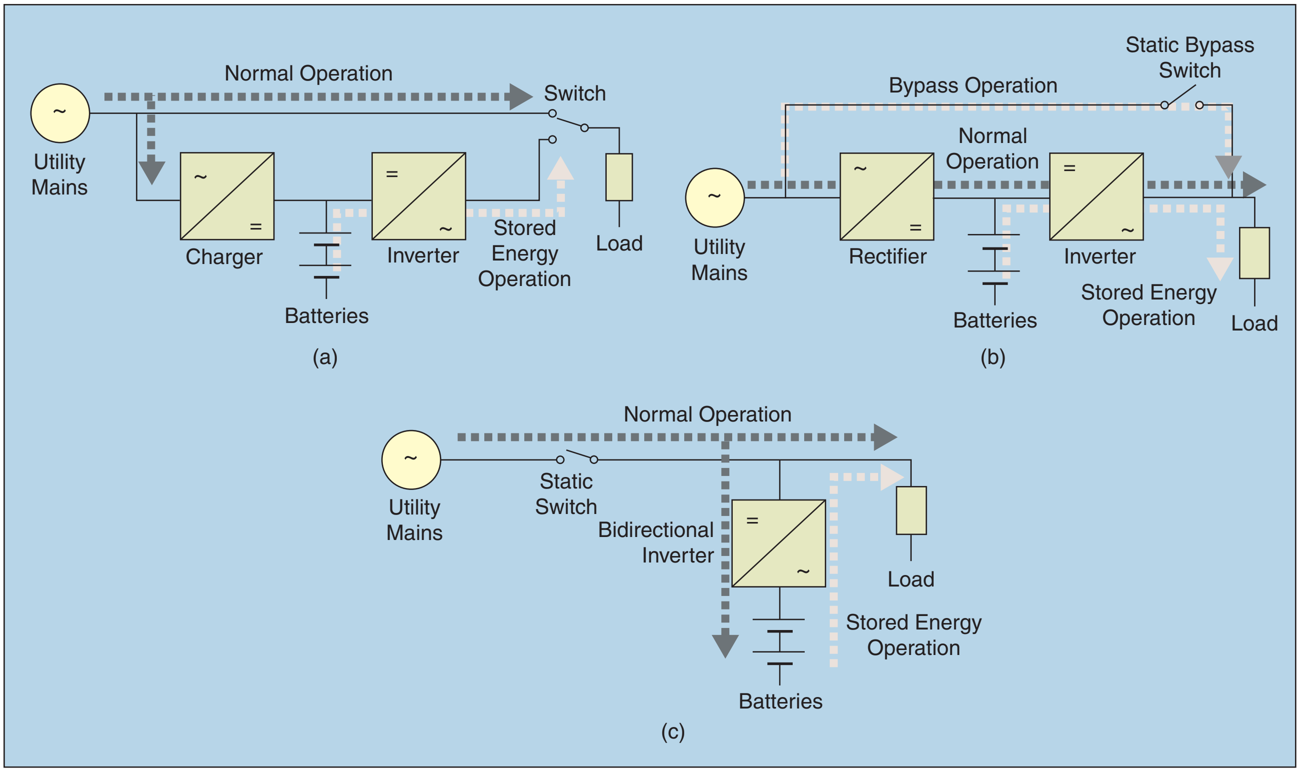


FIGURE 5 — UPS system classification: (a) offline, (b) online, and (c) line interactive.

to 94%, which is limited due to the double conversion effect. Online UPSs are typically used in environments with sensitive equipment or environments. Almost all commercial UPS units of 5 kVA and above are online.

Also available in the market is another subcategory of online UPSs with a standby battery, which uses a dedicated charger and is connected to the dc-link through a switch when a controller detects a fault in the mains. It means that the batteries are charged slowly and that it can be an output power disruption, since it is dependent on the identification and reaction to the fault, which can take several milliseconds. Consequently, this configuration is not considered as a *true* online UPS system.

Figure 5(c) illustrates the line-interactive UPS configuration, which can be considered as a midway between the online and the offline configurations [13]–[16]. It consists of a single bidirectional converter that connects the batteries to the load. Under normal operation, the mains supplies the load, and the batteries can be charged through the bidirectional inverter, acting as a dc/ac converter. It may also have active power filtering capabilities. When there is a failure in the mains, the static switch disconnects the load from the line and the bidirectional converter acts as an inverter, supplying energy from the batteries. The main advantages of the line-interactive UPS are the simplicity and the lower cost in comparison to the online UPS. Line-interactive units typically incorporate an automatic voltage regulator, which allows the UPS to effectively step up or step down the incoming line voltage without switching to battery power. Thus, the UPS is able to correct most long-term over-voltages or under-voltages without draining the batteries. Another advantage is that it reduces the number of transfers to battery, which extends the lifetime of the batteries. However, it has the disadvantage that under normal operation it is not possible to regulate output voltage frequency. Line-interactive UPS units typically rate between 0.5 kVA and 5 kVA for small server systems. Typical efficiency is about 97% when there are no problems in the line.

Figure 6 shows a special kind of line-interactive UPS, known as series-parallel or delta-conversion UPS [17], which consists of two inverters connected to the batteries: the delta inverter (rated at 20% of the nominal power), connected through a series transformer to the utility; and the main inverter (fully rated at 100% of the nominal power), connected directly to the load. This configuration achieves power factor correction, load harmonic current suppression, and output voltage regulation. The delta inverter works as a sinusoidal current source in phase with the input voltage. The main inverter works as a low-THD sinusoidal voltage source in phase with the input voltage. Usually, only a small portion of the nominal power (up to 15%) flows from the delta to the main inverter, achieving high efficiency. Nevertheless, this configuration needs complex control algorithms. In addition, unlike with online UPSs, there is no continuous separation of load and utility mains. Delta-conversion UPS systems provide protection from all line problems except for frequency variations.

Energy Storage Systems

One of the problems to be solved by future UPS systems is how to store the energy. This question raises several solutions that can be used alone or combined. Some of the energy storage technologies are summarized below [18].

