Technical Paper

Understanding Eaton Energy Saver System

A technical review of how Eaton ESS enhances reliability and efficiency

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Executive summary

Eaton's Energy Saver System (ESS) enables large uninterruptible power systems (UPSs) to operate at up to 99 percent efficiency without sacrificing reliability. Though it is rapidly gaining support in the UPS industry, many consultants and end users have questions about how ESS works and what enables it to lower power consumption while maintaining high availability. This technical paper answers those questions by providing in-depth technical information about ESS's architecture, reliability characteristics, computational infrastructure and surge suppression attributes.

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ESS reliability: building on double conversion

Mission MTBF (hr)	Power Xpert 9395 UPS Models			
	275 kVA	550 kVA	825 kVA	1100 kVA
ESS	2,076,334	1,038,204	692,161	519,140
AC Double Conversion Without ESS	1,008,234	504,054	335,994	251,964

Table 1: UPS load losses by preventive maintenance visits delivered in prior year. [1]

As the figures in Table 1 above indicate, UPSs with ESS deliver twice the mean time between failures (MTBF) as double-conversion UPSs. A close review of the reliability state diagram for ESS, shown in Figure 1 below, helps explain this somewhat surprising result.

> **ESS technology**
>
> ESS technology does not introduce new or unique components. Rather, it uses existing double-conversion components in a new and unique manner.

Note that the ESS reliability state diagram includes the entire double-conversion state diagram. This is because ESS encompasses and extends the traditional double-conversion architecture. In fact, the best way to understand ESS is as an enhancement of double-conversion technology that builds upon and augments its important strengths. Appendix A contains a more detailed description of the UPS reliability states shown in the diagram.

Figure 1 makes clear that while a double-conversion UPS has four possible reliability states, an ESS device has five. As a result, an ESS-equipped UPS is less likely to fall into the mission failure state and is therefore more reliable. A UPS in ESS mode can move to double-conversion mode or to battery backup mode or to bypass mode, depending on its operating state, system alarm state and system fault conditions. A traditional double-conversion system, by contrast, has only two possible transition states: the more classical bypass and on-battery states.

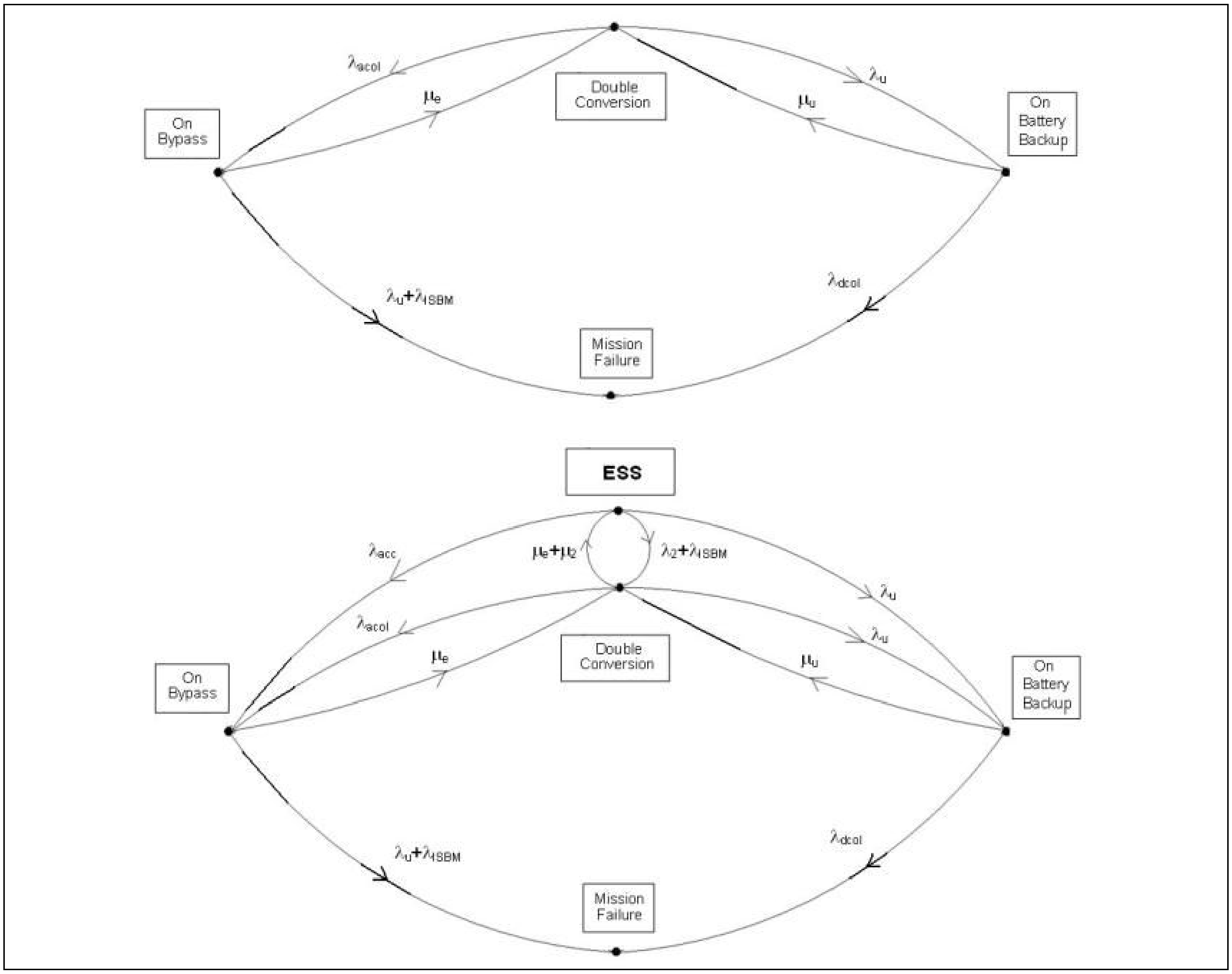


Figure 1: Simplified reliability state diagrams for double conversion and ESS.

Figure 2 displays a UPS with separate feeds to the static switch (STSW) input and the rectifier input, offering further illustration of how ESS extends double conversion's operational capability. Neither of the two double-conversion topologies depicted protects critical loads when on bypass. ESS, however, protects loads both on STSW and when drawing power from the rectifier feed.

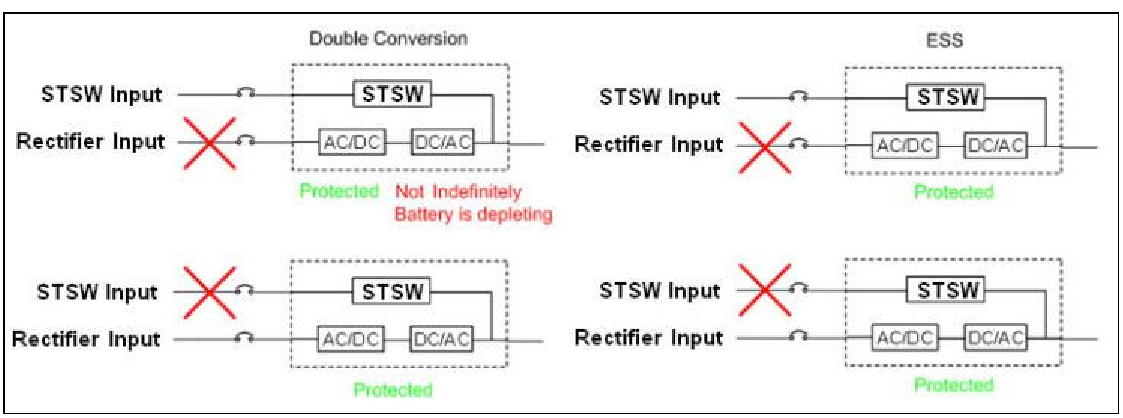


Figure 2: An ESS-equipped UPS offers more complete protection than a conventional double-conversion UPS.

