WHITE PAPER

VOLTAGE SAGS; A LITTLE STORAGE CAN GO A LONG WAY

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I.

Utility power in the U.S. is very reliable; we count on it to be there, expect it to be there, and it usually is. Barring natural disasters (ice storms, tornados, hurricanes are notorious for destroying local distribution) and the rare system wide blackout (such as the Northeast Blackout on August 14, 2003), the U.S. has a continuous supply of electrical power. But what is the quality of that power? It is not a digital product; on or off. It is an analog product, with continuous variations in voltage and phase, depending on load profiles and myriad variables across the transmission and distribution network. The utilities do an admirable job controlling what they can, but with the hundreds of thousands of local loads affecting power quality, local consumers with critical loads should consider what steps they can take on their own to harden their systems against poor power quality.

When we talk about this type of power quality, we are talking about brief instances that most applications ignore. Voltage can sag to sometimes as much as half the nominal line voltage for brief periods. These are brief sags, on the order of fractions of a cycle (at 60 Hz, equivalent to 16 msec) to as long as a second.

Voltage sags can be delivered from the grid, however, in most cases, sags are generated on the Facility side of the meter. For example, in residential installations, the most common cause of voltage sag is the starting current drawn by motors in refrigerators and air conditioners. In industrial installations, the numerous motors, compressors, etc. and their large size, generate many voltage sag events every day within the facility.

Sags do not generally disturb lighting (incandescent or fluorescent), motors, or electric heaters, all of which have a relatively slow frequency response because they contain an effective energy storage element, whether the mechanical inertia (kinetic energy) of a motor, or the thermal inertia (thermal energy) of incandescent lights, or the small reactive inertia (electrical energy) in fluorescent ballast.

Voltage sags are the most common power disturbance experienced by factory equipment. It is not unusual to see several sags per year at the service entrance of a typical industrial site, and due to power fluctuations within the confines of the site, far more sags are experienced at equipment terminals.

Electronic equipment with fast response times (e.g. programmable logic controllers (PLCs), adjustable speed drives, switching power supplies) lack sufficient internal energy storage to tolerate severe sags in the supply voltage. In recognition of the fact that voltage sags do occur, the Computer and Business Equipment Manufacturers' Association (CBEMA), and Semiconductor Equipment and Materials Institute (SEMI) have both published information defining what levels of poor power quality, specifically voltage sag, equipment should be able to tolerate. The CBEMA curve (Figure 1) includes voltage surges as well as sags, while the SEMI E10 curve (Figure 2) only defines sag tolerance. In addition, other agencies have also defined various power quality tolerance criteria. (Figure 3).

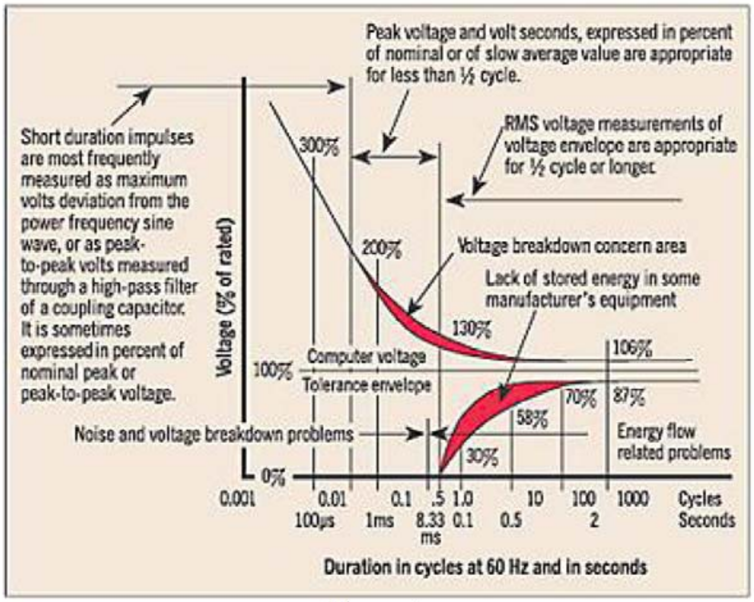

Figure 1
Computer and Business Equipment Manufacturers' Association (CBEMA)
Voltage Tolerance Curve