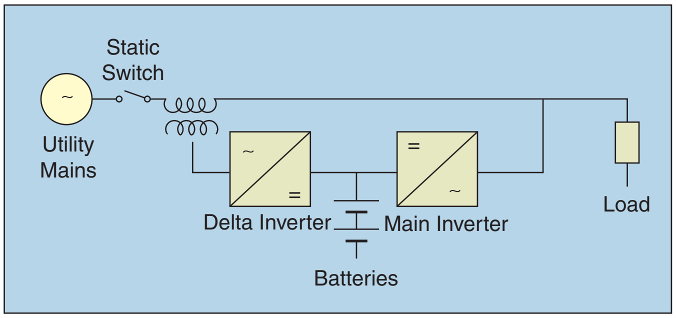


FIGURE 6 — Series-parallel line-interactive UPS or delta-conversion UPS.

Battery Energy Storage System (BESS)

Typical UPS systems use chemical batteries to store energy. Rechargeable batteries such as valve-regulated lead-acid (VRLA) or nickel-cadmium (Ni-Cd) are the most popular due to their availability and reliability [3]. A lead-acid battery reaction is reversible, allowing the battery to be reused. There are also some advanced sodium/sulfur, zinc/bromine, and lithium/air batteries that are nearing commercial readiness and offer promise for future utility application. On the other hand, flow batteries store and release energy by means of a reversible electrochemical reaction between two electrolyte solutions. There are four main flow battery technologies: polysulfide bromide (PSB), vanadium redox (VRB), zinc bromine (ZnBr), and hydrogen bromine (H-Br) batteries. However, batteries contain heavy metals, such as Cd or mercury (Hg), which may cause environmental pollution. A large majority of UPS designs use a characteristic constant-voltage charging system with current limit.

Flywheels

This system is essentially a dynamic battery that stores energy mechanically in the form of kinetic energy by spinning a mass about an axis. The electrical input spins the flywheel rotor and keeps it spinning until called upon to release the stored energy through a generator, such as a reluctance motor generator [9]. Sometimes the flywheel is enclosed in a vacuum or in gas helium in order to avoid friction losses. The amount of energy available and its duration is governed by the flywheel mass and speed. There are two available types of flywheel: low-speed (less than 40,000 rpm), which are based on steel rotors, and high-speed (between 40,000 and 60,000 rpm), which use carbon fiber rotors and magnetic bearings. Flywheels provide 1 to 30 s of ride-through time. In addition, the combination of modern power electronics and low-speed flywheels can provide protection against multiple power line disturbances.

Superconducting Magnetic Energy Storage (SMES)

This system stores electrical energy in a superconducting coil. The resistance of a superconductor is zero so the current will flow without reduction in magnitude. The variable current through the superconducting coil is converted to a constant voltage, which can be connected to an inverter. The superconducting coil is made of niobium titanium (NbTi) and it is cooled to 4.2 K by liquid helium [20]. Typical power rates for this application are up to 4 MVA.

Supercapacitors or Double-Layer Capacitors

These devices are able to manage similar energy densities as the batteries but with longer lifetime and lower maintenance. Typical capacity values for theses devices are up to several hundred of farads. However, they are only available for very low voltages (about 3 V), although this can be overcome by using bidirectional boost-type converters or by the series association of these devices [21].

Fuel Cells

These devices convert the chemical energy of the fuel directly into electrical energy. They are good energy sources to provide reliable power at steady-state. However, due to their slow internal electrochemical and thermodynamic characteristics, they cannot respond to the electrical transients as fast as it is desirable. This problem can be solved by using supercapacitors or BESS in order to improve the dynamic response of the system [22]. Fuel cells can be classified into proton exchange membrane (PEMFC), solid oxide (SOFC), and molten carbonate (MCFC). PEMFCs are more suitable for UPS applications since they are compact, lightweight, and provide high power density at room temperature, while SOFCs and MCFCs require between 800–1, 000 °C operation.

Compressed Air Energy Storage (CAES)

This technology uses an intermediary mechanical-hydraulic conversion, also called the liquid-piston principle [23]. These devices are raising interest since they do not generate any waste. They also can be integrated with a cogeneration system, due to the thermal processes associated with the compression and the expansion of gas. Their efficiency can be also optimized by using power electronics or combining CAES with other storage systems.

Novel trends in UPS storage combine several of the above systems. Figure 7 shows a hybrid online UPS system that uses both flywheels and CAES in order to store energy through the dc-link by means of dc/ac bidirectional converters. Other UPS systems include fuel-cell arrays and supercapacitors or BESS to provide fast transient response as shown in Figure 8. Notice that the dc-link of a UPS unit is the point where storage energy systems can be easily interconnected. These and other combinations are taken into account in new UPS designs.

Distributed UPS Systems

With the objective to further increase the reliability of UPS systems, the use of several UPS units connected in parallel is an interesting option. The advantages of a paralleled UPS system

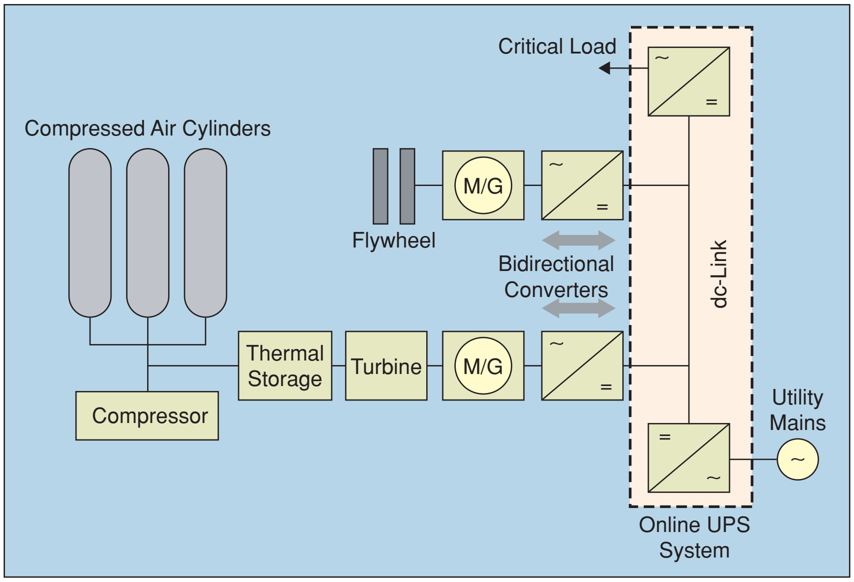


FIGURE 7 — Hybrid CAES/flywheel online UPS system.