Furthermore, Figure 2 makes clear that in the event of a utility outage, a double-conversion UPS protects the load until its DC source is depleted and then transfers to unprotected STSW. Under similar conditions, a UPS with ESS continues to run in ESS mode and only transfers to battery operation if an STSW input outage occurs. In effect, ESS can suffer two source outages before transferring to battery and depleting the backup DC power source. This is an important consideration when striving for maximum availability.

How ESS enhances component reliability

Electromechanical devices such as fans and contactors are essential to proper UPS operation. Unfortunately, such components contain moving parts that experience wear and tear and will eventually fail. ESS improves the reliability of many electromechanical devices by putting less strain on them than conventional double conversion systems.

> **ESS reliability**
>
> ESS systems utilize electromechanical components like fans, rectifiers and inverters in a manner that lengthens their lifespan, contributing to greater MTBF.

For example, fans are typically switched off in an ESS-equipped UPS, except when the device is charging batteries and needs additional cooling power. As a result, fans in an ESS system generally enjoy a longer lifespan and are less prone to failure, resulting in greater MTBF.

Similarly, ESS utilizes the STSW path to power the load and relies on the rectifier and inverter as alternate resources only when power quality conditions degrade severely or batteries need to be charged. Consequently, whenever a UPS is in ESS mode, both the rectifier and inverter are essentially in a logic-only, quiescent state and thus subject to very little electrical and thermal stress. Even when charging batteries, in fact, an ESS system's rectifier and inverter are under minimal load and stress. This can extend their lifespan and reliability significantly.

Finally, a UPS with ESS puts less strain on contactors by placing them in a closed state when in ESS mode. Closed contactors at near zero contact current experience little if any power dissipation and low electrical and thermal stress. Moreover, an ESS system with contactors in their closed state is no longer dependent on an electromechanical device vulnerable to failing when it's most needed. Transient conditions are, of course, traditionally excluded from MTBF calculations, but ESS's handling of contactors clearly improves overall reliability just the same.

In fact, the key point in all three examples above is that core aspects of ESS's design organically result in less wear on electromechanical devices, longer lifespans for those components and higher reliability.

Understanding ESS architecture

At its core, ESS is based on an architecture encompassing traditional UPS components shown in Figure 3, such as the rectifier, inverter and battery converter. Notice that ESS employs the same tried and tested power paths as a conventional double-conversion UPS, including STSW, rectifier-inverter, battery-inverter, rectifier-charger and inverter-charger, but makes more complete use of them. As a result, a UPS with ESS utilizes power paths with maximum efficiency, letting none go to waste.

> **ESS presents a paradigm shift**
>
> ESS changes the treatment of the UPS state machine or state diagram from the traditional form, with relatively static and mutually exclusive boundaries, to one that manages those traditional boundaries with an advanced computational infrastructure that appropriately blends energy saving and power quality objectives.

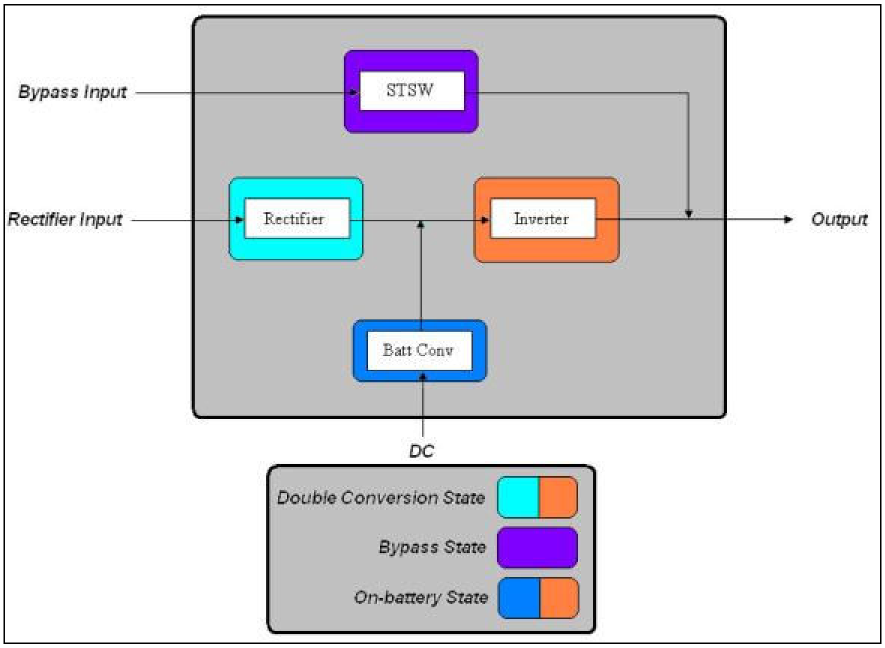


Figure 3: Traditional UPS states.

Figure 4 shows ESS and its relation to the traditional UPS modes of operation. The key point it illustrates is that ESS does not introduce any new or additional components to the traditional architecture.

