Liebert

November 2000

High-Availability Power Systems, Part I:
UPS Internal Topology

SUMMARY

"High-Availability" power systems require four elements: Reliability, Functionality, Maintainability, and Fault Tolerance. This paper examines different approaches to UPS internal topology and explains how each affects these four elements.

Bad Things Happen to Good Power

Utility power is generally very good. Utility companies do an excellent job of providing reliable AC power to virtually every part of the country. Unfortunately, we can't predict when disturbances caused by electrical storms, equipment failures and accidents may occur.

To mitigate this risk, the time-honored approach is to provide a static UPS and batteries for short-duration anomalies, plus a standby generator for long-term outages. This approach works well for many applications, but has limitations when applied to customers with 24 x 7 operations. These customers can never stop their critical loads, nor can they risk exposing the critical loads to unconditioned power while the UPS is receiving preventive maintenance.

High-Availability Power Systems

The computing industry talks in terms of "Nines" of availability. This refers to the percentage of time in a year that their system is available, on line, and capable of doing productive work. A system with four "Nines" is 99.99% available, meaning that downtime is less than 53 minutes per year. Five "Nines" (99.999% available) equates to less than 5.3 minutes of downtime per year. Six "Nines" (99.9999% available) equates to just 32 *seconds* of downtime per year.

At Liebert, we take this concept one step further and speak of the availability of *conditioned power*. We encourage our customers to configure their systems to minimize or completely eliminate exposure to unconditioned utility power.

1

A "High-Nines" power system has four key elements:

- **Reliability.** The individual UPS modules, static transfer switches and other power distribution equipment must be incredibly reliable, as measured by field-documented MTBF (Mean Time Between Failures). In addition, the system elements must be designed and assembled in a way that minimizes complexity and single points of failure.

- **Functionality.** The UPS must be able to protect the critical load from the full range of power disturbances, and only a true double-conversion UPS can do this. Some vendors offer single-conversion (line interactive) three-phase UPS products as a lower-cost alternative. However, these alternative UPSs do not protect against *all* disturbances – including power system short circuits, frequency variations, harmonics and common-mode noise. If your critical facility is truly critical, only a true double-conversion UPS is suitable. All Liebert 3-phase UPS units are true double-conversion products.

- **Maintainability.** The system design must permit concurrent maintenance of all power system components – supporting the load with part of the UPS system while other parts are being serviced. True maintainability is a function of system Redundancy Options (discussed in another paper), but all UPS systems should have some internal or external Maintenance Bypass capabilities.

- **Fault Tolerance.** The system must have fault resiliency, to cope with a failure of any power system component without affecting the operation of the critical load equipment.

UPS internal topology is the primary determinant of system Reliability and Functionality, and these will be the subject of this document. Other key elements of availability, especially Maintainability and Fault Tolerance, depend greatly on UPS Redundancy and Power Distribution Options, discussed in later papers in this series.

Review Criteria

To assess each UPS topology, we will examine several measures that affect one or more of the key elements of system availability.

The following items affect UPS **Reliability:**

- **Simplicity.** All else being equal, a simpler system will be more reliable.

- **Battery Management and Maintenance.** Battery reliability is a key factor in UPS system reliability. The UPS topology should minimize stress on the battery system and minimize the number of events that force the UPS to consume battery power.

The following affect UPS **Functionality:**

- **Range of Protection against Power Disturbances.** The UPS must protect the critical load against all conceivable types of input power disturbances.

- **Electrical Isolation.** The load must be protected from harmonics, common-mode noise and fault conditions on the input bus, and vice versa. An output isolation transformer is the accepted method of providing this isolation. But some products make the transformer an extra-cost (and extra-floor-space) option.

- **Generator Compatibility.** In critical facilities, an engine generator typically provides long-term outage protection to supplement the UPS's short-term outage protection. When the customer load increases sharply, both the frequency and voltage of the generator may fall out of specification for a short period. A well-designed UPS can operate successfully under these circumstances, but others will not.