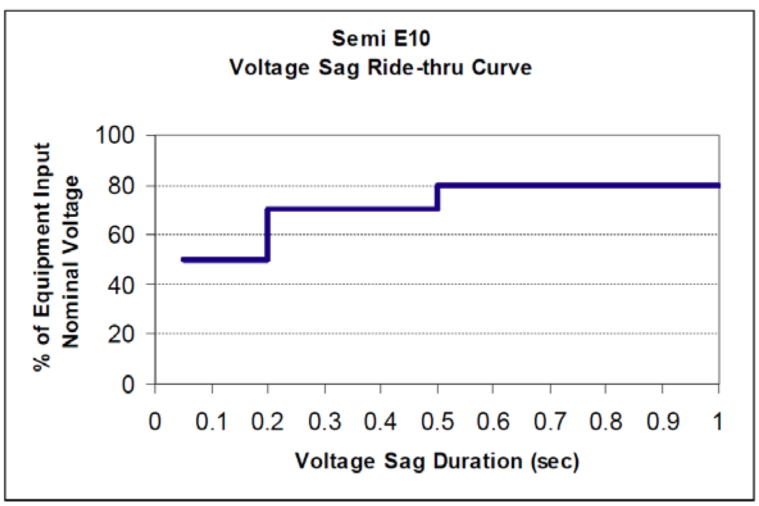

Figure 2
Semiconductor Equipment and Materials Institute (SEMI)
Voltage Sag Tolerance Curve

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Curve	*Year*	*Application*	*Source*
FIPS power acceptability curve	1978	Automatic data processing (ADP) equipment	U.S. federal government
CBEMA curve	1978	Computer business equipment	Computer Business Equipment Manufacturers Association
ITIC curve	1996	Information technology equipment	Information Technology Industry Council
Failure rate curves for industrial loads	1972	Industrial loads	IEEE Standard 493
AC line voltage tolerances	1974	Mainframe computers	IEEE Standard 446
IEEE Emerald Book	1992	Sensitive electronic equipment	IEEE Standard 1100

Figure 3
Power Quality Curves of Various Organizations

These curves are helpful in defining what voltage sags equipment should be capable of tolerating, but they give no indication of how one should design the equipment to do so. Some equipment may be able to ride through very brief, deep sags, or longer but shallower sags. In any event, the key element to surviving voltage sags is the presence of enough energy storage to ride through the sag event.

Ultracapacitors (UCs) are ideally suited as an energy storage solution for hardening sensitive equipment against voltage sag. They have extremely high energy density for capacitors (typically 1000 times greater than electrolytic capacitors), they can deliver very high power instantaneously, and they can sit at operating voltage for many years without any conditioning (unlike batteries). The key enablers for ultracapacitors to serve as hardening devices are extremely long operating life, flexible voltage, very high power, and affordability. Being a capacitor, they operate without chemical reactions, and have demonstrated operating life of greater than 10 years, and millions of cycles. As a capacitor, they have no fixed operating voltage, and so will not "fight" the power supply feeding the bus. Their power densities are very high, and can feed DC current for periods as long as 30 seconds or longer, though one would design the system to meet the requirements of hardening, reducing cost by optimizing energy storage. After all, the point is to use the ultracapacitor as hardening, not as an uninterruptible power supply. In the last decade, the price of ultracapacitors has come down considerably, and they are now a cost effective solution, with millions of units in the field.

Most AC-powered systems at some point rectify to DC, and it is at this point that the ultracapacitors are applied. In installations where a common DC bus is shared among multiple pieces of equipment, a single ultracapacitor subsystem can support the entire DC bus and all the associated loads (Figure 4). This type of solution can be implemented onsite by the systems integrator. Installations that have separately powered loads, each with an AC input feeding a rectifier or other DC power supply, ultracapacitors can be designed in at the DC bus level on each system (Figure 5). This type of solution more typically requires the power supply designer to implement ultracapacitors in an enhanced, hardened version of their product. For DC loads, the ultracapacitor may be used alone, or with a DC/DC converter.