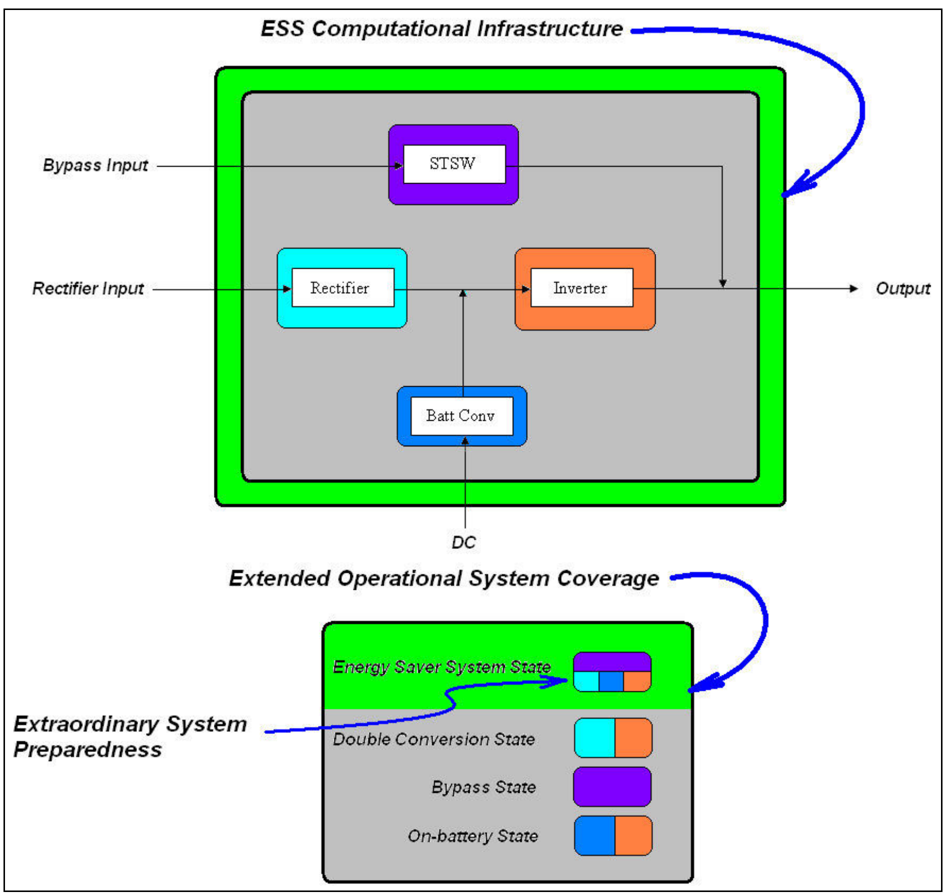


Figure 4: Traditional UPS states plus ESS.

The ESS architecture is based on insulated gate bipolar transistor (IGBT) technology and employs the principal of bidirectional power flow. Figure 5 illustrates how ESS uses a single set of hardware to transition seamlessly from one required power flow path to the other. Without that bidirectional power flow architecture, ESS would require a more complex set of power stages and controls featuring more circuits, which would raise the risk of component failure.

ESS is UPS productivity at its highest

Drawing on advanced IGBT power conversion and control techniques, ESS makes use of nearly every available UPS power flow path, resulting in agile and efficient UPS implementations.

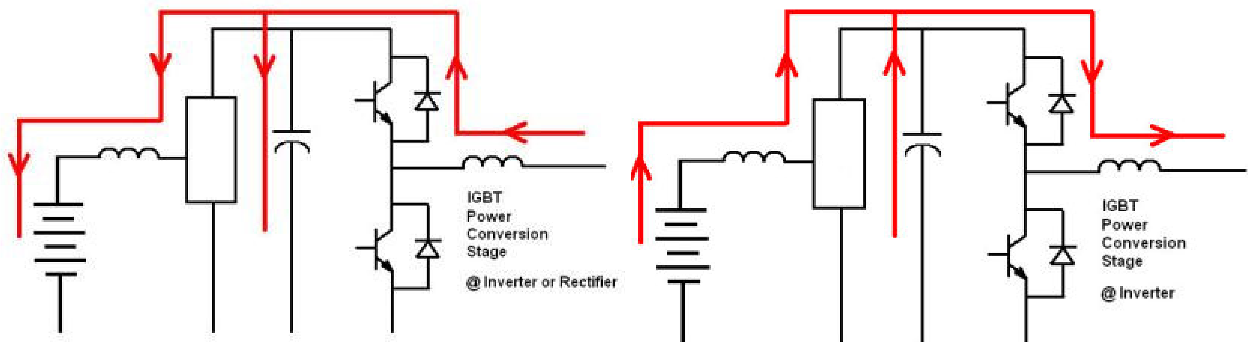


Figure 5: Bidirectional power flow diagrams

Bidirectional power flow is a proven technology used for many years in UPS products. Moreover, the 9395 UPS features a battery converter that can charge and discharge the battery using the same circuit. ESS simply extends the use of this traditional UPS hardware operating mode to achieve energy savings while still meeting power quality objectives.

ESS computational infrastructure: controls, logic and sensing

The controls, logic and sensing that drive ESS's operation, also known as its computational infrastructure, are key elements of its design. Within the computational infrastructure are system-wide digital signal processors and sensors that continuously monitor critical input and output parameters. Figure 4 displays the extent to which this infrastructure encompasses the UPS's operational elements, effectively adding a new state that goes beyond the traditional UPS states of double conversion, STSW and on-battery. What's more, ESS utilizes traditional, time-tested UPS components to establish this new state.

Though ESS is designed to improve energy efficiency, it keeps protection of critical output as its highest priority. ESS accomplishes this prioritization using logic that governs its computational infrastructure. An ESS-equipped UPS normally operates in ESS mode, but temporarily moves back to double-conversion mode should input power conditions require it to do so. ESS is thus essentially capable of multiple normal modes of operation, making it a state of extraordinary preparedness for the UPS.

Together, the ESS computational infrastructure's controls, logic and sensing produce a technology that is:

- Reliable, as it utilizes simultaneous voltage sensing in the integrated system bypass module (ISBM) and uninterruptible power module (UPM), aligning it with the parallel redundant architecture of the 9395 UPS.
- Adaptive, as it is equipped to detect partial outages and full outages in both three-phase and single-phase cases. The ESS infrastructure does not presume anything about the environment in which it is expected to function.
- Flexible, as it's structured using highly customizable settings that allow users to tune ESS operation for their particular power needs.

In addition, the ESS computational infrastructure also:

- Makes power quality its highest priority, by privileging load protection over efficiency.
- Employs transfer logic that is automatic both in activation (ESS to double conversion) and restoration (double conversion to ESS).

Finally, the ESS computational infrastructure is also responsible for numerous UPS performance benefits, such as these:

- High-speed response, as there is no dependence on mechanical device closure times or converter startup delays and high-speed detection algorithms.
- Discrimination between upstream and downstream faults.
- Response speeds that are consistent and compatible with downstream static transfer switch (STS).

Additional information about how ESS produces these performance advantages can be found in publications available on www.eaton.com/pq.

ESS transition time

An ESS-equipped UPS's high-speed transition from ESS mode to double-conversion mode depends on several factors:

- How fast the UPS can detect the input disturbance.
- How fast the UPS can gate the inverter.
- How fast the UPS can turn off the static switch.

Detection of an input line disturbance occurs in multiple locations within the 9395 UPS architecture. The ISBM and UPM share the job of output under voltage detection equally and work simultaneously. Control logic ensures that a transfer to online happens if either one concludes that such a transfer is necessary. The UPM is somewhat slower due to controller area network messaging delay. The same is true for the 9395 UPS as structured in a central bypass configuration or system bypass module (SBM). In this case, sensing is done by both the SBM and the UPMs.

In preparation for the transition, ESS pre-dispositions the output contactor in its closed state, the inverter in its ready state and the DC link in a pre-charged state. The ESS transfer thus depends heavily on the proper disposition of the inverter hardware, as well as the supporting detection sensing and logic.

When turning off the static switch, ESS utilizes proprietary techniques to commutate the static switch via the inverter. The system turns off the static switch immediately rather than wait for the next zero crossing, which could be as long as 10 milliseconds later.

The advantage of pre-dispositioning hardware

ESS's ability to disposition physical hardware in the most advantageous state is one of its top strengths. Test results for typical input disturbances have shown that ESS turns the inverter on in 600 microseconds and turns the static switch off in 600 microseconds—1.2 milliseconds total. Eaton publishes a transfer rate of two milliseconds, but in reality, the system is designed for even faster transfer.

