GE Digital Energy

UPS Topologies for Large Critical Power Systems (> 500 KVA)

As presented at the 13th Annual Power Quality Exhibition & Conference, October 30, 2002

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October 2002

UPS TOPOLOGIES FOR LARGE CRITICAL POWER SYSTEMS (>500 KVA)

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With the increasing demand of uninterrupted and high quality power for critical loads, high power (>500KVA) UPS systems are becoming more and more popular. In order to properly design the critical power system, the type of UPS and amount of redundancy must be matched to the nature of the load, the type of power distribution, the quality of local power, and the required reliability. This requires a general understanding of the performance of different UPS topologies and a guide to the trade-off analysis. In this article, the four popular UPS topologies for high power (>500KVA) applications are described and a comparative study of their response to grid-based PQ events is provided. A thorough analysis of the system design, desired reliability, and various site constraints using the guidelines presented here will help ensure that the customer receives the correct UPS topology.

Introduction

During the late 1990s, the rise of internet-based companies – those heavily dependent on servers and other computer loads – resulted in an explosion in demand for electrical infrastructure capable of protecting delicate equipment from outages (as short as 1.5 cycles). While these particular companies have suffered a recent downturn, the need for conditioned power continues due to the increased dependence on computer-controlled equipment in fields such as medicine, bio-technology, and semiconductor manufacturing. Even old economy processes like coating, painting, and machining now have a single computer controlling the finishing operation on millions of dollars worth of finished goods (such as the coatings on gas turbine blades).

Uninterruptible Power Supplies (UPSs) are used to improve power source quality as well as protect these critical loads against disturbances, such as frequency shifts, voltage spikes and interruptions.[1] There are three major types of UPSs as specified by IEC standard 62040-3.

- Passive Standby (IEC 62040-3.2.20)
- Line Interactive (IEC 62040-3.2.18)
- Double Conversion (IEC 62040-3.2.16)

These terms define how the UPS delivers power to the critical load. There are two popular styles of Line Interactive UPS: Static and Rotary. The static line interactive topology is popularly known as Delta Conversion topology and the rotary line interactive topology is termed as Rotary T topology in this document.

Double Conversion Topology

The most common type of large UPS today is the Double Conversion UPS, shown in Figure 1. In this topology, an inverter is connected in series between the AC input and the load, with power for the load flowing continuously through the inverter. Three operating modes are possible in this topology, namely "normal", "stored energy" and "bypass". Under normal mode, the load is continuously supplied by a rectifier-inverter combination, which carries out the double conversion (AC-DC, then DC-AC). The UPS goes into stored energy mode when the AC input to the system fails or goes out of the specified tolerance range. The inverter and the battery continue to support the load under this mode. The UPS runs in stored energy mode until the stored energy is exhausted or until AC input returns to the specified tolerance level.

This type of UPS is generally equipped with a static bypass switch, allowing instantaneous transfer of the load to the bypass AC input. This switch is used in the event of a UPS internal malfunction, load current transients (in-rush, or fault clearing), prolonged overloads, or at the end of battery back-up (autonomy time). However the presence of a bypass implies that the input and output frequencies and phase must be identical, and the voltage coordinated. The UPS is synchronized with the source of AC bypass supply to allow a transfer to bypass without any interruption.

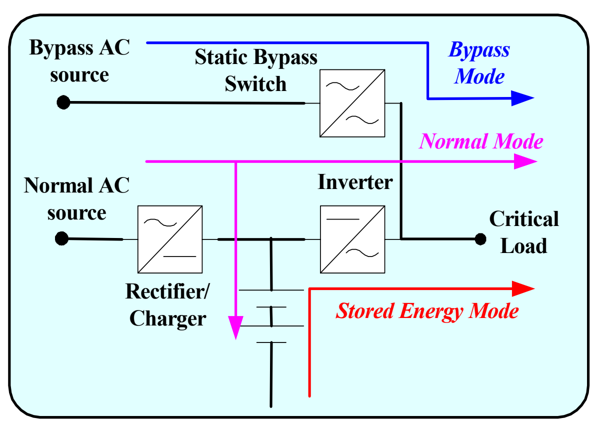

Fig. 1. Block diagram of Double Conversion Topology

At the input of this UPS there is a rectifier, which performs the AC-DC conversion. A 6-pulse rectifier with a 5th harmonic filter reflects less than 7% input current distortion. 12-pulse rectifiers or IGBTs reflect even less, although at reduced levels of efficiency, simplicity and reliability. While lower distortion is desired, it is rarely needed and 7% THD is sufficient to prevent any disruption to adjacent loads or to the incoming utility feed for most applications.