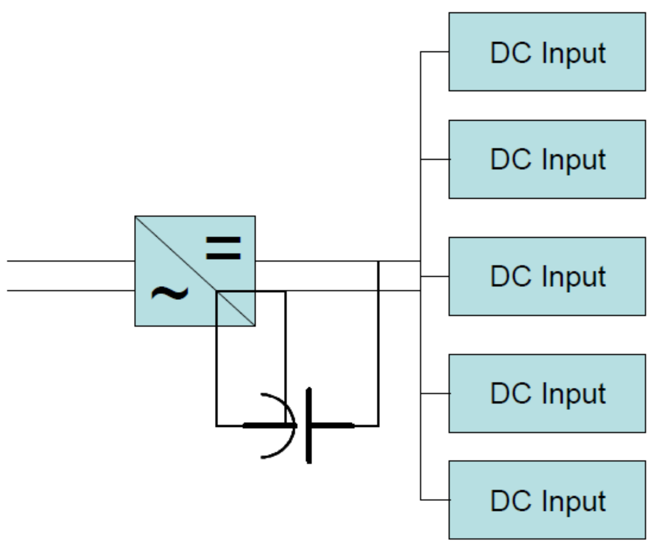

Figure 4
An ultracapacitor supporting multiple DC loads

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Standalone hardening solutions for systems with AC inputs only will couple the ultracapacitor to an inverter, similar in architecture to standalone uninterruptible power supplies (UPS) (Figure 6). This architecture can also be applied for adjustable speed drives, where the secondary AC output drives a motor at a frequency independent of the line frequency. Adjustable speed drives used in sensitive processes can be well-served by installing energy storage to allow them to ride through voltage sags in excess of CBEMA and SEMI requirements.

An integrated solution will have the ultracapacitor directly built into equipment (such as in the DC link of industrial motor drives, or the DC supply side of a PLC). Integrated solutions, or load-dedicated add-on hardening, are most advantageous, because they provide energy storage directly at the point of use. The limitation is that each and every critical load needs its own protection.

At the other extreme, power bus hardening with add-on energy storage equipment can take advantage of ultracapacitors. The advantage of power bus add-on equipment is that all new equipment installed on the hardened power bus is protected. The limitation is that this type of centralized hardening solution must be used where a common power bus feeds multiple loads, not always a common practice in facilities. Furthermore, in the limit, this architecture can come to protect too-wide a power bus, with the inherent inductance of the bus preventing the centralized hardening equipment from protecting a load at the far reaches of the bus when an adjacent load is switched on.

By integrating ultracapacitors into voltage sag-sensitive equipment and local power buses, equipment and facilities designers are able to harden critical factory equipment against the constant bombardment of voltage sags from within the facility. It only takes a little energy storage to have a big impact on the reliability of critical operations.

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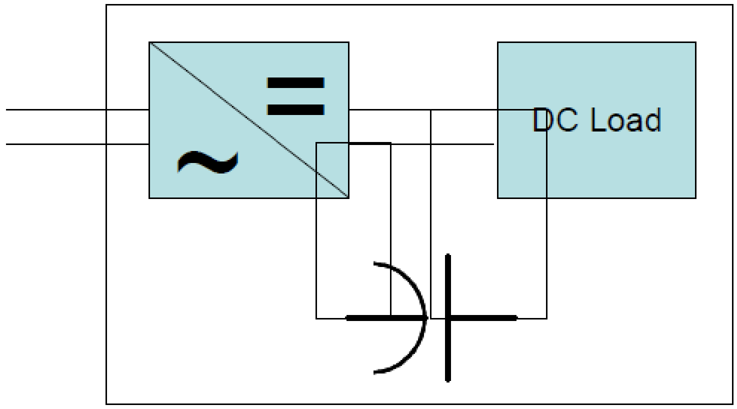