While an ESS system appears to switch from ESS mode to online mode immediately, a series of built-in delays helps guard against unnecessary transitions triggered by inaccurate sensing, such as can occur during self-induced system load steps as UPMs go into and out of their individual suspend states. The UPM contains specifically allocated fast meters to assist in the detection of single-phase outages that can pose challenges to three-phase sensing algorithms.

The importance of detecting single-phase outages cannot be overstated with regard to 4-wire loads, where single phase-to-neutral loads are commonly found. It is worth observing here that ESS's support for both the 480V 3-wire US market as well as the 400V 4-wire European market demonstrates that it is a truly global technology. Combining ESS with the efficiency advantages inherent to 4-wire applications allows organizations to maximize overall system efficiency. (For more information about the efficiency advantages offered by 4-wire applications, see Eaton's "Alternative DC Power" white paper).

The detection of all possible outage scenarios

The detection time for single-phase outages is dependent on the level of the dip in the affected phase. For many single-phase outages, the fast thresholds will be triggered in a half line cycle or less.

In an ESS system, targeted filtering guards against false transfers. Both STSW input and output detection use a debounce function that is driven by settable parameters in the UPS. This function enables the ESS computational infrastructure to strike the optimal required balance between detection speed and sensitivity.

Note that Appendix B displays ESS transition waveforms that illustrate this point. Note as well that ESS transition time is 2 ms max for the case of resistive loads and complete outages.

ESS transition points

A UPS with ESS remains in ESS mode over the following fixed-input voltage and frequency range:

- ± 10 % for voltage.
- ± 3 Hz for frequency.

Table 2 describes UPS operating modes with respect to a set of factory-configured voltage ranges.

9395 480V L-L/277V L-N Model – ESS					
Input / Output Characteristics					
	Input Voltage (Vac)		Output Voltage (Vac)		
Operating Mode	Line to Line	Line to Neutral	Line to Line	Line to Neutral	Efficiency
Battery	at or below 407	at or below 235	475 to 485	274 to 280	n/a
Online Mode	407 to 433	235 to 250	475 to 485	274 to 280	94%
ESS	433 to 528	250 to 304	433 to 528	250 to 304	99%
Battery	At or above 528	At or above 304	475 to 485	274 to 280	n/a

Table 2: UPS operating modes.

ESS does not presume anything about the power system or application in which it is being used. ESS transition points are highly configurable and can be easily adjusted in accordance with specific site requirements. As noted in an Eaton white paper on maximizing UPS availability:

> "Double-conversion and high-efficiency, multi-mode UPSs supply conditioned power well within the acceptable voltage and frequency range of the IT and industrial equipment they support." [2]

A 25-plus year history of computer load tolerance

The historical record of input tolerance of downstream computer loads helps shed light on the default thresholds chosen for ESS. Figure 6 shows over 25 years of published data describing computer load tolerance to upstream disturbances (including 100 percent outages and significant overvoltage). This data makes clear that:

1. While FIPS, IEEE, ITI-CBME and IEC have each taken turns dominating the computer load disturbance tolerance landscape over the years, overall voltage levels and time durations have trended closely.

2. The ESS voltage thresholds of ± 10 percent align well with the historical trend of +10 percent and -20 percent.
3. The ESS transition time performance of 2 ms maximum far exceeds the historical trend of 8 to 20 ms. Power supply designers consider 10 ms to be the 2012 standard for power supply tolerance to total electrical outages.

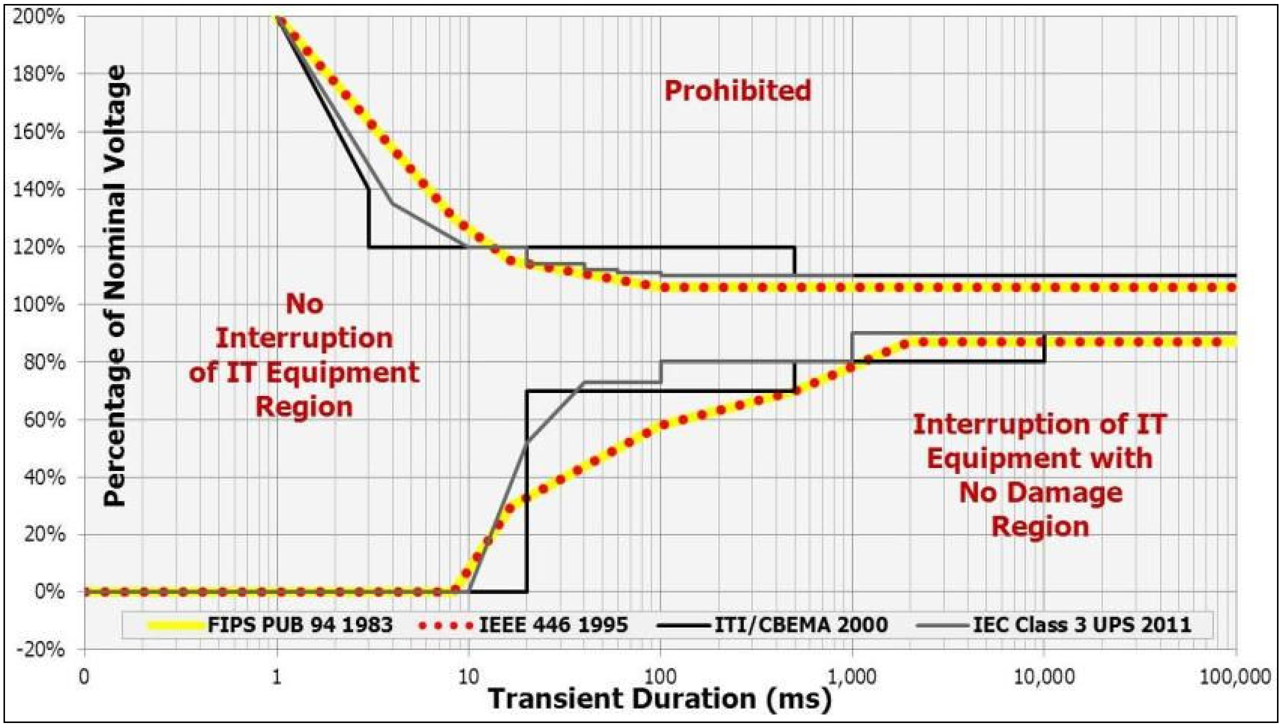


Figure 6: Historical perspective of IT equipment disturbance tolerance.

The following quote from FIPS speaks volumes about real-world conditions:

> "With a little care and with help by power companies, line voltage should not vary beyond -10 to +5%. With much more care and power conditioning, it should be possible to maintain the ADP [or Automatic Data Processing Equipment] input line voltage within -3 to + 3% of nominal. Added benefits of greater reliability or improved system performance would not be expected with tighter regulation limits." [3]

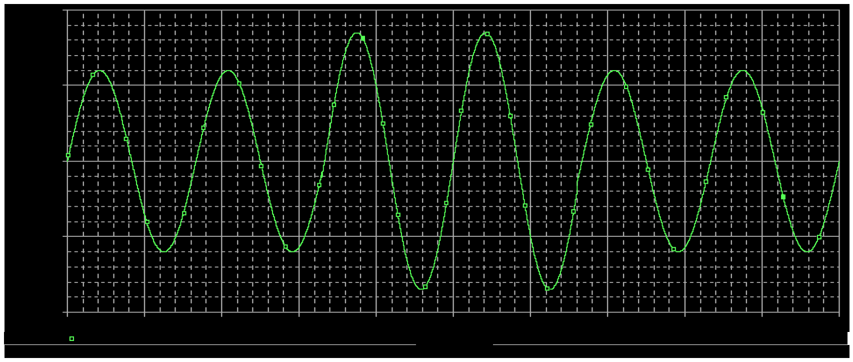
ESS surge suppression performance

Though surge suppression is not one of ESS's primary functions, core attributes of its architecture help protect critical hardware from surges more effectively.