Delta Conversion Topology

The static line-interactive topology is termed Delta Conversion, and shown in Figure 2. This is a line interactive UPS topology with active series–parallel power conditioning capability. The sinusoidal output voltage regulation capability results in low input current and output voltage THD, in back up as well as in standby mode. The series converter (mains side) can be operated as a current source and the parallel converter (Load side) as voltage source. In this case the battery charging is done through the series converter. Alternatively the parallel converter can be operated as a current source and the series converter as a voltage source under standby mode. In stored energy mode, the parallel converter changes its operating mode from current source to voltage source. The static switch is switched off during stored energy mode to prevent any power flow from the battery to the mains. An advantage of this line interactive topology over the double conversion topology is its increased overall efficiency.

The input power factor and the line current harmonics can be controlled in Delta Conversion. The power factor is typically controlled to be close to unity and the reflected line current distortion is controlled to near 1% in many instances.

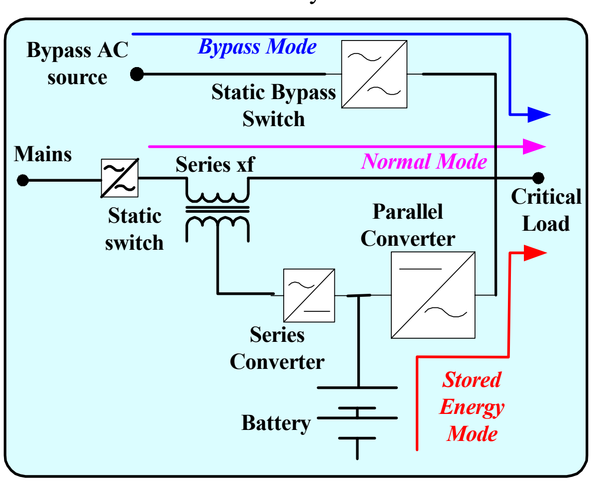

Fig. 2. Block diagram of Delta Conversion Topology

Rotary T UPS topology

The most common line-interactive topology is the Rotary T, illustrated in Figure 3. Under normal operating conditions (i.e. when the mains voltage is within the accepted range), the synchronous motor draws a compensating current so as to maintain a constant load voltage level. Also during normal operation, kinetic energy is stored in the flywheel (or induction coupling). When the mains fail, the stored flywheel energy is extracted to support the load. Flywheel inertia (or induction coupling speed range) is sized to support the full load operation for a specific period (typically a few seconds), during which time the backup diesel generators are started.

Special construction of the synchronous motor allows this topology to provide good harmonic compensation of the line current. Bi-directional power converters are used to control power flow between the dual winding synchronous motor/generator and the flywheel synchronous motor/generator.

The buffer inductor consists of two inductively coupled windings. The impedance of the isolation (mains side) is high (~49%) while the coupling winding has a low impedance (~1%). The mutual inductance between the two windings is equal to the sub-transient reactance of the generator. The isolation winding provides high impedance de-coupling between the input and output of the UPS while the generator regulates the voltage. The mutual inductance between the windings offsets any voltage variations at the output of the generator.
The main advantage of this topology is the ability to clear large faults or start motors without transfer to bypass. It is also favored for its compact size and relatively high efficiency.

