pq commentary

EPRI

The Power Quality Implications of Conservation Voltage Reduction

Energy Savings, Peak Power Shaving, and Other Expectations

Proposals for conservation voltage reduction ("CVR" in engineering documents and "brownout" in the popular language) have been driven by the commendable desire to conserve energy and/or reduce peak power demand. The rationale is based on the real fact that as the supply voltage is reduced, resistive loads will draw less current, according to the EE 101 formula $W = V^2/R$. This reduction that might be expected is based on the postulate that the resistance is a constant term, with of course the recognition that not all loads are pure resistances. However, resistive loads are only a small fraction of the total, and the response of some loads to a systematic voltage reduction has not been fully investigated (see Figure 1).

For some loads however, a CVR might not produce a reduction of power consumption and, worse yet, their sensitivity to power quality events occurring during the CVR can produce unexpected adverse side effects. The purpose of this PQ Commentary is to examine on a qualitative basis what is known on the behavior of different types of loads under reduced voltage conditions, in order to focus on those where a careful quantitative assessment will require comprehensive testing rather than sweeping generalities. By no means does this PQ Commentary provide a definitive answer to the question "What is the power quality impact of a CVR on end-use equipment?" nor does it intend to debate the merits of CVR proposals.

CONSERVATION CONVERSATION

On paper, it looks very simple: With the same letters, all you have to do is switch the position of two of the letters to go from talking about it (conversation) to achieving it (conservation). In reality, it will not be so simple, such as a blanket reduction of voltage. What we need is indeed some conversation, but the kind that will also include inputs from manufacturers to make a realistic assessment of the effects of brownouts on power quality (also known as compatibility between the load requirements and the parameters of the voltage supply).

We hope that the issues raised in this document will lead to a consistent approach to equipment testing, field investigations, and evaluations with the key parties involved, including manufacturers, end-users, utilities, and research organizations. Such an approach will provide a more objective understanding of the power quality impact of CVR on the operation of customer equipment.

In simple words, the conservation issue is not so simple, and a careful and accurate accounting has to be conducted to quantify the benefits and examine their limitations, and possible adverse side effects. Expected benefits of course are peak power shaving

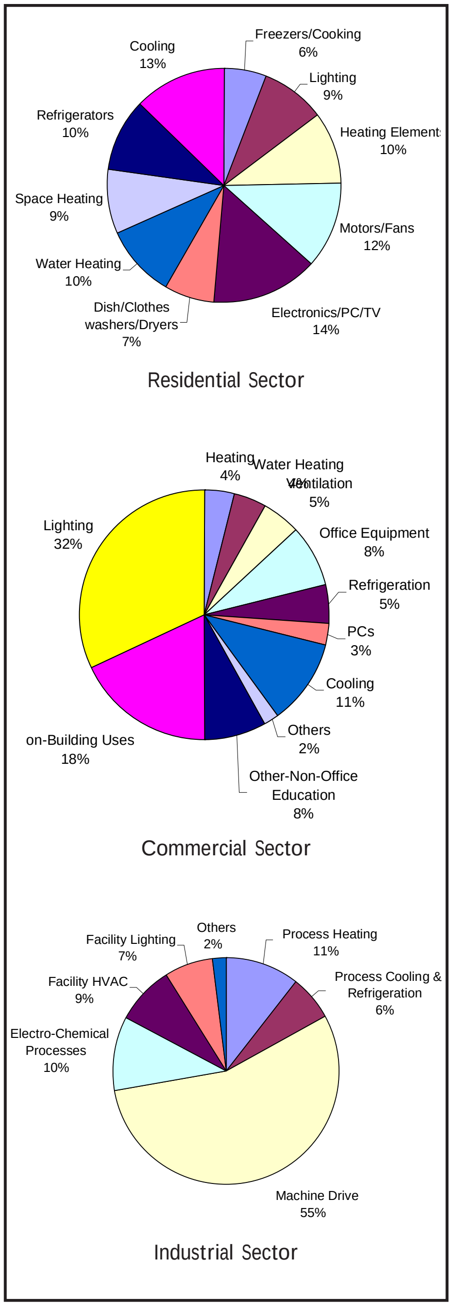


Figure 1. Breakdown of Electricity End-Use Load Consumption in Residential, Commercial and Industrial Sectors in U.S. (Sources: Residential/ Commercial: Annual Energy Outlook, 2001, Department of Energy; Industrial: 1998 Manufacturing Energy Consumption Survey, Department of Energy)

and possibly energy conservation. Side effects range from some reduction of the expected benefits to increased likelihood of process disturbances and, in extreme cases, equipment damage.