The following affect UPS **Maintainability:**

- **Dual-Bus Compatibility.** Some UPS topologies are not compatible with dual-bus power systems, which are now considered industry "Best Practice." Dual-bus power systems feature two or more independent UPS systems powering two or more independent power distribution systems. Each item of load equipment, then, has access to *both* power distribution systems. Loads with dual power cords can directly utilize both systems. Single-corded loads require an upstream Static Transfer Switch, so they can be switched between distribution systems should one falter. However, these load transfers cannot be made unless the UPS systems are synchronized under all conditions, including on-battery operation. Certain UPS topologies cannot sync to anything except their own input sources.

- **Concurrent Maintenance.** The ideal situation is to be able to service portions of the UPS system while other portions continue to provide conditioned power to the connected load. A multi-module, parallel-redundant system enables a certain amount of concurrent maintenance on the UPS power modules. However, even a multi-module system needs to be completely powered down at least once per year for maintenance extending back to the building service entrance. Only a dual-bus system enables 100% concurrent maintenance, since one entire UPS and distribution system can be powered down while the other supports the critical load with conditioned power.

- **Internal and External Maintenance Bypass Circuits.** Every UPS needs to be de-energized for periodic maintenance and repairs. All three-phase UPS products should have some type of internal maintenance bypass circuits, to enable the load to operate on unconditioned utility (or generator) power while the UPS is removed from service. These circuits typically include the internal bypass static switch plus either switches, contactors or circuit breakers. These switching devices must work in concert to reliably transfer the load between the bypass line and the UPS inverter output, and back again when required. In addition, high-availability systems should have external "wraparound" maintenance bypass cabinets, panelboards or switchboards to allow the UPS to be completely de-energized for annual preventive maintenance.

The following affect UPS **Fault Tolerance:**

- **Single vs. Dual Input.** A single-input UPS is simpler to design and install, but is less fault-tolerant than one with separate inputs for rectifier and bypass. The input breaker or contactor of a single-input system can be a single point of failure. Likewise feeding both the rectifier and bypass inputs from the same Automatic Transfer Switch introduces a single point of failure.

- **Internal Fault Tolerance.** The UPS internal design must be rugged enough to handle input faults, load faults, temporary overloads, and input power disturbances.

- **Single Points of Failure.** It is inevitable that components inside and outside the UPS will eventually fail or wear out. The UPS must be designed to protect the load through any known failure mode and transfer to bypass, if necessary, should a failure occur.

Each UPS topology will be graded on these elements, and a summary report table will be presented at the end of this document.

UPS Topologies: The Offline UPS or Standby Power Supply (SPS)

The simplest type of UPS is the *offline* topology, shown in Figure 1 below. Under normal operating conditions, AC power from the utility passes straight through the UPS to the critical load. A charger or "4-quadrant converter" converts AC power to DC to charge the battery. The inverter is used to convert the DC power from the battery to create AC power to support the load when the utility fails. Normally the inverter is operating in the stand-by mode, keeping the batteries charged. Should the utility power go out of specification, the inverter powers the load, drawing energy from the battery.

This topology is labeled "single-conversion" because at any point in time, power is only being converted once (AC to DC, or DC to AC). In normal operation, a small amount of power is being converted from AC to DC to maintain battery charge. When input AC power goes out of specification, the inverter converts the DC power to AC to support the load. When the input power goes out of specification, there is a power disturbance in output voltage as the power failure is detected, the transfer relay operates, and the output inverter turns on to begin supplying the load.
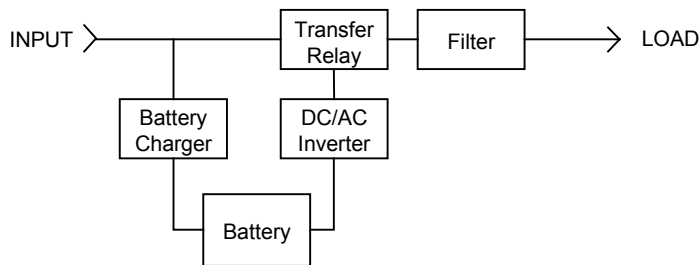
INPUT ⟩——————[Transfer Relay]——[Filter]——⟩ LOAD

[Battery Charger]   [DC/AC Inverter]

[Battery]

Figure 1. Offline UPS

The offline UPS can be made very inexpensively, and the efficiency is very high in normal operation. These products (like the Liebert PowerSure Personal) are ideal for home use or for powering individual computer workstations running non-critical applications that only require outage protection. Offline products sometimes have surge suppression and/or "buck and boost" circuits to compensate for high or low input voltage, but otherwise do not attempt to provide any significant input power conditioning.