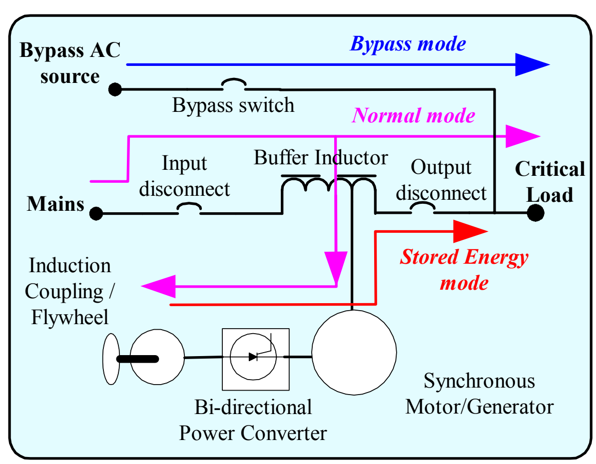

Fig. 3. Block diagram of Rotary T UPS Topology

Passive Stand-By

In this topology, the system monitoring and control unit continuously monitors the utility voltage and frequency to determine if they are within the specified limits. If the utility source parameters are within +/-10%, the load is directly fed from the utility mains through the fast acting static switch. During this condition (standby mode) the power inverter remains energized but does not supply any power to the load. The battery charger maintains the voltage level of the batteries during this time.

In the event of any power failure at the mains or if the mains power parameters go out of the specified limit, the system control turns off the fast acting static switch and turns on the inverter. Under this condition (Stored energy mode) the inverter supplies the load power by converting energy from the battery.

Operation of the UPS under stored energy mode is the same as that of a double conversion topology. The major drawback of this topology is that it does not condition the utility power in any way during standby mode operation. Thus, in this topology the UPS transfers to stored energy mode very often. However, a major advantage of this topology is its simplicity of control, high efficiency and low cost.

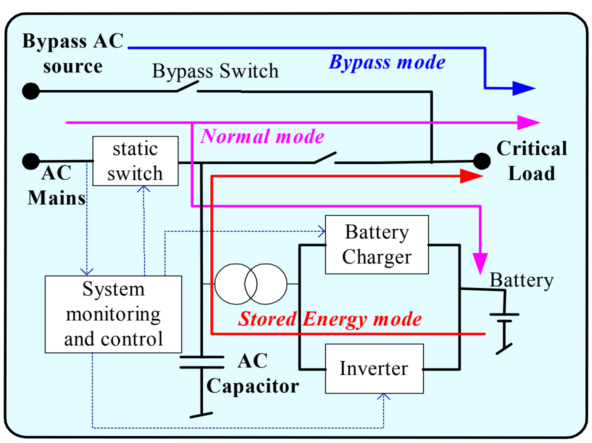

Fig. 4. Block diagram of Passive Standby UPS Topology

Response to Power Quality Events

The four UPS topologies described in the previous section were simulated[2] in Saber, a commercially available computer modeling tool. The models did not include all components. However, they were suitable to simulate the macro behavior of the UPS in response to typical grid-based power quality events with sufficient detail to make comparative performance assessments.

Line voltage sag and swell. Line voltage sags and swells happen during the application or removal of large loads to the grid system. These are also caused by fault conditions at various points in the AC distribution system. The typical duration of voltage sags and swells at the grid system is 0.5 sec.

In Double Conversion and Rotary T topologies, the output is very well isolated from the input side voltage sags and swells. For the Delta Conversion topology with a voltage swell >15%, the load voltage experiences the swell until the static switch is commutated off. Natural commutation at current zero crossing can lead to maximum commutation time of ½ cycle. In the Passive Standby topology input sag / swell directly gets passed to the load for short durations (~15ms).

Line frequency variation: For satisfactory operation of most of the computer equipment, frequency variation should be limited to +/-0.5Hz. UPS topologies other than Double Conversion cover mains frequency variations by tapping into the stored energy resource (Flywheel or Battery). Double Conversion topology can maintain the load frequency variation within +/-0.1%, without tapping the stored energy. In the line-interactive topologies as well as in the Passive Standby topology, the load experiences equal frequency variation as the mains. When this variation reaches unacceptable levels, the control circuit isolates the load from the mains through the input disconnect. This results in a discharge of stored energy until the utility source is back within tolerance. If this type of frequency variation is very common, the battery/ flywheel discharges frequently, resulting in possible early battery failure or a high level of nuisance starts on the genset. This may also result in a decreased amount of stored energy during an actual power interruption.