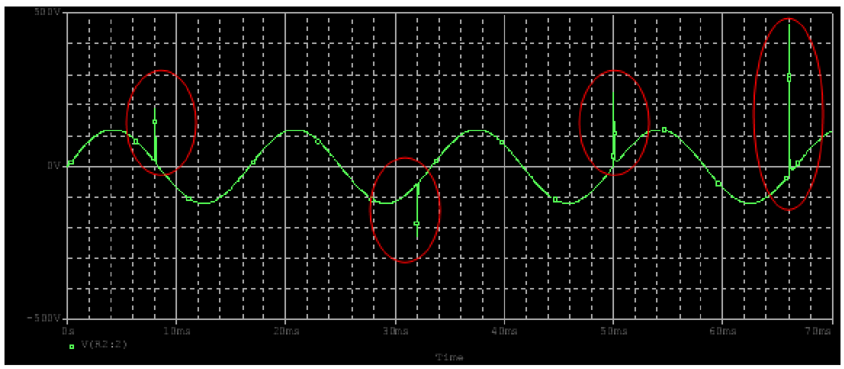
Origins and frequency of power surges

Figure 7 depicts two types of surge-related utility disturbance. The voltage swell, shown in Figure 7a, is an increase in voltage at or very near 50 or 60 Hz line frequency. The voltage impulse, shown in Figure 7b, is a fast-rising excursion that contains components of much higher frequency than the line cycle frequency. Also important about both surges are these facts:

- Surges come and go from one moment to the next.
- The surge duration and frequency of occurrence can be wide ranging.
- The power system returns to normal after a surge.



a) Voltage swell and recovery



b) Voltage impulse and recovery

Figure 7: Sample utility disturbances.

Surges can derive from multiple sources, and while this paper focuses on input-related surges, other surges are imposed on a UPS's output by downstream load transients.

> "Approximately 80% of recorded surges are due to internal switching transients caused by turning on/off motors, transformers, photocopiers or other loads. The IEEE C62.41 surge standard has created the Category B3 ring wave and the B3/C1 combination wave to represent higher energy internal surges." [4]

A surge's location, or distance from its source, is another crucial consideration. Location is in fact so important that standards bodies categorize surges according to their location, as shown in Figure 8. These categories then drive the methods used to test for surge performance.

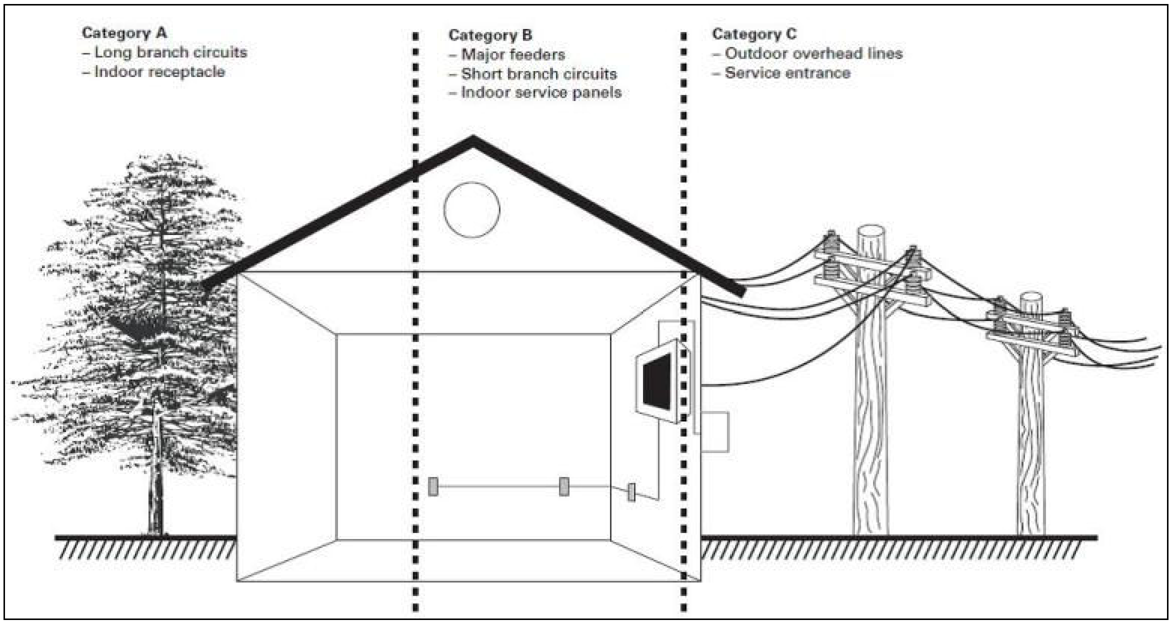


Figure 8: Surge categories and locations within a structure.

The further a sensitive device is from the source of a surge, the greater the inductance. Stray inductance of wires serves to limit the surge's impact on downstream loads so much that "voltage amplitude falls to a level below which the surge loses significance". But this reality applies only to fast-rising surges:

> **How often do surges occur?**
>
> Very large surges occur as little as a few times a year in medium exposure areas to 40 times a year in high exposure areas, as they are typically produced by thunderstorms. However, surges over 1000 volts may occur many times a day, since they are usually caused by normal equipment operation.
>
> **What causes power-line surges?**
>
> Surges can be classified as external and internal. External surges are generally more severe than internal surges, while internal surges generally occur more frequently. In fact, about 80 percent of all surges are internal.

"Limitation of current surges by the wiring impedance applies only during the fast-changing parts of the surges. For surges with long duration (unidirectional with several hundreds of microseconds, or low frequency oscillations), this limitation will be substantially reduced or will not apply." [5]

Standard waveforms should be used to represent or understand real-world surge environments with caution, as they may not properly reflect the importance of surge location. For example, the inductance of branch circuits can act to decrease the severity of a lightning surge as distance from the service entrance increases. Yet this is not true of low-frequency surges or swells such as those shown in Figure 7a. It is therefore important to examine how a given surge propagates and disperses itself within the power system, as one set of conditions could inherently mitigate a surge while another set produces an entirely different result.

Standard surge protection devices

Though the surge performance afforded by ESS is not great enough to make standard power system surge suppression devices (SPDs) unnecessary, it does:

1. Provide definable and measureable surge suppression performance.
2. Supplement the standard surge suppression devices already in the power system.