Figure 5
An ultracapacitor integrated onto an internal DC bus

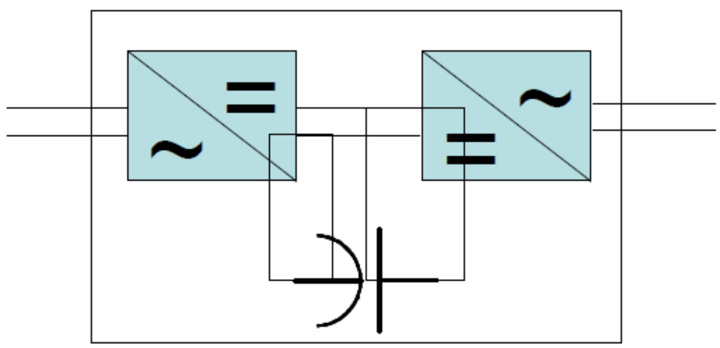

Figure 6
An ultracapacitor integrated onto an AC supply.

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II.

Power quality encompasses a myriad of disruptions such as voltage sag, voltage flicker or power disruption. For the purpose of this discussion voltage sag will be considered. Voltage sag is defined as a decrease in voltage below 90% of nominal with a typical duration lasting 3 to 10 cycles (50 to 167 milliseconds). End use equipment sensitive to voltage sag include computers, programmable logic controllers (PLC), controller power supplies, motor starter contactors, control relays and adjustable speed drives.

EPRI conducted a survey [1] on the economic impact voltage disturbance had on varying industries. Although the impact can vary significantly a range is provided in Figure 1 as a guideline for determining which industries are most susceptible from an economic standpoint. From the summary chart it is seen that power quality economically affects semiconductor manufacturing significantly more than any other industry with pharmaceuticals and electronics as the next most significant industries. With semiconductor manufacturing so sensitive to power reliability, standards were developed specifying the ride through requirements of semiconductor equipment. These standards are referred to as SEMI F47 and a depiction is provided in Figure 2.

In order to address the needs for desensitization of manufacturing several approaches are typically considered and include premium power service, facility wide protection or point of use protection. Premium power service may employ redundant power source protection from the utility to guarantee higher 9's of service. This may seem to offer improved reliability but if a voltage sag results in one hour of down time the promised power delivery service vs. actual uptime reliability may not actually be significantly improved, especially considering the premium paid. Facility wide protection may employ dynamic voltage regulation (DVR) or uninterruptible power supply (UPS) techniques at the facility level. The downside to this approach is that only 20-30% of the system loads may be sensitive to the voltage sag conditions and will not protect sensitive equipment from internal disturbances within the factory. Point of use protection is generally the optimal choice allowing the customer to select the critical load equipment and prioritize based on allowable budgets.

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	Cost of Momentary Interruption ($/kW demand)	
Industry	***Min***	***Max***
Semiconductor manufacturing	$20.0	$60.0
Pharmaceutical	$5.0	$50.0
Electronics	$8.0	$12.0
Communications, information processing	$1.0	$10.0
Automobile manufacturing	$5.0	$7.5
Glass	$4.0	$6.0
Petrochemical	$3.0	$5.0
Food processing	$3.0	$5.0
Rubber and plastics	$3.0	$4.5
Textile	$2.0	$4.0
Metal fabrication	$2.0	$4.0
Mining	$2.0	$4.0
Hospitals, banks, civil services	$2.0	$3.0
Paper	$1.5	$2.5
Printing (newspapers)	$1.0	$2.0
Restaurants, bars, hotels	$0.5	$1.0
Commercial shops	$0.1	$0.5

Figure 1: Economic impact of voltage disturbances by industry

Point of use protection can be further subdivided into built in equipment protection or stand alone protection. Built in equipment protection may be the customer preferred methodology but does not aid existing equipment installations. Traditional approaches for both methodologies for point of use protection employs UPS systems based on batteries. Due to the maintenance, handling, and disposal concerns related to batteries the semiconductor industry desires alternatives.