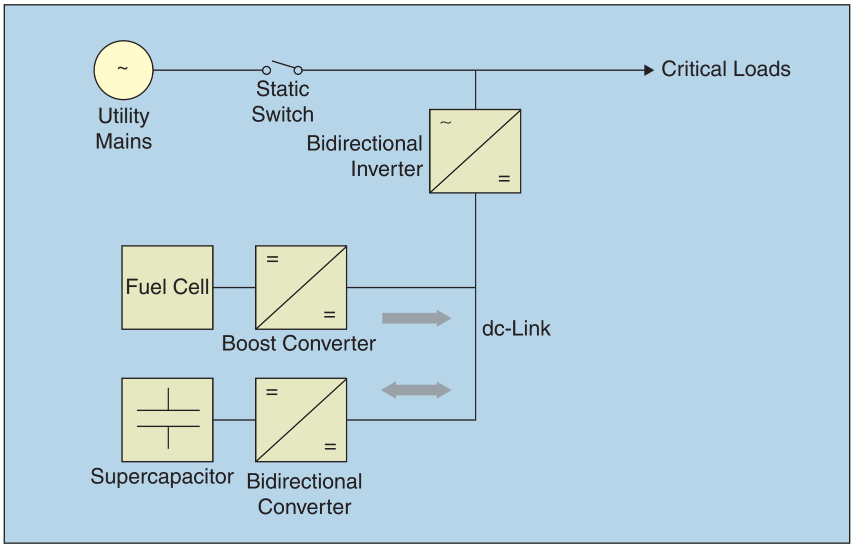


FIGURE 8 — Hybrid FC/supercapacitor line-interactive UPS system.

over one centralized unit are flexibility to increase the power capability, enhanced availability, fault tolerance with $N + 1$ modules (N modules supporting the load plus one reserve standby module), and ease of maintenance due to the redundant configuration [24].

Parallel operation is a special feature of high-performance industrial UPS systems. The parallel connection of UPS inverters is a challenging problem that is more complex than paralleling dc sources, since every module must share the load properly while staying synchronized. In theory, if the output voltage of every module has the same amplitude, frequency, and phase, the current load could be equally distributed. However, due to the physical differences between the modules and the line impedance mismatches, the load will not be properly shared. This fact will lead to a circulating current among the units, as shown in Figure 9. Circulating current is especially dangerous at no-load or light-load conditions, since one or several modules can absorb active power operating in rectifier mode. This increases the dc-link voltage level, which can result in damage to the dc capacitors or in a shutdown due to overload. Generally speaking, a paralleled UPS system must achieve the following features:

- the same output voltage amplitude, frequency, and phase
- equal current sharing between the units
- flexibility to increase the number of units

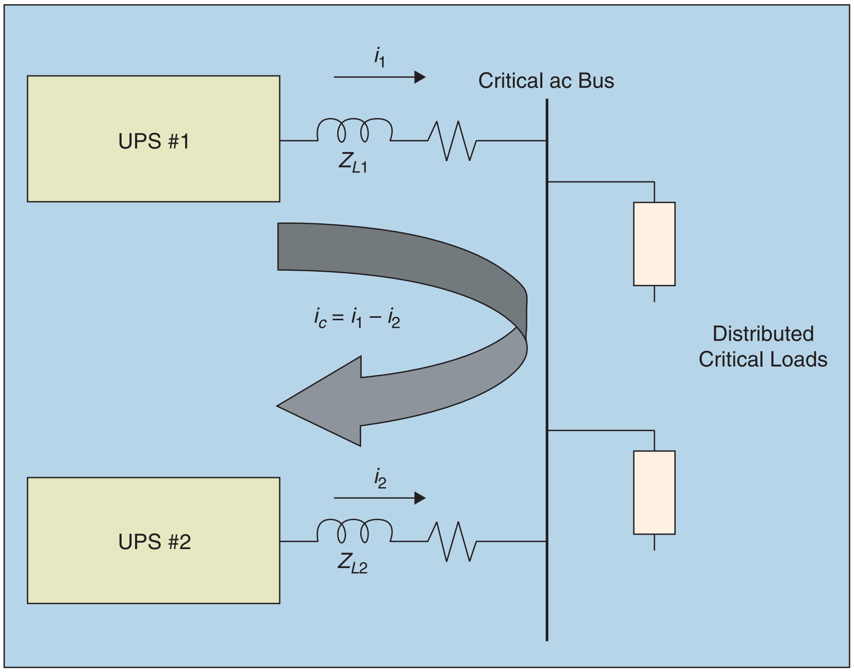


FIGURE 9 — Circulating current concept.