In fact, ESS literally performs the same function as the surge suppression capacitors used in some industry standard SPDs. For example, line surge capacitors are used to supplement MOV-based SPDs by reducing the “front steepness” of the input line voltage impulses. From a surge performance perspective, a capacitor is a zero-threshold SPD. Standard SPDs come in two forms: the basic suppressor (MOV only) and the hybrid filter suppressor (MOV and filtering), as shown in Figure 9.

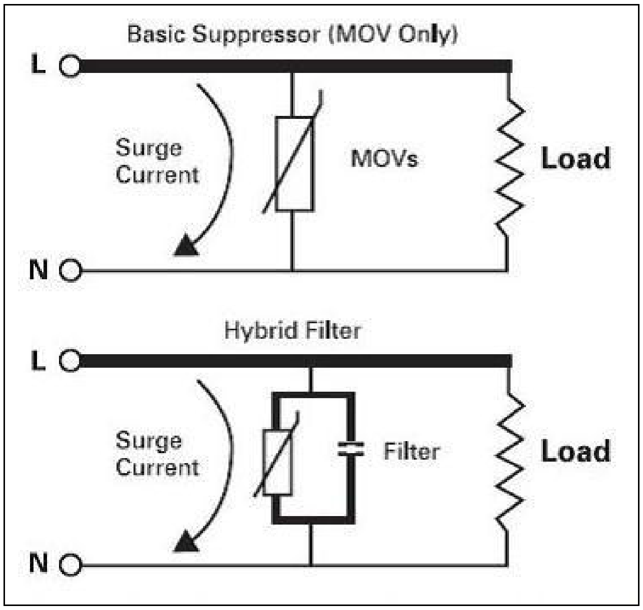


Figure 9: Basic suppressor and hybrid filter.

How ESS handles surges

It is commonly believed that ESS is just another “eco-mode” of operation that does nothing to protect critical output loads from dangerous incoming surges. A close review of Eaton’s ESS implementation, however, reveals a very different story.

ESS utilizes the UPS input and output filter capacitors to suppress steep, front-ended input surge voltages. These are the same capacitors that do the heavy lifting of surge suppression in conventional double conversion mode UPSs.

Moreover, an ESS system’s surge suppression qualities complement the suppression provided by surge protection devices. Consequently, ESS improves the reliability and lengthens the lifespan of SPDs by reducing the amount of energy they must absorb.

ESS surge capability = surge capacitance

- Thanks to their energy storage capability, surge capacitors reduce the “front steepness” of incoming voltage impulses and serve as supplementary surge protection devices.
- ESS capacitors also reduce the impact of incoming surge voltages both at the UPS input and output terminals.

Figure 10 provides a simplified view of the capacitors that do the work of absorbing incoming surge in an ESS system. Note the large number of paralleled capacitors. Note also how UPMs distribute the incoming surge, effectively dividing and conquering it. The net effect is that an extremely high voltage input surge is reduced to an insignificant surge rise on the output load voltage.

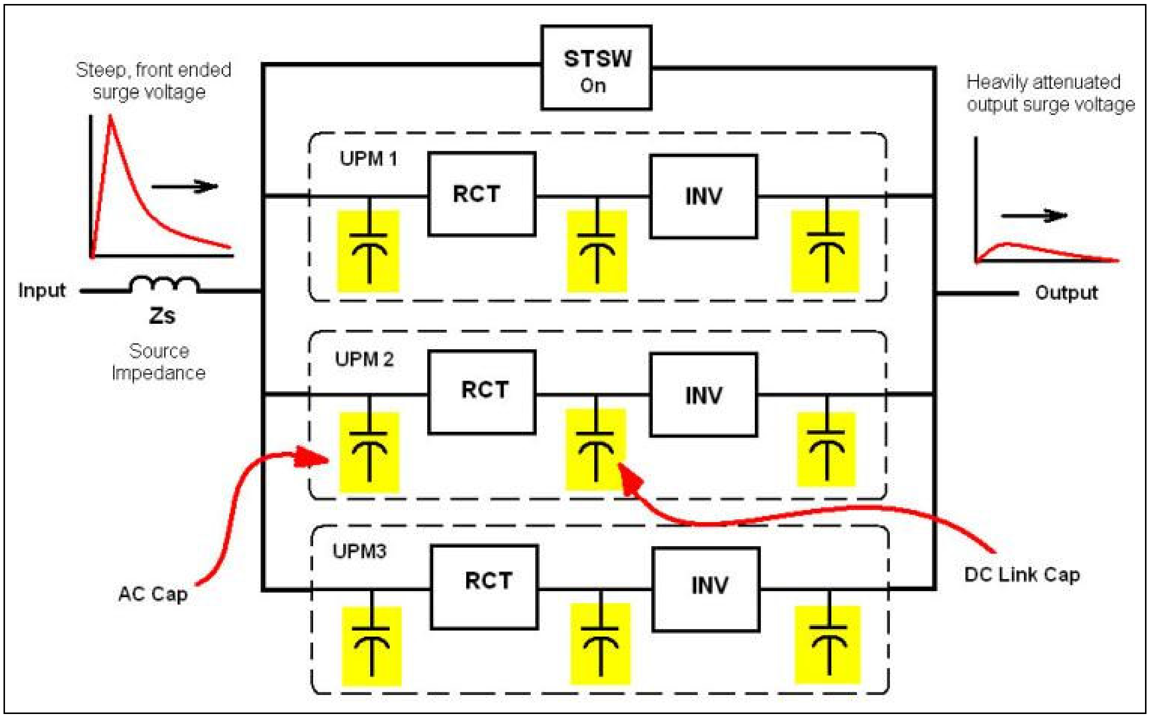


Figure 10: One-line diagram of ESS: input, output and DC link capacitors are connected in a manner that maximizes the system-wide surge suppression capability.

Eaton's ESS implementation utilizes a low impedance bypass power path. Unlike products that place chokes or autotransformers on the bypass power path of their eco-mode offering, ESS maximizes the system's energy absorption characteristics by effectively placing the ESS UPS input and output capacitors in parallel. It also maximizes impulse energy dissipation by buffering the upstream source and other loads tied to that source for input energy demands due to downstream faults that appear, clear and go away. The end result is reduced burdens on the other elements of a power system environment.

Performance test results

The standard waveforms have a long history of successful application in power management and thus may be considered sufficient in most cases as bases for assessing surge immunity. To demonstrate ESS's surge suppression abilities, tests were conducted in accordance with IEEE Std C62.41, 2.5/50uS-8/20uS Combination Wave, Category B, 6Kv, 3000A, commonly referred to as the "lightning type surge." The table values below are best viewed in terms of the surge waveform itself. Before viewing the results of those tests, please note the following:

- The values shown for Location Categories A and B have been set by consensus to provide guidance and uniformity in test procedures.
- The actual surge measurements include the loading effect of the UPS and power system on surge test equipment as a natural and expected consequence of the test method.

Location Category	Peak Values		Effective Impedance (Ω)
	Voltage (kV)	Current (kA)	
A	6	0.5	12
B	6	3	2

Table 3: Standard 1.2/50 μs-8/20 μs combination wave expected voltages and current surges in Location Categories A and B.

Figure 11 shows the anatomy of the lightning strike in terms of Category B performance testing.