Input voltage unbalance and single phasing. The ANSI (American National Standards Institute) recommended limit of voltage unbalance in power distribution system is 3%. Approximately 98% of US distribution systems have unbalances less than or equal to 3%. Single phasing can be considered as a special case of voltage unbalance equal to 100%.

All the UPS topologies except passive standby protect the load from typical input voltage unbalance (<3%). For higher levels of unbalance, the losses in the Rotary T topology increase.

When there is single phasing at the incoming utility feed, all of the UPS topologies draw from the stored energy source. Double Conversion and Delta Conversion topologies transfer the load to stored energy instantaneously without any disturbance. In the Rotary T topology, the load voltage experiences a ~20% dip for ~200ms. In Passive Standby topology, the UPS load experiences the single phasing for a minimum of 4ms.

Voltage waveform distortion at input. In the double conversion topology the load side voltage is completely independent of the mains waveform distortion. In delta conversion topology the parallel converter is controlled as a voltage source and regulates the load voltage to achieve a good voltage THD on the order of 3%, irrespective of the input voltage THD. In case of Rotary T topology, the isolation inductor acts as a filter to the input voltage distortion. However, the isolation inductor does not filter any sub-harmonics in input voltage and passes on the distortion to the load side. A passive standby UPS does not protect the load from utility voltage distortion.

Input switch commutation time. Among the four topologies discussed here, all but double conversion have a switch at the input which dictates the performance of the UPS.

Delta conversion topology has a line commutated thyristorized switch at the input, which is commutated naturally at the current zero crossing. Thus the time delay for the switch to isolate the UPS from input side fault depends on the type and instant of occurrence of the fault. This static switch operates within 1ms for faults like input short circuit or input open circuit provided input power factor is maintained at unity. For other faults, the maximum time is ½ cycle. Rotary T topology has one motorized breaker at the input. Operation of this breaker is relatively infrequent as the UPS isolates the output from input side faults very well, including large sags and swells at the input. Typical time of operation of this switch is 200ms. Slow operation of the breaker does not affect the performance of the UPS, as the UPS can isolate load voltage from mains for short duration (about 1-sec). The breaker operation time varies depending upon the rms ac as well as the DC content of the current through it. Passive standby UPS has one forced commutated static switch at the input. Typical commutation time of this switch is 4ms (¼ cycle).

The total input disconnection time is the sum of switch commutation time and fault detection time. The fault detection time depends on the control circuit, and is typically on the order of ½ cycle.

ITI (CBEMA) compliance of UPS topologies:

The Information Technology Industry Council (ITI) Curve[3], formerly the Computer & Business Equipment Manufacturers Association (CBEMA) Curve, describes an AC input voltage envelope, which typically can be tolerated by most Information Technology Equipment. The curve describes both steady state as well as transient conditions. It may be noted that this curve does not address frequency variation and waveform distortion directly, except for some guidelines as to energy absorption (80 J). Figure 5 shows the voltage envelope offered to the load by double conversion and Rotary T topologies. Overlaid on this envelop is the CBEMA or ITIC boundary, which is the general performance standard required by computer power supplies and is roughly similar to the SEMI F47 curve used in the semiconductor industry.

Table 1: Overview of system responses

	Double Conversion	Delta Conversion	Rotary T	Passive Standby
Voltage Sag	Load voltage is regulated within +/-0.5% at Steady State, and +/-5% in dynamic state (1 power cycle)	Load voltage is regulated within +/-0.5% at Steady State, and +/-5% in dynamic state (1 power cycle)	Load voltage is regulated within +/-1% at Steady State, and +/-5% in dynamic state (200ms)	During normal operation up to 10% voltage sag is experienced by the load
Voltage Swell	Load voltage is regulated within +/-0.5% at Steady State, and +/-5% in dynamic state (3 power cycles)	Voltage surge (>140%) is experienced at the load for short duration (~1 cycle)	Load voltage is regulated within +/-1% at Steady State, and +/-5% in dynamic state (200ms)	Voltage surge is experienced at the load for short duration (~1cycle)
Frequency variation	Frequency variation is restricted to +/-0.5% at load	No control on line frequency variation	No control on line frequency variation	No control on line frequency variation
Voltage waveform distortion	Load voltage waveform is not distorted by line voltage distortion	Line voltage distortion is corrected by the parallel converter at the load point	Line voltage distortion is corrected to a large extent by the synchronous motor (short circuit ring) at the load point	Line voltage distortion is passed on to the load
Voltage unbalance	Load does not see the input voltage unbalance	Load does not see the input voltage unbalance	Line voltage unbalance is corrected to a large extent by the synchronous motor (low negative sequence impedance) at the load point	Line voltage unbalance is passed on to the load