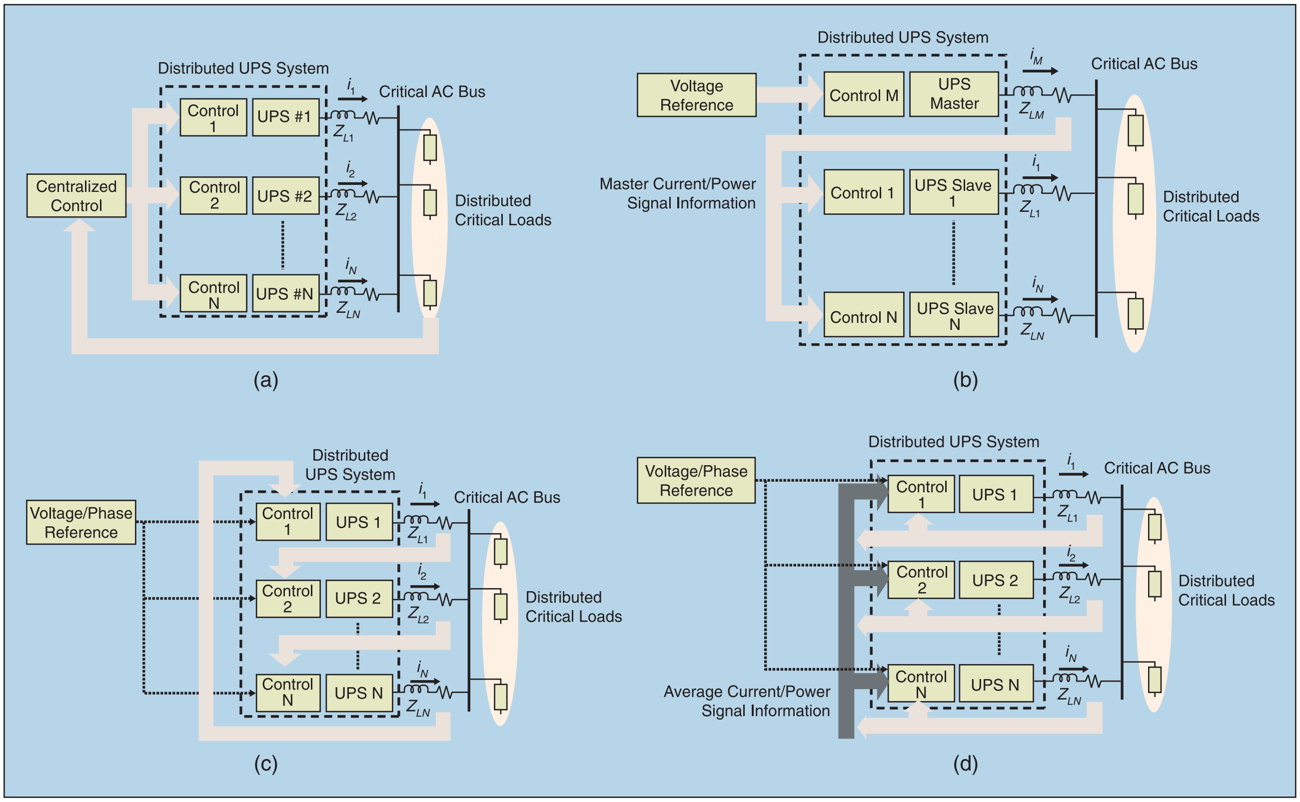


FIGURE 10 — Active load-sharing control schemes for the parallel operation of distributed UPS systems: (a) centralized control, (b) master-slave control, (c) current chain control, and (d) average load sharing.

- plug-and-play operation at any time (*hot-swap* operation capability).

The fast development of digital signal processors (DSPs) has brought about an increase in control techniques for the parallel operation of UPS inverters. These control schemes can be classified into two main groups with regard to the use of control wire interconnections. The first one is based on active load-sharing techniques, which can be classified as follows [7], [25], [26], (see Figure 10):

- *Centralized Control*: the total load current is divided by the number of modules *N*, so that this value becomes the current reference of each module. An outer control loop in the central control adjusts the load voltage. This system is normally used in common UPS equipment with several output inverters connected in parallel [27].
- *Master-Slave*: the master module regulates the load voltage. Hence, the master current fixes the current references of the rest of the modules (slaves) [28]–[30]. The master can be fixed by the module that brings the maximum rms or crest current or can be a rotating master. If the master unit fails, another module will take the role of master in order to avoid the overall failure of the system. This system is often adopted when using different UPS units mounted into a rack.
- *Circular Chain Control (3C)*: the current reference of each module is taken from the above module, forming a control ring [31]. Note that the current reference of the first unit is obtained from that of the last unit. The approach is interesting for distributed power systems based on ac-power rings [32].
- *Average Load Sharing*: the current of all modules is averaged by means of a common current bus [33]–[35]. The average current of all the modules is the reference for each individual one, so that all the currents become equal. This control scheme is highly reliable due to the real democratic conception, in which no master-slave philosophy is present. Also, the approach is highly modular and expandable, making it interesting for industrial UPS systems. In general, this scheme is the most robust and useful of the above controllers.

In general, these last two control schemes require that the modules share two signals: the output voltage reference phase (which can be achieved by a dedicated line or by using a PLL circuit to synchronize all UPS modules) and the current information (a portion of the load current, master current, or the average current). In a typical UPS application, the reference voltage is either synchronized with the external bypass utility line or, when this is not present, to an internal oscillator signal. Another possibility is to use active and reactive power information instead of the current. Thus, we use active and reactive power to adjust the phase and the amplitude of each module but using the same three control schemes [30], [33], [36], [37]. Although these controllers achieve both good output voltage regulation and equal current sharing, the need for intercommunication lines among modules reduces the flexibility of the physical location and its reliability, since a fault in one line can result in the shutdown of the system. In order to improve reliability and avoid noise problems in the control lines, digital communications by using a CAN bus or other digital buses are proposed [26]. In this sense, low bandwidth communications can be performed when using active and reactive average power instead of instantaneous output currents.

The second kind of control scheme for the parallel operation of UPSs is mainly based on the droop method (also called independent, autonomous, or wireless control). This concept stems from power system theory, in which a generator connected to the utility line drops its frequency when the power required increases [38]. In order to achieve good power sharing, the control loop makes tight adjustments over the output voltage frequency and amplitude of the inverter, thus compensating for the active and reactive power unbalances. The droop method achieves higher reliability and flexibility in the physical location of the modules, since it uses only local power measurements [39]. Nevertheless, the conventional droop method