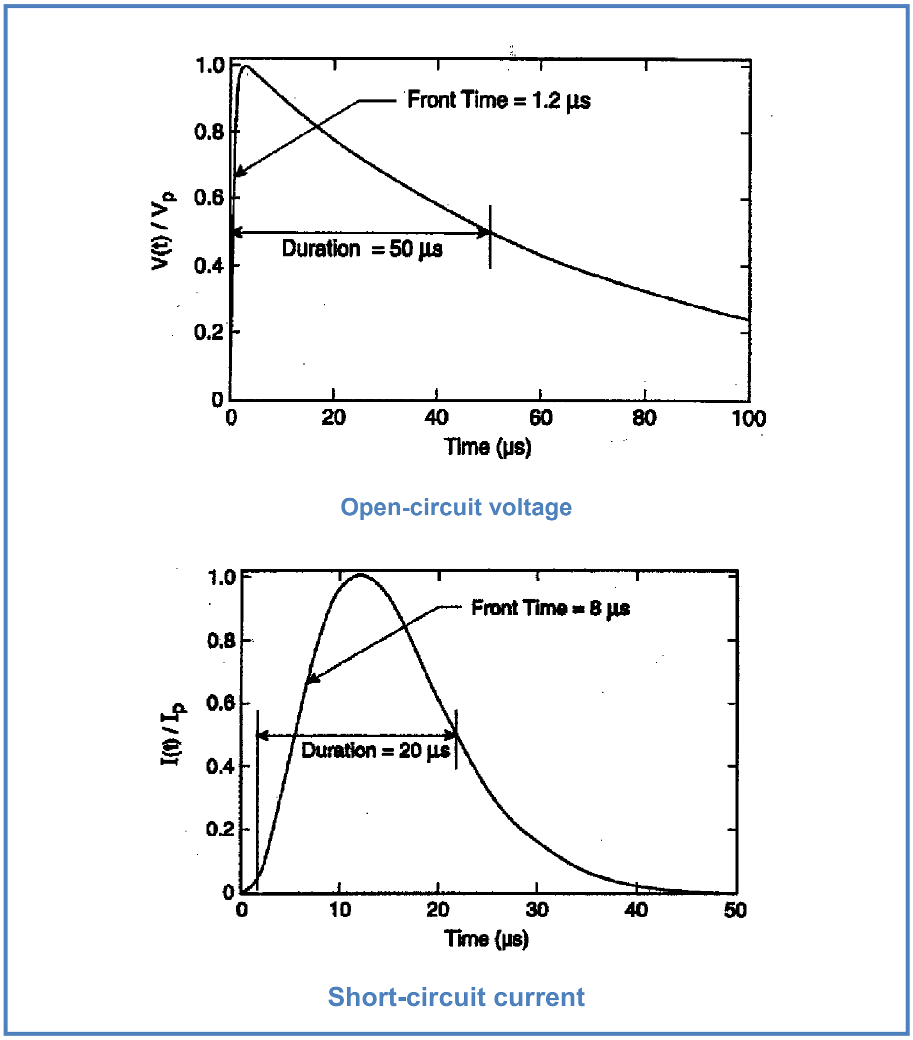


Figure 11: Anatomy of the 1.2 - 8 µs combination wave.

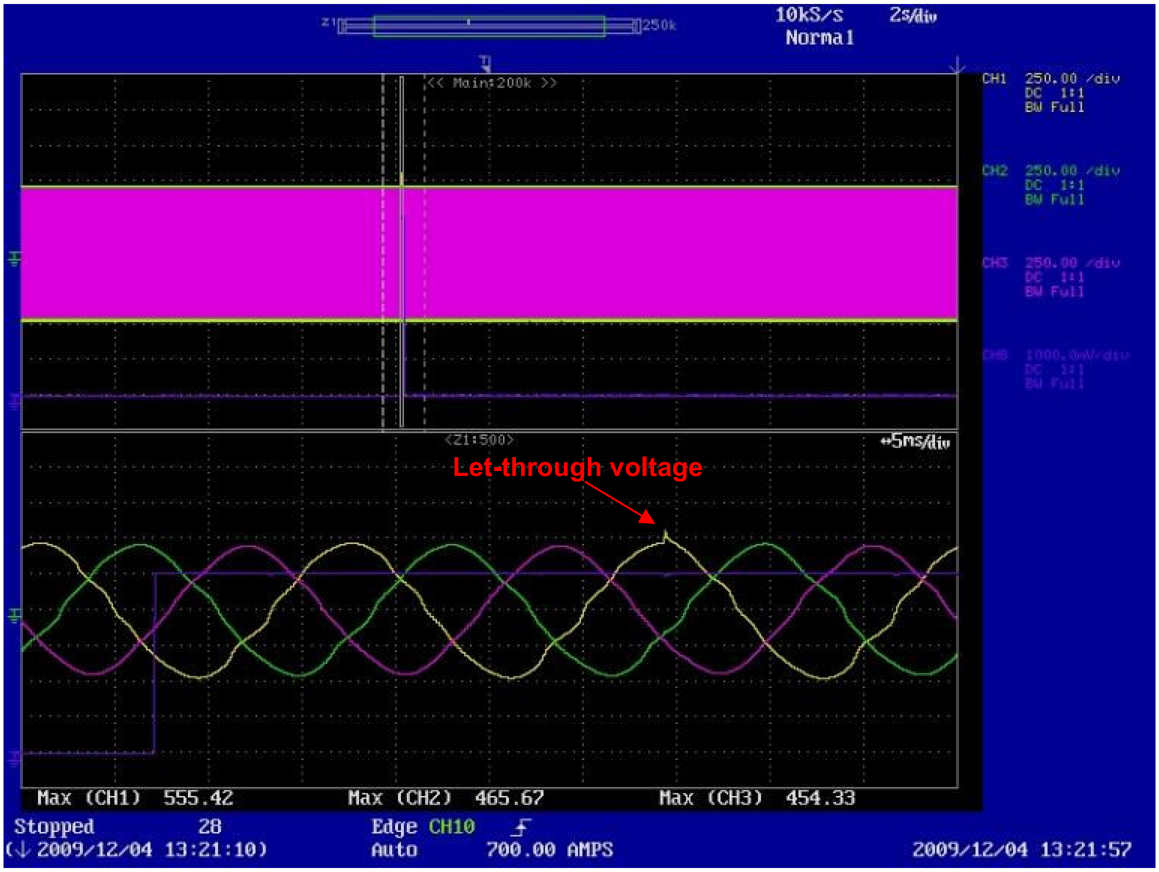


Figure 12: 9395 1100 kVA, ESS, C62.41 Category B, combination wave, 6 kV surge pulse (phase A - N, positive polarity, ESS Mode 90 degrees, no load).

Coupler	CDN3083-100	89	Teseq
Surge generator	NSG 2050	212-01	Schaffner
Combination wave module	PNW2050	200711-604LU	Schaffner

Table 4: Test equipment details.