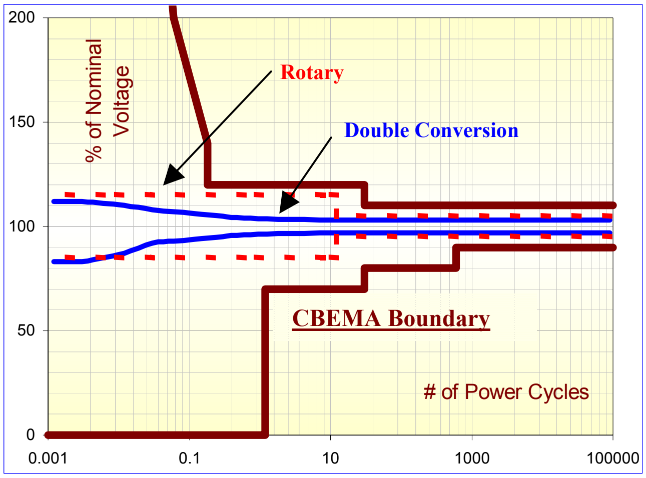

Fig. 5. Operating boundaries of Double Conversion and Rotary-T

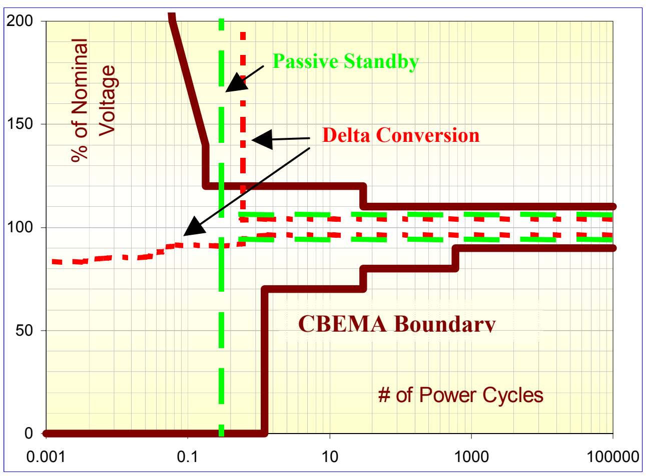

Fig. 6. Operating boundary of Delta conversion and Passive Standby

In the double conversion topology, output voltage reaches steady state within a maximum of three power cycles. At steady state, the output voltage is tightly regulated within +/-2% of the nominal voltage. During dynamic conditions (duration less than three power cycles), the voltage does not go beyond +/- 10% of the nominal.

The rotary T topology operating boundary looks very similar to that of the double conversion topology, except that, its dynamic response time is slower. Thus larger voltage variation at the output can be observed for longer duration. However, in this topology, all operating points, including dynamic state, fall within the CBEMA Curve.

Figure 6 shows the voltage envelope offered to the load by delta conversion and passive standby topologies. In these topologies, the operating boundaries are dependent on the input static switch commutation time. For delta conversion and passive standby topology the maximum commutation time for the static switch is assumed to be 0.5 cycles and 4ms respectively. From this plot, it is seen that many operating points in these topologies can go out of the CBEMA boundary. This is especially true for input voltage swells.

Figures 7 and 8 are scatter plots which show the results of simulations aimed at illustrating how various UPS topologies are able to protect a typical semiconductor fabrication laboratory from grid voltage sags and swells. All round points on these plots indicate the practical data collected from the site (Source: EPRI Distribution Power Quality study).