The offline UPS gets high marks for simplicity of design, but low marks in other measurements. The table below tells the complete story.

Offline UPS Products		
Criterion	**Score**	**Comment**
Simplicity	4	Partially offset by corner cutting on low-end products
Battery Reliability	2	UPS must go to battery more frequently than others
Range of Protection	2	Must go to battery for harmonics, noise or frequency excursions
Power Conditioning	1	High-end models may have buck-and-boost circuits or TVSS
Electrical Isolation	0	None
Generator Compatibility	0	Takes itself back offline when voltage is restored or oscillates on/off
Dual-Bus Compatibility	0	Can only sync to its own input source
Concurrent Maintenance	0	Generally not available in multi-module configurations
Internal Maintenance Bypass	0	Some have external bypass device
Dual Input	0	Not available
Internal Fault Tolerance	1	Minimal
Single Points of Failure	0	Many. Unit must instantly go from standby to 100% load

The offline UPS is normally only applied to single-phase (workstation-level) non-critical loads. Its limitations, especially the generator incompatibility discussed in the next section, make it unsuitable for three-phase applications.

UPS Topologies: The Line-Interactive UPS

The next step upward is the *line-interactive* topology, shown in Figure 2 below. It resembles the offline product, but inserts a transformer or inductor in series between the utility power source and the load. This inline inductor enables the UPS inverter to "interact" with incoming power and provide a measure of power conditioning to the load. This "buck-and-boost" circuitry helps with high and low input voltage conditions.

Typically these 4-quadrant converters are constant-voltage devices. They adjust to shifting loads or varying input voltages by changing the output phase angle. Dynamic load changes cause power to be extracted from the battery. The resulting frequent hits on the battery can shorten battery life.

Another limitation of line-interactive products is that they cannot completely isolate the critical load from the input line without operating on battery. Small perturbations in frequency and power quality can get passed directly to the critical load. Without electrical isolation, common-mode noise also passes right through to the load.
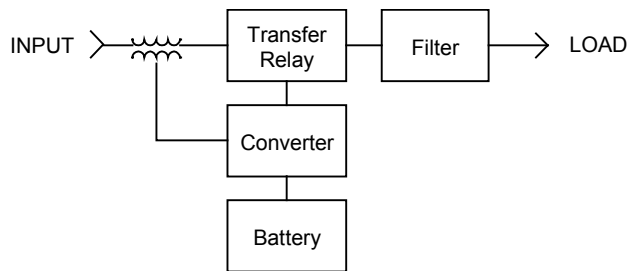

Figure 2. Line-Interactive UPS

Like the offline UPS, the line-interactive products can be inexpensive and efficient because they only support the entire critical load during power disturbances, and only for the duration of the battery. Compared to the offline UPS, the line-interactive units pay a small efficiency penalty for the series inductor and for losses associated with their power conditioning functions. And like offline products, the line-interactive products usually have a small (but measurable) amount of voltage sag on at least one phase during the transition to battery power. Liebert's PowerSure Interactive and PowerSure ProActive UPSs are examples of line-interactive products.

Generator Compatibility

Generator interaction problems for offline and line-interactive UPSs are well documented. Offline and line-interactive products require stable source frequency and phase shift. Stable source frequency is required since the inverters must track the supply frequency to provide the voltage and current correction. Therefore the output frequency of the system is the same as the input frequency unless the UPS is operating on battery.

A classic operational problem is the starting of other loads on the generator causing the generator's output frequency to vary, which then causes the offline or line-interactive UPS to cycle on to battery operation. The problem is especially pronounced with natural-gas-powered gensets. This repetitive battery cycling can cause the battery to discharge completely, while significantly shortening battery life. Another potential problem is the generator instability that occurs when the UPS load is transitioned to the generator. The UPS load transfer causes the generator voltage and frequency to sag, causing the UPS to go back to battery operation. Soon thereafter, the UPS senses stable generator output, transfers the load back to the generator, then transfers back to battery operation when generator output dips again.