The designs of many load equipment have been based on the assumption of standardized line voltages; unilateral changes could produce unexpected adverse side effects if not carefully reviewed by all parties. Only after such a careful review can reliable conclusions and recommendations be made on potential benefits of conservation voltage reduction. Manufacturers should also be involved and consulted in this process.

The advantages of voltage reduction are more pronounced when used to achieve an instantaneous load reduction, such as to compensate for a temporarily lost generating unit, or to avoid an immediate blackout in a region. This would be necessary to permit additional generation to be placed in service, or to avoid catastrophic loss of service. The use of CVR for long term load relief would need to be demonstrated in practice to convince a number of doubters – including end users – of its worth. In the present examination, loads are classified in several categories, based on their nature and mode of operation. Reviewing the proportion of the total demand for each of these loads (Figure 1) is also a significant part of the assessment.

Open Loop Loads

- Lighting – incandescent and other
- Unregulated motors
- Relays and motor starters

Closed Loop Loads

- Motor drives
- Variable output power, fixed outcome
- Regulated constant power

A Quick Look at Loads and Expected Benefits

Open-Loop Loads

By open-loop loads we mean those in which there is no control mechanism that would change the operation of the load to correct or compensate for the reduction of the input voltage. A brief description of theses types of loads and the expected savings benefits they might provide follows.

Incandescent Lamps

The concept of voltage reduction as a peak shaving and energy saving mechanism is based on the most elemental of electrical laws – Ohm's Law, which states that power is directly proportional to the square of the voltage. Incandescent lighting is an example: a 100-watt light bulb rated at 120 volts, if operated at 95% of nominal, that is, 114 volts in a system rated 120 volts nominal, will draw only (0.95 x 0.95) of the rating, 90 watts.

Indeed, the formula $W = V^2/R$ describes what can be expected from a load with constant resistance. However, the tungsten filament has a resistance/temperature coefficient such that a decrease in its temperature will reduce its resistance – admittedly by only a small percentage – thereby losing some of the expected benefit. On the positive side, no adverse effects to ordinary incandescent lamps would occur, and even a small but significant beneficial side effect would be that the reduced temperature of the filament will increase the life of the lamp. However, in the case of tungsten halogen lamps, some adverse side effects might occur (see the NEMA sidebar).

All of this, of course, has to be assessed keeping in mind the respective load portion represented by incandescent lighting in the diverse sectors of activity. Given the absence of adverse side effects (except as noted later on), even a small decrement would be welcome.

Fluorescent Lamps

Compact fluorescent lamps as well as new electronic-ballast lamps offer considerable savings over conventional incandescent lamps (Table 1), an attractive alternative to expected savings by way of CVR. The performance of fluorescent lamps under conditions of moderate CVR, such as a 2.5% reduction is not well documented.

High-Intensity Discharge Lamps

High-intensity discharge lamps operate in a complex mode where the arc is initiated at low pressure, followed by an equilibrium between the arc voltage, the current drawn in the arc and hence the temperature on the one hand, and the resulting higher pressure within the discharge enclosure on the other hand. As the lamp ages, this equilibrium becomes more difficult to maintain, to the point that the typical end-of-life is a “drop out” with on-off cycling. Lowering the voltage at the point of use is likely to make this condition occur earlier in the life of the lamp, but the effect needs to be quantified.