Conclusion

ESS significantly improves UPS energy efficiency without compromising power quality, and builds on the strengths of traditional double-conversion architectures in ways that increase reliability. ESS's advanced architecture makes maximum use of UPS power paths while reducing exposure to component failures. Its computational infrastructure and hardware pre-dispositioning enable rapid transition from ESS mode to double-conversion mode when needed. ESS provides definable and measureable surge suppression performance that supplements and enhances the conventional surge protection technologies found in any power system. The end result is an energy saving technology that is both highly efficient and highly reliable—two qualities that the world of mission-critical power quality once thought of as being mutually exclusive.

References

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2. Eaton white paper: "Maximizing UPS Availability: A comparative assessment of UPS designs and deployment configurations for the high availability data center".
3. Federal Information Processing Standards (FIPS) Publication 94 (1983).

4. Eaton Guide to Surge Suppression, SA01005003E.
5. IEEE Std C62.41 .1 and .2 -2002 Guide on the Surge Environment in Low-Voltage (1000 V and Less) AC Power Circuits.

About Eaton

Eaton Corporation is a diversified power management company with more than 100 years of experience providing energy-efficient solutions that help our customers effectively manage electrical, hydraulic and mechanical power. With 2011 sales of $16.0 billion, Eaton is a global technology leader in electrical components, systems and services for power quality, distribution and control; hydraulics components, systems and services for industrial and mobile equipment; aerospace fuel, hydraulics and pneumatic systems for commercial and military use; and truck and automotive drivetrain and powertrain systems for performance, fuel economy and safety. Eaton has approximately 73,000 employees and sells products to customers in more than 150 countries. For more information, visit www.eaton.com.

About the author

George Navarro is a technical solutions engineering specialist for Eaton Corporation. He has worked in the design and development of UPS products for more than 20 years, specializing in power electronics hardware and later expanding his knowledge to UPS firmware development. He serves as the bridge between the customer, business development and product development. George creatively applies his technology knowledge to support and resolve challenging customer application needs, establishes product vision tied to market dynamics, and drives for new business opportunities at the platform level. Mr. Navarro has a Bachelor of Engineering degree from Stevens Institute of Technology and an MBA degree from Monmouth University.

Appendices

Appendix A: reliability state diagram and UPS modes

ESS consists of six reliability states, all of which are considered transient. That is, the system can move in and out of these states in response to a given event, such as a failure or repair. The reliability states are listed in Table A-1 and the connections between states or transition probabilities are shown in Table A-2. The circles for each state on Figure 1 represent the probability of remaining in that state as opposed to jumping to another. The probability of remaining in a given state is simply the probability of leaving. For example, the probability of remaining in State 1 is 1- $(\mu_e+\mu_2+\lambda_{acol}+\lambda_u+8\lambda_f)$.

State	Description	State	Description
0	Mission Failure	4	On Battery + Fan Fail
1	AC Double Conversion	5	On Bypass
2	Energy Saver	6	On Battery Backup
3	Fan Failure		

Table A-1: UPS operating and failure states.

The transition probabilities define the chance of moving from one state to another, or of remaining in the existing state for a given time interval. In most reliability analyses, these equate to the failure rates of the blocks in Figure 1. The transition probabilities are listed in Table A-2.

Transition Probabilities	Description
λ_{acol}	rectifier + inverter + upm boards
λ_f	Fan
λ_{dcol}	battery converter + inverter + upm boards
λ_{ISBM}	bypass module
λ_u	utility failure rate
μ_u	utility repair rate
μ_e	equipment repair rate
λ_{acc}	upm boards
λ_2	utility disturbance rate
μ_2	utility return rate

Table A-2: Transition probability definition.

Appendix B: the ESS transfer

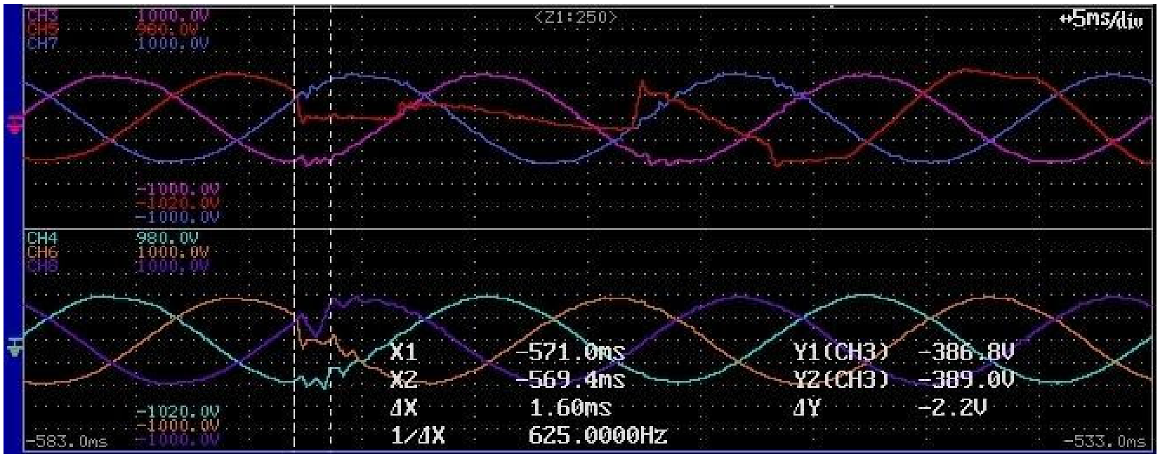

Figure B-1: Single-phase outage, output voltage recover in 1.6 ms, input voltage on top, output voltage below.

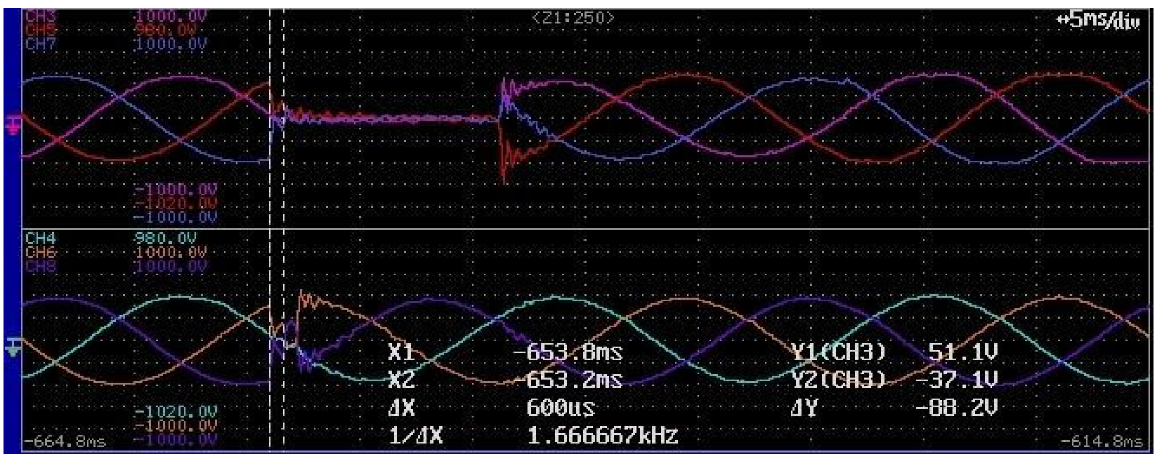

Figure B-2: Three-phase source fault, output voltage recover in 1.2 ms, input voltage on top, output voltage below.