Ultracapacitors are ideally suited as an alternative energy storage solution for hardening sensitive equipment against voltage sag. Typical specifications for these products range from 2-5 seconds backup power. Backup times of this duration make ultracapacitors extremely competitive with batteries especially when considering the life cycle costs. They have extremely high energy density for capacitors (typically 1000 times greater than electrolytic capacitors), they can deliver very high power instantaneously, and they can sit at operating voltage for many years without any conditioning (unlike batteries). The key enablers for ultracapacitors to serve as hardening devices are extremely long operating life, flexible voltage, very high power, and affordability. Being a capacitor, they operate without chemical reactions, and have demonstrated operating life of greater than 10 years, and millions of cycles. Their power densities are very high, and can feed DC current for periods as long as 30 seconds or longer. In the last decade, the price of ultracapacitors has come down considerably, and they are now a cost-effective solution, with millions of units in the field.

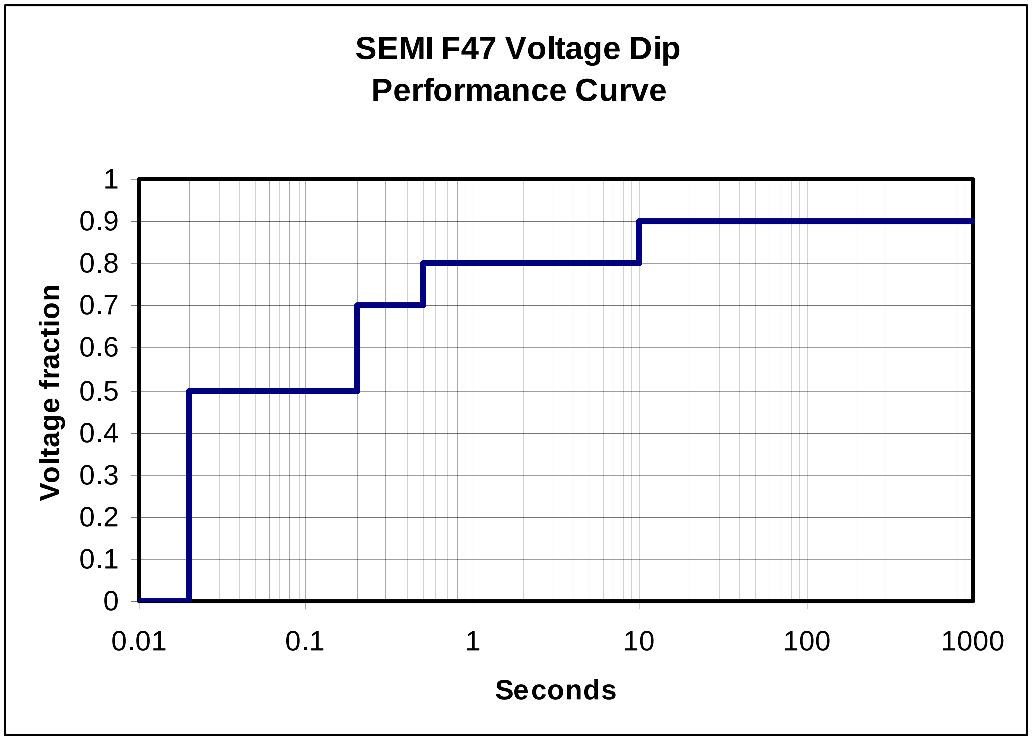

Figure 2: Semiconductor equipment voltage ride through requirements

EPRI has also evaluated the effect of voltage sags on machine tooling in an effort to derive similar standards for machine tooling as in semiconductor equipment [2]. Tool shutdowns were found to occur at 80% of nominal voltage. The study determined that ultracapacitors could be designed into the power supply of the machine tools to protect the units from voltage sag.

Additional alternatives considered for voltage sag plus longer term UPS have included a parallel arrangement of ultracapacitors and batteries. Ultracapacitors would provide the short duration ride through associated with voltage sag while the batteries would be available for long term power outages. The idea is the ultracapacitors would shield the battery from pulses required during voltage sag and only be utilized for long duration power outage, thereby extending the life of the batteries. Battery life extension has been demonstrated in various applications when ultracapacitors are employed in parallel. A demonstrated example is digital cameras employing alkaline batteries. Ultracapacitors were arranged in parallel with alkaline batteries as depicted in Figure 3.