Table 1. Alternatives to CVR Encourage Change to Energy Star-Labeled Appliances
(Source: EPA—http://www.epa.gov/nrgystar/purchasing/2c_savings_calc.html)

Appliance	*kWh/year Savings for 1 Unit*	*Payback Period*
Compact Fluorescent	250	0.4
Residential Ceiling Lamps	400	0.5
Refrigerator	250	2.8
Central Air Conditioner	1300	3.8
Clothes Washer	400	8.4

Unregulated Motors

The chart depicting the proportions of industrial load types shows how large the allocation to motor loads is, but does not differentiate the modes of control or the tasks performed by these motors. Under the heading of "unregulated motors" we can find many induction motors that operate in an open loop mode. By open loop, we understand here a motor operating without a control system calling for a set power output but rather a set operating time cycle. Examples of these include ventilation motors, residential washing machines, escalators, etc. A synchronous motor, of course, will not change speed but the current and power factor will change according to the demands of the load.

Relays and motor starters

Seen as a "load" these devices have a completely negligible impact on power consumption and could be neglected except for the critical role they play and, in some marginal cases of undervoltage, they will drop out and cause major disturbances in process control. Numerous studies have been conducted, and remedies applied, in response to incidents associated with sags. Lowering the voltage at the point of use will aggravate the sensitivity to sags of these devices, and this would be in an unpredictable amount because of the complexity of their response.

Closed-Loop Loads

By closed-loop loads we mean those in which there is a control mechanism that will change the operation of the load to correct or compensate for the reduction of the input voltage. This category includes three basic types:

- Loads that produce motion to accomplish a given mechanical task, typically motor drives
- Loads in which power output will be reduced by the CVR but a fixed, controlled outcome will prolong the duration of operation, typically heating systems
- Loads that are controlled to maintain constant power in their output, typically electronic power supplies

Motor Drives

The most important process device actually producing work, as well as the largest consumer of electrical energy nationwide, is the electric motor. The response of motors to reduced voltage operation depends primarily on their connected loads. The continuous operation at low voltage of motors already near their nameplate current and connected to constant horsepower loads might be expected to cause overheating and eventually result in their failure. Fortunately, standard motor protection is designed to prevent motor burnout under these conditions. Small motors have imbedded temperature switches, which de-energize the motors when excessive temperatures are sensed. Large motors are protected by devices called "heaters" incorporated in the motor control centers. These heaters are sized to specifically protect a motor of a given size. They permit momentary overloads of the motor, but inherently have a time constant that prevents motor failure. The burnout of motors caused by sustained operation at low voltage is not the most likely problem area. First, most motors are not run at 100% of nameplate current, allowing the motor some margin during off-normal operation and secondly, if the acceptable current is exceeded, the protective devices should disconnect the motor. However, this reassuring note should not understate the consequence of a motor tripping off during a CVR. Actual damage to the motor (if any at all) on the one hand, and actual impact on customer operation (and customer dissatisfaction) on the other hand, are two distinct components of the equation.

Variable Power, Fixed Outcome

A common, purely resistive load but with a closed-loop control (thermostat) is the electric water heater. Assume that the heater element is 4000 watts. A voltage reduction to 95% would result in a considerable reduction of power consumption to 3600 watts. However, in order to achieve the same amount of water heating, of course, the element will need to operate for a longer time. It takes the same amount of energy to heat a gallon of water twenty degrees. Energy is equal to power over a given time period. If only a single customer were involved, this peak shaving would be extremely effective. However, consider the effect on a large number of heaters, still cycling "on-off" but now overlapping their "on" periods as they have become longer. If each of a thousand separate water heaters normally operates 15 minutes an hour, they each will now operate 10% longer during a CVR, considerably reducing the expected peak power shaving, and with no effect on total energy consumption.

Regulated Constant Power

The nature of electrical loads, and how they have evolved since voltage reduction was initially considered in the 1970s as a means of energy control (or more properly, power control) should be taken into consideration. Unlike the power output of resistive heating, which is totally voltage dependent, electronically controlled devices are designed to compensate for varying input voltages. They will regulate their operation to maintain a constant power output over their design limit of input voltage. This means that as the input voltage is lowered, the output will be maintained by increasing input current. Lowering the voltage to these devices will not alter the amount of power consumed. If, instead of the water heater, the load were a precisely controlled furnace used to melt gold, operating at 240 volts and 4800 watts, it would normally draw 20 amperes. If the voltage were reduced to 220 volts, the furnace would merely respond by drawing almost 22 amperes, and no effective reduction in power or energy would be achieved. Note in passing the increase in current demand and thus power loss in the distribution system, an adverse side effect on overall system efficiency.