Figure 7 shows the sensitivities of a Double conversion UPS and Rotary T UPS to typical voltage sag/swell events in a power distribution system. Double conversion UPS regulates the load voltage to +/-5%, with maximum dynamic time of 3 cycles. Output is maintained within +/-2%, instantaneously for grid voltage sag and swell of 15% or less. (In the above plot, instantaneous operation is considered as 1ms, for presentation only). For higher sag and swell also the output voltage is regulated to +/-2% at steady state. However, during dynamic condition the output voltage can deviate by maximum of +/-5%. The time period for this deviation may vary from 1 cycle to 3 cycles.

The rotary-T topology UPS regulates the load voltage to +/-5% instantaneously for grid voltage variation within +20% to -50%. For higher sag and swell the output voltage is also regulated to +/-5% at steady state. However, during a dynamic condition but before the input motorized breaker is opened, the output voltage can deviate by maximum of +/-10%. The time period for this deviation may vary from 10 cycles to 20 cycles.

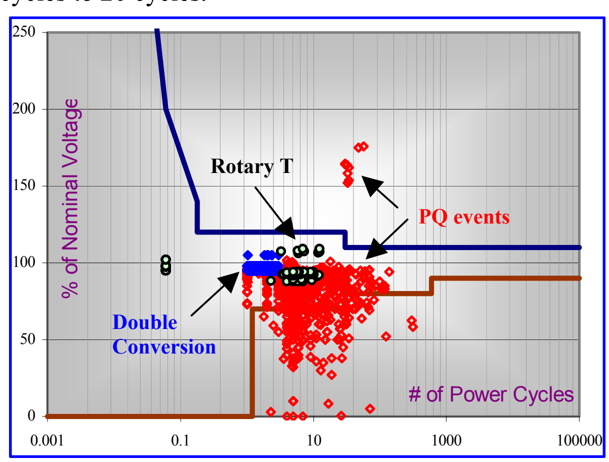

Fig. 7. PQ events with Double conversion and Rotary T

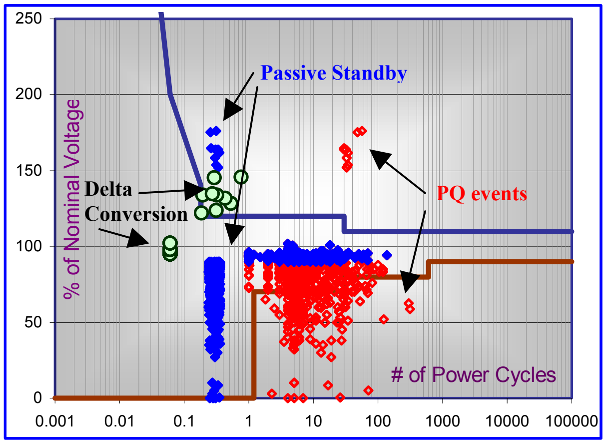

Fig. 8. PQ events with Delta conversion and Passive Standby

Figure 8 shows the sensitivities of Delta conversion UPS and Passive Standby UPS to typical voltage sag/swell events in a power distribution system. A delta conversion ups regulates the load voltage to +/-2% instantaneously for mains voltage of +/-15%. For higher sags and swells the output voltage is regulated to +/-2% at steady state. However, during dynamic condition, before the input static switch is commutated off, the output voltage experiences the input voltage swell in a reduced scale. The time period for the static switch commutation (including fault detection time) may vary from 0.3 cycles to 0.8 cycles, depending upon the fault condition.

The passive standby UPS passes the grid voltage to the load without conditioning for sags/swells less than 10%. For higher sags/swells, the input static switch is commutated off and the output voltage is regulated to +/-2% at steady state. However, until the static switch is commutated off, the output voltage experiences the input voltage sags and swells unattenuated. The time period for the static switch commutation may vary from 0.2 cycles to 0.3 cycles.

Figures 7 and 8 indicate that whereas Double Conversion and Rotary T topologies protect the load satisfactorily, the load voltage may experience a voltage swell exceeding the CBEMA limit if it is protected by Delta conversion or Passive Standby topology UPS. The probability of such an event is 0.8%, as calculated from the above sample data. Improvements to this failure rate require sophisticated control algorithms for the switching, similar to those found in PDUs. However, this can lead to different failure modes and care is advised.