The solution requires that the frequency window (delta f) and sychronizing slew rate (df/dt) of the line-interactive UPS that defines a "power failure" be widened well beyond generally accepted critical load

tolerances, which are ± 1 Hz for frequency window and 1 Hz/second for slew rate. In order to operate properly on gensets (i.e. to avoid going on battery too often), line-interactive products must be set to sychronize in a ±4-8 Hz window and at a 4 Hz/second slew rate. These variations are passed on to the critical load.

These problems don't exist for conventional double-conversion UPSs, as we'll see in the next section. Double-conversion UPSs rectify the input supply and can accommodate large swings in supply frequency while continuing to provide regulated, stable output frequency, without the use of the battery. Further, the major double-conversion UPS manufacturers have developed input current distortion reduction techniques that greatly improve the compatibility of UPS with generators to allow closer load sizing. Double-conversion UPS products can be used with a 1.25x to 1.5x generator size without operational problems.

Line-Interactive UPS Products		
Criterion	**Score**	**Comment**
Simplicity	3	Depends on features included in a particular model
Battery Reliability	2	UPS must go to battery more frequently than others
Range of Protection	3	Can't stop harmonics, noise or frequency excursions except on battery
Power Conditioning	2	Can adversely affect battery life
Electrical Isolation	0	None
Generator Compatibility	1	Only by passing frequency excursions on to the critical load
Dual-Bus Compatibility	0	Can only sync to its own input
Concurrent Maintenance	0	Some products have multi-module versions
Internal Maint. Bypass	0	Generally external devices
Dual Input	0	Not available
Internal Fault Tolerance	1	Minimal
Single Points of Failure	1	Many

UPS Topologies: Line-Interactive with Power Factor Correction (including "Neo-Online" products)

In recent years, a few companies have introduced line-interactive 3-phase UPS products with power factor correction. These have enhanced power-conditioning features compared to offline and typical line-interactive products. These features come at a price however. Efficiency is lower, because of the active power conditioning. In fact, efficiency when powering non-linear loads (typical computer loads) is frequently less than that of double-conversion products. Complexity approaches (and sometimes exceeds) that of double-conversion products. Sadly, the marketing hype also exceeds that of double-conversion products. Some of these products are being touted as "online" – because their inverters are "on" all the time providing either voltage regulation or input power factor correction.

These are line-interactive UPSs in the classic sense, meaning that the series transformer and output inverter interact with the incoming utility voltage to alter the output voltage. Some products have a small input inverter/charger (sometimes called a "delta" inverter) to modify the input voltage. The small inverter typically attaches to the DC bus, which it uses as a pipeline to exchange power with the output (main) inverter. The output inverter is used for both input power factor correction and outage protection.
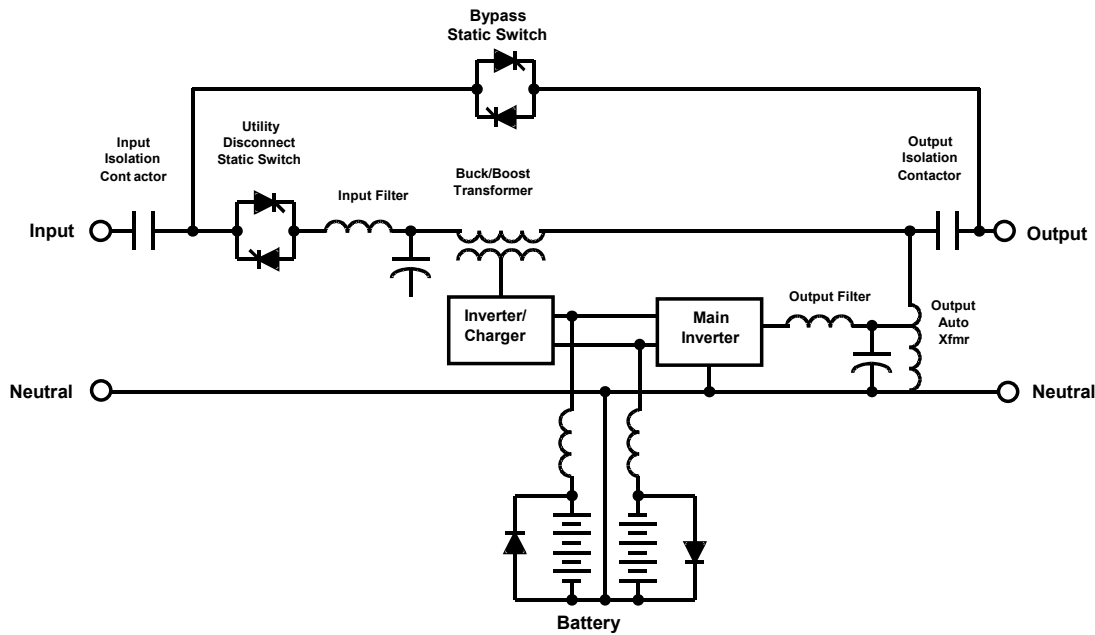