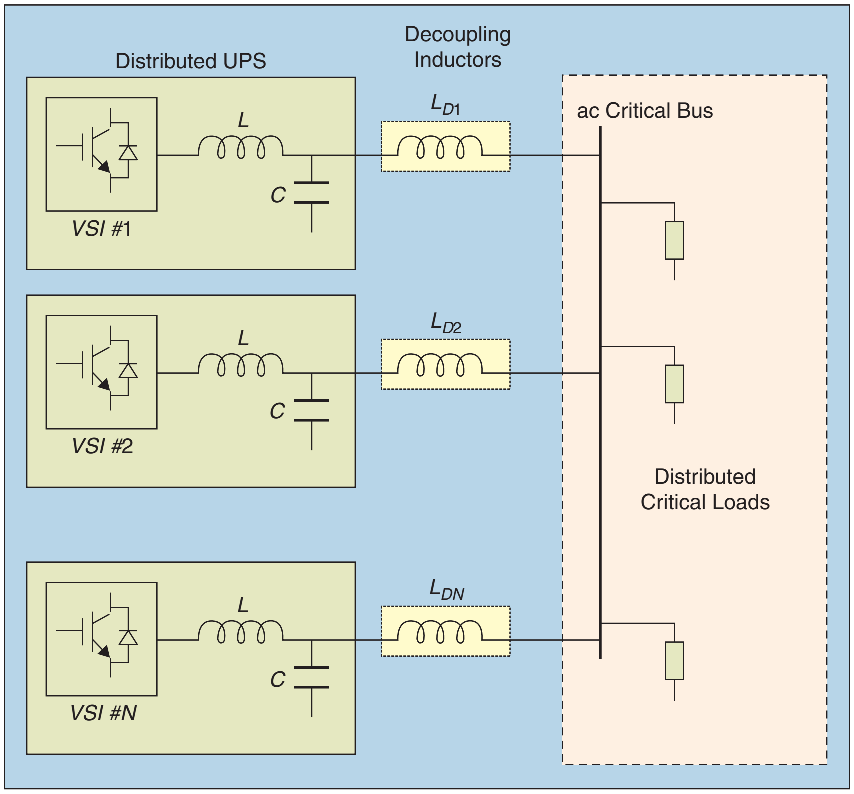


FIGURE 11 — Equivalent circuit of a distributed UPS system.

shows several drawbacks that limit its application, such as [40]–[42]: slow transient response, trade-off between the power sharing accuracy and the frequency and voltage deviations, unbalanced harmonic current sharing, and high dependency on the inverter output-impedance.

Another drawback of the standard droop method is that the power sharing is degraded if the sum of the output impedance and the line impedance is unbalanced. To solve this, interface inductors can be included between the inverter and the load bus, as depicted in Figure 11, but they are heavy and bulky. As an alternative, novel control loops that fix the output impedance of the units by emulating lossless resistors or reactors have been proposed [43].

Usually, the inverter output impedance is considered to be inductive, which is often justified by the high inductive component of the line impedance and the large inductor of the output filter. However, this is not always true, since the closed-loop output impedance also depends on the control strategy, and the line impedance is predominantly resistive for low voltage cabling. The output impedance of the closed-loop inverter affects the power sharing accuracy and determines the droop control strategy. Furthermore, the proper design of this output impedance can reduce the impact of the line-impedance unbalance. Figure 12 illustrates this concept in relation to the rest of the control loops. The output impedance angle determines to a large extent the droop control law. Table 2 shows the parameters that can be used to control the active and reactive power flow in function of the output impedance. Figure 13 shows the droop control functions depending on the output impedance [41].

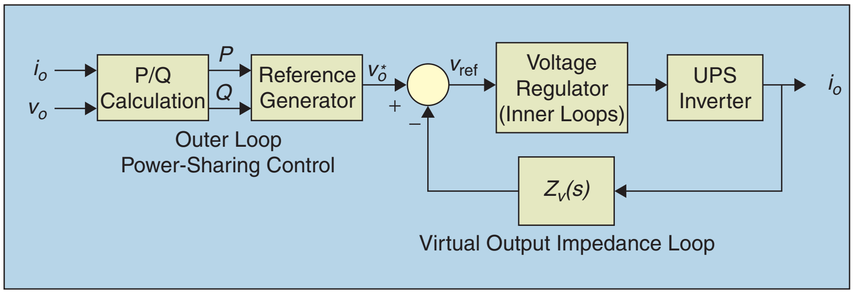


FIGURE 12 – Block diagram of the closed-loop system with the virtual output impedance path.

TABLE 2–OUTPUT IMPEDANCE IMPACT OVER POWER FLOW CONTROLLABILITY.

Output impedance	Inductive (90°)	Resistive (0°)
Active power (P)	Frequency (ω)	Amplitude (E)
Reactive power (Q)	Amplitude (E)	Frequency (ω)

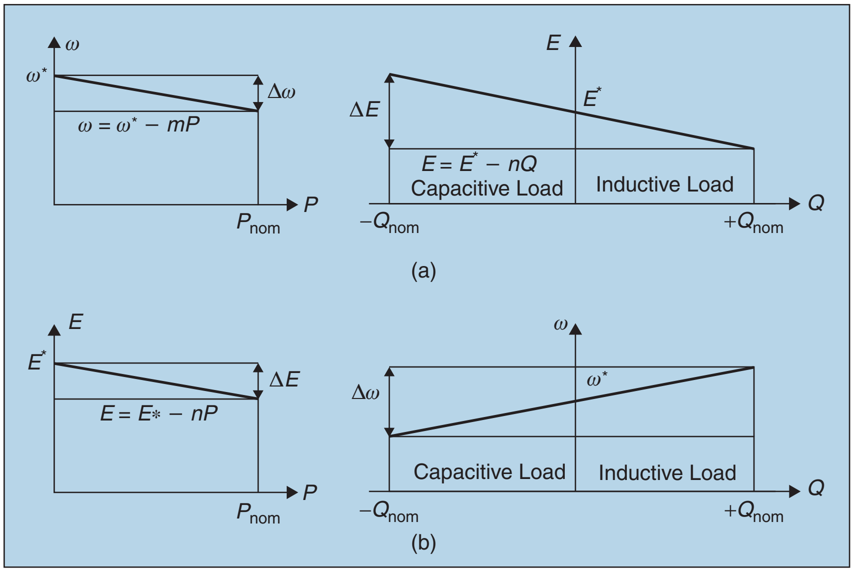


FIGURE 13 – Droop functions for the independent parallel operation of UPSs.

On the other hand, the droop method has been studied extensively in parallel dc converters. In these cases, resistive output impedance is enforced easily by subtracting a proportional term of the output current from the voltage reference. The resistive droop method can be applied to parallel UPS inverters. The advantages of such an approach are the following: 1) the overall system is more damped; 2) it provides automatic harmonic current sharing; and 3) phase errors barely affect active power sharing.