Tradeoff Analysis

In order to properly design the critical power system, the type of UPS and amount of redundancy must be matched to the nature of the load, the type of power distribution, the quality of local power, and the required reliability. These attributes vary by location and customer, so it is important not to prejudge the solution going strictly by past experience. The objective of this section is to present some of the tradeoffs that can be used to constrain the myriad of options available to the design engineer or customer.

The first step is to identify the size of the UPS by choosing the type of distribution system. There are three general approaches:

1. A distributed architecture where the UPS is placed directly next to each critical load.
2. A centralized architecture where all UPS are grouped together
3. A grouped approach where a handful of UPS systems are located strategically around the facility.

For large UPS systems, it is generally accepted that the distributed architecture leads to a system that is difficult and costly to maintain. The decision of whether to group or centralize is often more subtle, and is partly dependent on the type of UPS and the layout of the site. However, in either case, the UPS system is most reliable when kept in blocks of 2-5 units, provided the units are connected in an architecture like Redundant Parallel Architecture™ (RPA™) as shown in Figure 9. This guideline is the result of a classic tradeoff between the greater dynamic response and proven fault tolerance of multi-unit systems with the higher theoretical MTBF of single-unit systems.

With the understanding that 2-5 units comprise the design target, simply knowing the power requirements of the facility will constrain the unit size. Consider a 5-MW facility, common in the semiconductor industry. The UPS size would need to be 1-2 MW. On the other hand, a 1-MW data center could use a group of 200-500 kVA units.

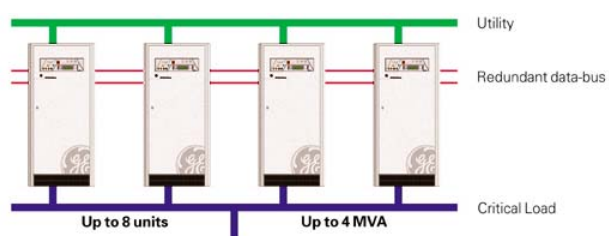

Fig. 9 Redundant Parallel Architecture (RPA) implementation.

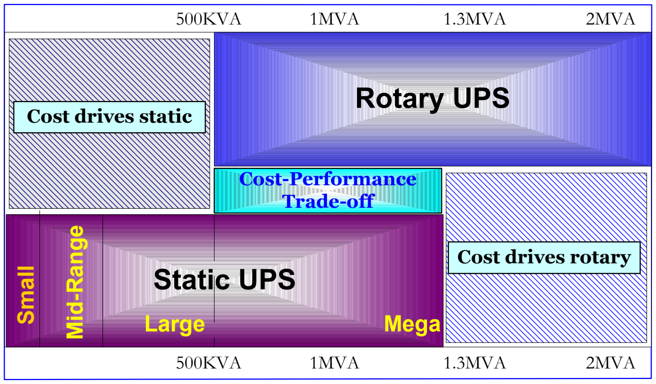

Fig. 10. Tradeoff between Static and Rotary systems.

For the large semiconductor facility, it may make sense to use a rotary UPS because of the larger unit size, higher efficiency, and lower installed cost (on a $/kW basis). However, the smaller data center is more likely to choose a static UPS because of the better dynamic response, lower maintenance, and general ease of use of a static UPS system. This tradeoff is illustrated in Figure 10.

The last item to consider is the local power quality. While the response to general faults is indicated in Table 1, it is sometimes more instructive to consider the covered faults along with their estimated likelihood at the proposed facility, as shown in Figure 11. Some events, like waveform distortion, can occur monthly. Others, like a phase reversal, may occur only once in a 1000 yrs.

While that is indeed very unlikely, consider that this implies a 0.1% chance of failure each year, essentially bounding the reliability that can be achieved at the site. This further serves to narrow down the choice of UPS by bracketing the desired level of reliability as shown in Figure 12.

The analysis used to derive Fig. 12 is asymptotic in nature, meant to capture the basic influence of the event probability in Fig. 11. The techniques are simplified from Ref. 5 & 6 and assume that any PQ event that slips past the chosen topology will cause a 24-hr outage.