Figure 3. Line-Interactive UPS with Power-Factor Correction

In the normal mode (nominal input waveform, linear load on UPS), the input isolation contactor, the utility disconnect static switch and output isolation contactor are closed and utility power is directly supplied to the output. The input inverter operates as a charger and delivers a float charge to the battery system. The main inverter is off or idling under these ideal (unreal) conditions.

When the input voltage is present but not nominal, the delta inverter injects a voltage into the buck/boost transformer to add or subtract from the input voltage to create a regulated output voltage, similar to some electronic voltage regulators on the market today.

When the input power goes out of specification, the main inverter is activated to supply full output power and the utility disconnect static switch must be turned off to prevent backfeeding, similar to an offline UPS. Line-interactive UPSs using naturally commutated utility disconnect static switches are

particularly susceptible to failure under certain input source faults; since they cannot turn off quickly, the inverter will attempt to feed into the fault and will shut down.

These units can also provide load harmonic current and input power factor correction. The main inverter operates to inject the required compensation currents -- both harmonic currents and fundamental frequency reactive currents. Whenever the inverters operate, either the voltage correcting inverter/charger or the harmonic current and power factor-correcting main inverter, there are additional losses that significantly reduce the unit efficiencies well below their advertised efficiency.

Line-Interactive UPS Products with Power-Factor Correction		
Criterion	Score	Comment
Simplicity	2	Extra features add complexity; controls are significantly more complex
Battery Reliability	2	UPS must go to battery more frequently than others
Range of Protection	3	Can't stop harmonics, noise or frequency excursions except on battery
Power Conditioning	3	Can shorten battery life, plus input disturbances can affect output voltage
Electrical Isolation	0	None, without optional isolation transformers
Generator Compatibility	3	Only by passing frequency excursions on to the critical load
Dual-Bus Compatibility	0	Can only sync to its own input
Concurrent Maintenance	3	Some products have multi-module versions
Internal Maint. Bypass	3	Static-switch based
Dual Input	0	Not available
Internal Fault Tolerance	3	Varies by manufacturer
Single Points of Failure	2	Many

UPS Topologies: The Double-Conversion On-line UPS

The premium UPS topology is the true *on-line* or *double-conversion* product shown in Figure 4 below. Incoming AC power is rectified to DC power to supply the internal DC bus of the UPS. The output inverter takes the DC power and produces regulated AC power to support the critical load. Batteries attached to the DC bus are float charged during normal operation. When the input power is out of spec, the batteries provide power to support the inverter and critical load.
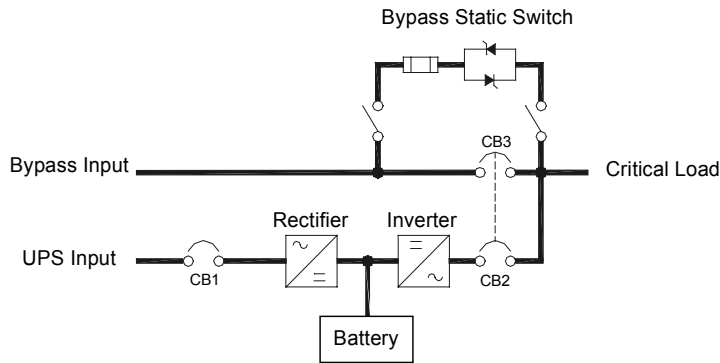

Figure 4. On-line UPS

Liebert double-conversion UPS products include the UPStation GXT, the UPStation S, the Nfinity, the UPStation S3, the Series 300, the Npower and the Series 600T.