However, although the output impedance of the inverter can be well established, the line impedance is unknown, which can result in an unbalanced reactive power flow. This problem can be overcome by injecting high-frequency signals through power lines [44] or by adding external data communication signals [45], [46]. Some control solutions are also presented to reduce the harmonic distortion of the output voltage when supplying nonlinear loads by introducing harmonic sharing loops. This solution consists of adding into the virtual impedance loop a bank of bandpass filters that extracts current harmonic components in order to droop the output voltage reference proportionally to these current harmonics [47]. Figure 14 shows the behavior of a two-parallel-UPS system when sharing a nonlinear load. It shows the load voltage and current and the output current of the two units. Note that the circulating current is very low due to the good load sharing capability when supplying nonlinear loads. The mentioned autonomous control for parallel UPS systems is expanding in the market, which highlights its applicability in real distributed power systems.

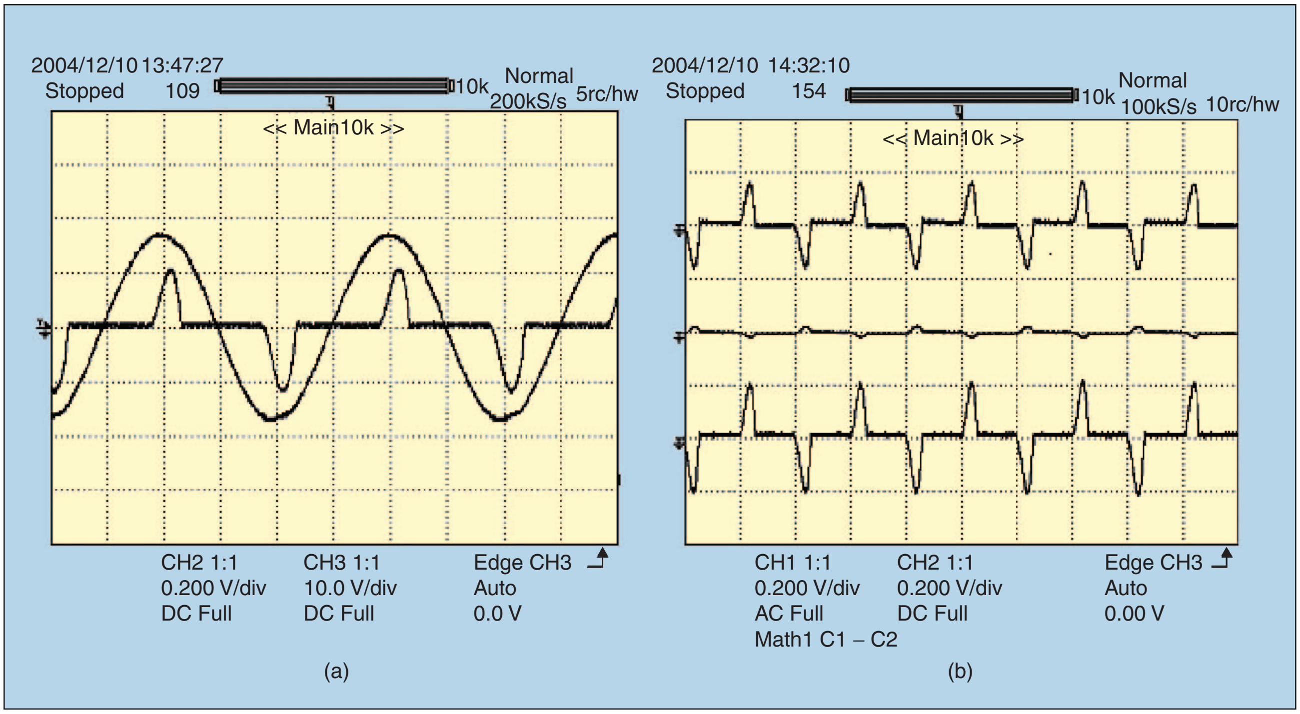


FIGURE 14 – Waveforms of the parallel system sharing a nonlinear load: (a) output voltage and load current (x-axis: 5 ms/div, y-axis: 40 A/div), (b) output currents and circulating current (x-axis: 10 ms/div, y-axis: 20 A/div).

Future Trends

In the coming years, the penetration of distributed generation systems will cause a change of paradigm from centralized electrical generation. It is expected that the utility grid will be formed by a number of interconnected microgrids. However, the onsite generation near the consumption points can be a problem if we are not able to manage the energy by means of novel kinds of UPSs. One of the problems is that classic renewable energy sources such as photovoltaic and wind energy are variable since they rely on natural phenomena like sun and wind. In order to accommodate these variable sources to the energy demanded by the loads, it is necessary to regulate the energy flow adequately.

On the other hand, the interactivity with the grid and the islanded operation will be requirements for these new UPSs. In addition, the use of technologies such as compressed-air energy devices, regenerative fuel cells, and flywheel systems will be integrated with renewable energy sources in order to ensure the continuous and reliable electrical power supply. Distributed generation becomes a viable alternative when renewable or nonconventional energy resources are available, such as photovoltaic arrays, fuel cells, co-generation plants, combined heat and power microturbines, or small wind turbines. These resources can be connected to local low-voltage electric power networks, such as mini- or microgrids, through power conditioning ac units (i.e., inverters or ac-ac converters), which can operate either in grid-connected mode or in island mode. Grid-connected operation consists of delivering power to the local loads and to the utility grid. In such a case, the output voltage reference is often taken from the grid voltage sensing and using a synchronization circuit, while an inner current loop ensures that the inverter acts as a current source.

Currently, when the grid is not present, the inverters are normally disconnected from the ac line, in order to avoid islanding operation. In the coming years, inverters should be able to operate in island mode due the high penetration of distributed generation. In addition, in certain zones where a stiff grid is not accessible (e.g., some physical islands, rural or remote areas), islanding operation mode is necessary. In this situation, the output voltage reference should be provided internally by the distributed generation units, which operate independently without mutual intercommunication due to the long distance between them, by using proper droop functions. Hence, the connection in parallel of several UPSs to a common microgrid is also rising as a new concept in order to supply energy in a distributed and cooperated form. This way, future UPS systems for renewable or nonconventional dispersed energy sources should take into account novel law codes that will regulate the use of such grids, while keeping the necessary energy storage.

Biographies

Josep M. Guerrero received the B.S. in telecommunications engineering, the M.S. in electronics engineering, and the Ph.D. in power electronics from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1997, 2000, and 2003, respectively. He is a senior lecturer at the UPC and responsible for the Sustainable Distributed Generation and Renewable Energy Research Group at the Escola Industrial de Barcelona. He is an associate editor of *IEEE Transactions* *on Industrial Electronics* and a guest editor of the "Uninterruptible Power Supply (UPS) Systems" special section.