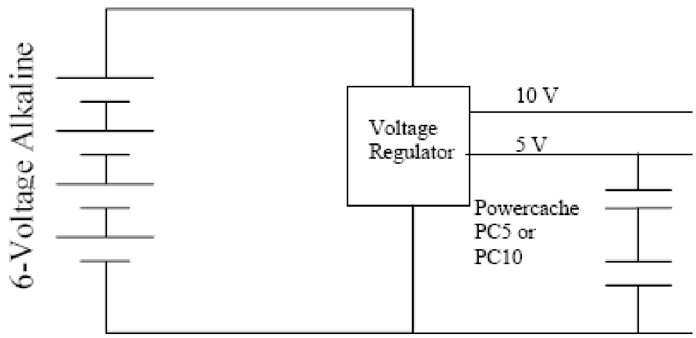

Figure 3: Battery/Ultracapacitor arrangement for digital camera

A simulated load involving pulsed peak loads 10 times higher than nominal loads were continually applied on the battery/ultracapacitor system. The same load was then applied on a battery only arrangement. The resulting voltages of both configurations were monitored. The results are depicted in Figure 4. From the plot it is seen run time was increased almost two fold with the addition of the ultracapacitors.

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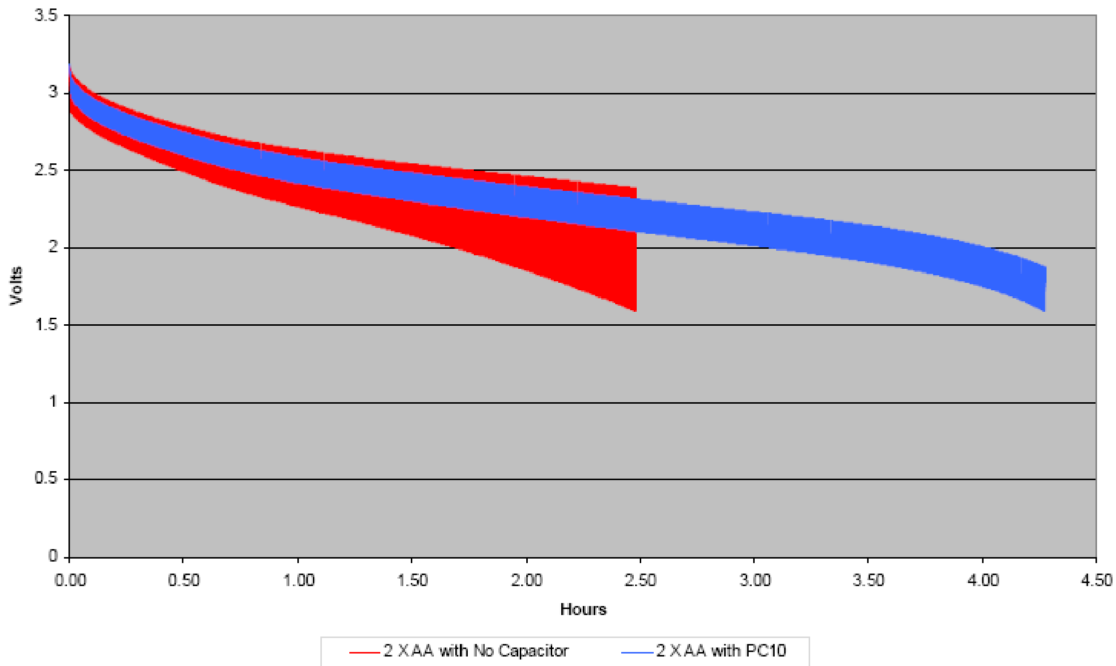

Figure 4: Battery/ultracapacitor testing results

Ultracapacitor based voltage sag protection equipment deployments have been employed within the semiconductor industry. As the cost of ultracapacitors continues to decline the economic viability in additional industries will be realized for voltage sag protection equipment.

1. McGranaghan, et al., **The Economics of Voltage Sag Ride Through Capabilities**, EC&M, May 2005.
2. Banerjee, P., **Cost Effective Storage Technologies as Embedded Solutions for Ride Through**, EPRI Solutions Report 1001014, Oct. 2000

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