Notice that for the assumed event frequency, no amount or configuration of passive standby UPS's can reach the level of reliability afforded by a properly designed and installed double conversion UPS system. However, there are many applications where the lower cost is more important to the customer, and they will simply accept the lower reliability as a business decision. In fact in most cases with N+0 UPS designs, it is more likely that the UPS itself will fail than one of the power quality

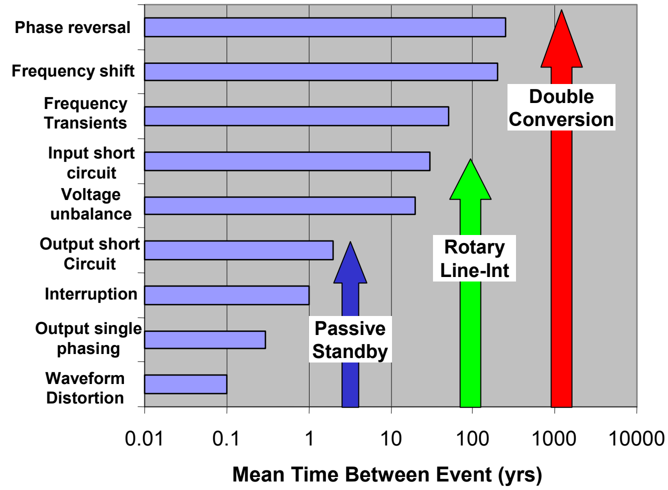

Fig. 11 Sample probability of events and ability of different topologies to clear.

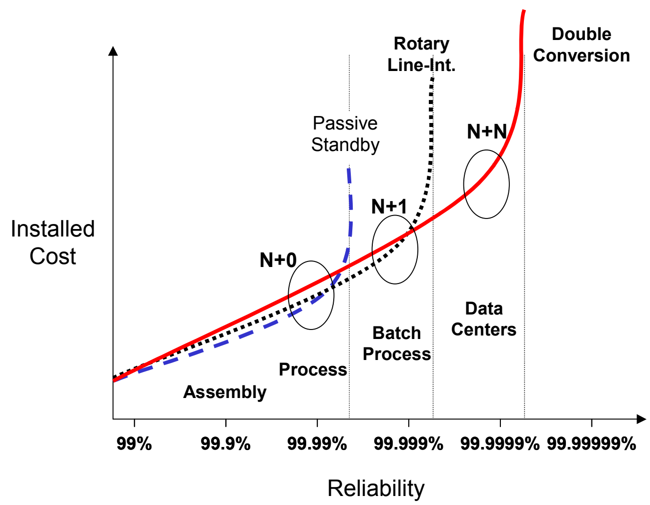

Fig. 12 Asymptotic cost analysis of different topologies as a function of reliability using probabilities from Fig. 11. While no amount of redundancy can produce a 6-9s system with passive standby, not all customers require this or even N+N systems.[4]

events will sneak past the system, even one that is switch-based.

Summary

There are several important UPS topologies available today for large critical power systems. Because of the degree of isolation in a Double-Conversion UPS, this topology offers superior protection from line-side PQ events. The Rotary-T topology provides a balance between line-side and load-side protection, although with reduced levels of isolation and dynamic response as compared to Double Conversion. The Delta Conversion topology has some advantages with regard to improved efficiency over the Double Conversion. However, it has the potential to allow voltage surges and some other PQ events to pass through to the load. In addition, the manner in which the UPS mitigates PQ events often results in battery drainage, which in turn leads to reduced battery life. This last issue also applies to Passive Standby, which does little to no power conditioning, and must switch to battery power whenever the input voltage is out of tolerance.

Static Double Conversion topology and Static Line interactive topology (Delta Conversion) are viable solutions in lower power ranges (unit size <1MVA). With large unit power ratings and availability at medium voltage, the Rotary-T topology is the preferred solution for the larger installations. The passive standby solutions are viable for customers looking to avoid the business interruption caused by only the most common PQ events.

A thorough analysis of the system design, desired reliability, and various site constraints using the guidelines presented here will help ensure that the customer receives the correct UPS topology.

Acknowledgements

The numerical analysis of the topology response was led by Bansi Phansalker and his team at the Jack F. Welch Technology Center, part of GE Global Research-Bangalore. The interpretation of results was done in conjunction with Robert Delmerico at GE Corporate Research-Niskayuna.

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