Luis García de Vicuña received his M.S. and Ph.D. degrees in telecommunications engineering from the Universitat Politècnica de Catalunya, Barcelona, Spain, in 1980 and 1990, respectively, and the Dr. Sci. degree from the Université Paul Sabatier, Toulouse, France, in 1992. From 1980 to 1982, he worked as an engineer with control applications. He is currently an associate professor in the Department of Electronic Engineering, Universitat Politècnica de Catalunya. His research interests include power electronics modeling, simulation and control, active power filtering, and high-power-factor ac-dc conversion.

Javier Uceda received his M.S. and Ph.D. degrees in electrical engineering from the Universidad Politécnica de Madrid, Spain, in 1976 and 1979, respectively. Since 1986, he has been a professor at the Universidad Politécnica de Madrid. His research interests include high-frequency, high-density power converters, high-power-factor rectifiers, and modeling of magnetic components. He is an editorial board member of the *EPE Journal* and of the Steering Committee of the EPE Association. He was an associate editor of *IEEE Transactions on Industrial Electronics* and a guest editor of the "Uninterruptible Power Supply (UPS) Systems" special section. He is a senior AdCom member of the IEEE Industrial Electronics Society.

References

[1] M.H.T. Bollen, *Understanding Power Quality Problems. Voltage Sags and Interruptions.* New York: Wiley, 2000.

[2] W. Sölter, "A new international UPS classification by IEC 62040-3," in *Proc. IEEE Telecommunications Energy Conf*, pp. 541–545, 2002.

[3] A. King and W. Knight, *Uninterruptible Power Supplies and Standby Power Systems*. New York: McGraw-Hill, 2003.

[4] A. Kusko and S. Fairfax, "Survey of rotary uninterruptible power supplies," in *Proc. IEEE Telecommunications Energy Conf.*, Boston, MA, pp. 416–419, Oct., 1996.

[5] R.C. Dugan, M.F. McGranaghan, S. Santoso, and H.W. Beaty, *Electrical Power System Quality.* New York: McGraw-Hill, 2003.

[6] S. Karve, "Three of a kind," *IEE Rev.*, vol. 46, no. 2, pp. 27–31, Mar. 2000.

[7] S.B. Bekiarov and A. Emadi, "Uninterruptible power supplies: Classification, operation, dynamics, and control," in *Proc. IEEE APEC'02*, Dallas, TX, pp. 597–604, 2002.

[8] M.T. Tsai and C.H. Liu, "Design and implementation of a cost-effective quasi line-interactive UPS with novel topology," *IEEE Trans. Power Electron.*, vol. 18, pp. 1002–1011, July 2003.

[9] C.-C. Yeh and M.D. Manjrekar, "A reconfigurable uninterruptible power supply system for multiple power quality applications," in *Proc. IEEE APEC'05*, Mar. 2005, pp. 1824–1830.

[10] J.-H. Choi, J.-M. Kwon, J.-H. Jung, and B.-H. Kwon, "High-performance online UPS using three-leg type converter," *IEEE Trans. Ind. Electron.*, vol. 52, pp. 889–897, June 2005.

[11] T.-J. Liang and J.-L. Shyu, "Improved DSP-controlled online UPS system with high real output power," *IEE Proc. Electr. Power Appl.*, vol. 151, no. 1, pp. 121–127, Jan. 2004.

[12] C.-H. Lai and Y.-Y. Tzou, "DSP-embedded UPS controller for high-performance single-phase on-line UPS system," in *Proc. IEEE IECON'02*, pp. 268–273, 2002.

[13] H.-L. Jou, J.-C. Wu, C. Tsai, K.-D. Wu, and M.-S. Huang, "Novel line-interactive uninterruptible power supply," *IEE Proc. Electr. Power Appl.*, vol. 151, no. 3, pp. 359–364, May 2004.

[14] Y. Okui, S. Ohta, N. Nakamura, H. Hirata, and M. Yanagisawa, "Development of line interactive type UPS using a novel control system," in *Proc. IEEE INTELEC'03*, Oct., pp. 796–801, 2003.

[15] F. Kamran and T.G. Habetler, "A novel on-line UPS with universal filtering capabilities," *IEEE Trans. Power Electron.*, vol. 13, pp. 410–418, May 1998.

[16] W.-J. Ho, J.-B. Lio, and W.-S. Feng, "Economic UPS structure with phase-controlled battery charger and input-power-factor improvement," *IEE Proc. Electr. Power Appl.*, vol. 144, no. 4, pp. 221–226, July 1997.

[17] S.A.O. da Silva, P.F. Donoso-Garcia, P.C. Cortizo, and P.F. Seixas, "A three-phase line interactive UPS system implementation with series-parallel active power-line conditioning capabilities," *IEEE Trans. Industry Appl.*, vol. 38, pp. 1581–1590, Nov./Dec. 2002.

[18] B. Roberts and J. McDowall, "Commercial successes in power storage," *IEEE Power Energy Mag.*, vol. 3, no. 2, pp. 24–30, Mar./Apr. 2005.

[19] R.G. Lawrence, K.L. Craven, and G.D. Nichols, "Flywheel UPS," *IEEE Ind. Appicat. Mag.*, pp. 44–50, May/June 2003.

[20] T. Mito, A. Kawagoe, H. Chikaraishi, R. Maekawa, K. Okumura, R. Abe, T. Baba, T. Hemmi, M. Iwakuma, M. Yokota, H. Ogawa, Y. Morita, K. Yamauchi, A. Kuge, and F. Sumiyoshi, "Validation of the high performance conduction-cooled prototype LTS for UPS-SMES," *IEEE Trans. Appl. Superconduct.*, vol. 19, pp. 608–611, June 2006.

[21] M.H. Nehrir, C. Wang, and S.R. Shaw, "Fuel cells: Promising devices for distributed generation," *IEEE Power Energy Mag.*, vol. 4, no. 1, pp. 47–53, Jan./Feb. 2006.

[22] W. Choi, P. Enjeti, and J.W. Howze, "Fuel cell powered UPS systems: Design considerations," in *Proc. IEEE PESC'03*, pp. 385–390, June 2003.