Some advantages of this configuration include.

- The critical load is completely isolated from the incoming AC input power.
- The critical load is always being supplied by the output inverter, which is always being supplied from the internal DC bus. When input power fails, there is no transitional sag in the output voltage because the inverter is already operating on DC input.
- The input voltage and frequency may fluctuate, but the double-conversion UPS doesn't care, since the rectifier is only making DC power to feed the DC bus. For example, a Liebert Series 600 UPS can operate indefinitely and even recharge its batteries with input voltage at 15% below nominal. It can continue to operate, without discharging the batteries, through voltage sags of 20% below nominal. Likewise if input frequency is fluctuating in and out of specification, the rectifier will continue to make DC power and the output inverter will continue to make 60 Hz power without using the battery.
- The output inverter usually contains an isolation transformer that can produce a separately derived neutral. This enables the UPS to be electrically isolated and provide common mode noise protection for the load. All Liebert three-phase UPS products have output isolation transformers as standard.
- The double-conversion UPS is inherently dual-input, meaning that it has separate inputs for the rectifier and bypass circuits. The customer may request a single-input model as a convenience for installation, but dual-input UPS products are incrementally more fault-tolerant.
- In Liebert three-phase UPS products, the output inverter can sychronize to any internal or external reference source while operating in the normal mode (without using the battery). In normal operation, it will sync to its own bypass source. When operating on system batteries, it will normally sync to its internal reference clock. However, a true double-conversion UPS can be used in a dual-bus power system, where the UPS will sync to the designated reference source in all operating modes: on utility, on batteries, or on the backup generator.
- A fault on the input line causes the UPS to go to battery power, but the UPS rectifier will not allow power from the DC bus to flow upstream.

9

- This design is very mature and very well understood. It has been applied successfully to every imaginable application. All of Liebert's medium and large three-phase UPS products are double-conversion topology and have achieved million-hour critical bus MTBF.

Double-Conversion UPS Products		
Criterion	**Score**	**Comment**
Simplicity	4	Mature technology
Battery Reliability	4	Line-rectified DC bus minimizes battery discharges
Range of Protection	5	Handles all power disruptions
Power Conditioning	5	Full-time conditioned power from the inverter
Electrical Isolation	5	Assumes output isolation transformer (optional for some products)
Generator Compatibility	4	Generally very good, depending on input power factor characteristics
Dual-Bus Compatibility	5	Generally 100%
Concurrent Maintenance	5	Ideal on dual-bus systems
Internal Maint. Bypass	5	Static switch plus bypass breakers or contactors
Dual Input	5	Available, but not always specified
Internal Fault Tolerance	4	Withstands input and output faults better than line-interactive products
Single Points of Failure	4	Few to none, depending on manufacturer

Conclusion

All UPS topologies can provide outage protection, and can play a role in today's power protection industry:

- The Offline UPS is a low-cost solution for convenience-level protection against power outages. Single-phase workstation applications only.

- The Line-Interactive UPS provides adequate performance and some power conditioning for small network applications. Single-phase workstation and non-critical server applications.

- The Line-Interactive UPS with Power-Factor Correction provides better power conditioning for small network applications. Suitable for single-phase workstations and non-critical server applications. Not suitable for facility-wide three-phase applications.

- The Double-Conversion UPS provides the best performance and protection against all power disturbances. Recommended for all critical single-phase and three-phase applications, particularly high-availability, 24x7 applications.

Summary Table, All Topologies				
Criterion	**Offline**	**Line-Interactive**	**Line-Interactive with PF Correction**	**Double-Conversion**
Simplicity	4	3	2	4
Battery Reliability	2	2	2	4
Range of Protection	2	3	3	5
Power Conditioning	0	2	3	5
Electrical Isolation	0	0	0	5
Generator Compatibility	0	1	3	4
Dual-Bus Compatibility	0	0	0	5
Concurrent Maintenance	0	0	3	5
Internal Maint. Bypass	0	0	3	5
Dual Input	0	0	0	4
Internal Fault Tolerance	0	1	3	4
Single Points of Failure	1	1	2	4
Totals	**9**	**13**	**24**	**55**