[23] S. Lemofouet and A. Rufer, "A hybrid energy storage system based on compressed air and supercapacitors with maximum efficiency point tracking (MEPT)," *IEEE Trans. Ind. Electron.*, vol. 53, pp. 1105–1115, Aug. 2006.

[24] J. Sears, "High-availability power systems: redundancy options," Power Pulse, Darnell.Com Inc., 2001 [Online]. Available: http://www.powerpulse.net/techpaper.php?paperID=90&page1.

[25] D. Shanxu, M. Yu, X. Jian, K. Yong, and C. Jian, "Parallel operation control technique of voltage source inverters in UPS," in *Proc. IEEE PEDS'99*, Hong Kong, pp. 883–887, July 1999.

[26] T. Kawabata and S. Higashino, "Parallel operation of voltage source inverters," *IEEE Trans. Ind. Applicat.*, vol. 24, no. 2, pp. 281–287, Mar./Apr. 1988.

[27] J. Holtz and K.H. Werner, "Multi-inverter UPS system with redundant load sharing control," *IEEE Trans. Ind. Electron.*, vol. 37, no. 6, pp. 506–513, Dec. 1990.

[28] H. van der Broeck, and U. Boeke, "A simple method for parallel operation of inverters," *in Proc. IEEE INTELEC'98 Conf.*, San Francisco, CA, pp. 143–150, Oct. 1998.

[29] C.S. Lee, S. Kim, C.B. Kim, S.C. Hong, J.S. Yoo, S.W. Kim, C.H. Kim, S.H. Who, and S.Y. Sun, "Parallel UPS. with a instantaneous current sharing control," in *Proc. IEEE IECON'98 Conf.*, Aachen, Germany, pp. 568–573, Aug. 1998.

[30] Y. Pei, G. Jiang, X. Yang, and Z. Wang, "Auto-master-slave control technique of parallel inverters in distributed ac power systems and UPS," in *Proc. IEEE PESC'04*, pp. 2050–2053, 2004.

[31] T.F. Wu, Y.-K. Chen, and Y.-H. Huang, "3C strategy for inverters in parallel operation achieving an equal current distribution," *IEEE Trans. Ind. Electron.*, vol. 47, pp. 273–281, Apr. 2000.

[32] M.C. Chandorkar, D.M. Divan, Y. Hu, and B. Barnajee, "Novel architectures and control for distributed UPS systems," in *Proc. IEEE APEC'94*, Orlando, FL, pp. 683–689, Feb. 1994.

[33] J. Tao, H. Lin, J. Zhang, and J. Ying, "A novel load sharing control technique for paralleled inverters," in *Proc. IEEE PESC'03 Conf.*, pp. 1432–1437, June 2003.

[34] Y. Xing, L. Huang, S. Sun, and Y. Yan, "Novel control for redundant parallel UPSs with instantaneous current sharing," in *Proc. IEEE PCC'02 Conf.*, Osaka, Japan, pp. 959–963, Apr. 2002.

[35] X. Sun, Y.-S. Lee, and D. Xu, "Modeling, analysis, and implementation of parallel multi-inverter system with instantaneous average-current-sharing scheme," *IEEE Trans. Power Electron.*, vol. 18, pp. 844–856, May 2003.

[36] J.M. Guerrero, L. García de Vicuña, J. Miret, J. Matas, and J. Cruz, "Output impedance performance for parallel operation of UPS inverters using wireless and average current-sharing controllers," in *Proc. IEEE PESC'04 Conf.*, pp. 2482–2488, June 2004.

[37] L. Chen, X. Xiao, C. Gong, and Y. Yan, "Circulating currents characteristics analysis and the control strategy of parallel system based on double close-loop controlled VSI," in *Proc. IEEE PESC'04*, pp. 4791–4797, June 2004.

[38] A.R. Bergen. *Power Systems Analysis*. Englewood Cliffs, NJ: Prentice-Hall, 1986.

[39] T. Kawabata and S. Higashino, "Parallel operation of voltage source inverters," *IEEE Trans. Ind. Applicat.*, vol. 24, pp. 281–287, Mar./Apr. 1988.

[40] J.M. Guerrero, L. García de Vicuña, J. Matas, M. Castilla, and J. Miret, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," *IEEE Trans. Power Electron.*, vol. 9, pp. 1205–1213, Sept. 2004.

[41] J.M. Guerrero, L. Garcia de Vicuña, J. Matas, M. Castilla, and J. Miret, "Output impedance design of parallel-connected UPS inverters with wireless load-sharing control," *IEEE Trans. Ind. Electron.*, vol. 52, pp. 1126–1135, Aug. 2005.

[42] J.M. Guerrero, J. Matas, L. Garcia de Vicuña, M. Castilla, and J. Miret, "Wireless-control strategy for parallel operation of distributed-generation inverters," *IEEE Trans. Ind. Electron.*, vol. 53, pp. 1461–1470, Oct. 2006.

[43] S.J. Chiang, C.Y. Yen, and K.T. Chang, "A multimodule parallelable series-connected PWM voltage regulator," *IEEE Trans. Ind. Electron.*, vol. 48, pp. 506–516, June 2001.

[44] A. Tuladhar, H. Jin, T. Unger, and K. Mauch, "Control of parallel inverters in distributed AC power systems with consideration of line impedance," *IEEE Trans. Ind. Applicat.*, vol. 36, pp. 131–138, Jan./Feb. 2000.

[45] M.N. Marwali, J.-W. Jung, and A. Keyhani, "Control of distributed generation systems—Part II: Load sharing control," *IEEE Trans. Power Electron.*, vol. 19, pp. 1551–1561, Nov. 2004.

[46] Y.J. Cheng and E.K.K. Sng, "A novel communication strategy for decentralized control of paralleled multi-inverter systems," *IEEE Trans. Power Electron.*, vol. 21, pp. 148–156, Jan. 2006.

[47] J.M. Guerrero, N. Berbel, J. Matas, L. García de Vicuña, and J. Miret, "Decentralized control for parallel operation of distributed generation inverters in microgrids using resistive output impedance," in *Proc. IEEE ISIE'06*, Montreal, pp. 5149–5154, July 2006.