At the other end of the technological spectrum when considering sophistication is the computer. In an engineering sense, the computer performs no work. No weight is lifted, no steel is squeezed, no water is heated. Of course, we all are familiar with the human energy and economical costs associated with a computer crash. Contrary to generally accepted beliefs, actual testing has shown that computer power supplies are relatively immune to moderate steady-state disturbances of the power system (but not immune to interruptions). These are for the most part very robust devices. Testing at EPRI PEAC has shown that when the voltage to an operating computer station is lowered beyond its design range, the monitor is more likely to shutdown or show ill effects than the computer itself. Most likely the imposition of a voltage reduction will be heralded by the alarms sounded by the uninterruptible power supply (UPS). Although these alarms are not a direct indication that the connected computer is about to crash, the most significant effect of an extended CVR might indeed be computer crashes associated with a UPS battery failure. These crashes will most likely happen upon a sag occurring at a later time, appearing totally unrelated to earlier voltage reductions (see explanations of this effect in the UPS sidebar).

Power Quality Implications and Side Effects

Resistive loads – the root of expectations for power consumption reduction – are only a small fraction of the total, and the response of some loads to a systematic voltage reduction has not been fully investigated. For such loads, first, CVR might not produce a reduction of power consumption and, second and worse yet, their sensitivity to power quality events occurring during the CVR can produce unexpected adverse side effects. Therefore, it is important to focus on the response of equipment from a power quality point of view, and identify the need for characterizing the equipment response by appropriate tests.

The significance of a voltage reduction on customer operation must be examined from two perspectives. One involves the potential for permanent equipment damage due to sustained operation beyond acceptable limits, such as those identified in ANSI Standard C84 (see sidebar). The second, and more probable effect is the misoperation of equipment causing loss of productivity and/or tooling and product. At the time that ANSI C84 was adopted, utility systems were much more subject to wide variations in voltage. Since those early days, utility systems have become much more stable with respect to voltage levels. During the same period, manual gearboxes and typewriters have been superseded by adjustable speed drives and gigahertz computing. This has led to an increase in the sensitivity of loads to disturbances, even those that last for extremely short durations, sags in particular. These often last less than 1/5 of a second. This short duration is in contrast to the one-minute period stated in C84 as the minimum operating time for utility response. This situation has led to the development of an entire industry known as Power Quality and the wide use of as “curve” initially developed for computers, but often applied to other electronic loads (see sidebar “The CBEMA Curve”).

Aggravation of Sag Events

The major concern about a systematic and quasi-permanent CVR is the possible impact on load equipment inherently sensitive to power quality disturbances, sags in particular. Many case histories have illustrated the risk that sags can disrupt the operation of critical equipment, and measurements have been performed to quantify that risk, based on the power system operating within the ANSI C84 range. If a systematic voltage reduction were implemented, the sag effect, which is not an absolute voltage level but a percentage of the operating voltage, is likely to bring many types of equipment closer to the threshold of disruption. The following paragraphs present a discussion of the sensitivity of equipment to sags and the likely aggravation that can be brought by lowering the baseline voltage. See a more detailed discussion in the sidebars “Impact of CVR on Voltage Sag Sensitivity of End-use Equipment” and “Voltage Sag Sensitivity of the Petrochemical industry.”

In a high-tech environment such as California, the customer’s risk of actual connected equipment damage due to CVR may quickly be seen as secondary to the losses incurred due to the effects of Power Quality events. These PQ events can appear during lowered voltage operation as an increased sensitivity to utility sags due to a shrinking of the margin between the fixed dropout voltage and the new, reduced normal condition. They can also appear at a later time due to failures of some types of

A Long-Standing Standard – ANSI C84.1, “*American National Standard for Electric Power Systems and Equipment – Voltage ratings (60 Hz)*”

ANSI C84.1 is a consensus standard among balanced representation from electricity suppliers, manufacturers of electric supply equipment, manufacturers of utilization equipment, and general interest groups. It “establishes nominal voltage ratings and operating tolerances for 60-hertz electric power systems above 100 volts and through 230 kilovolts.” The standard lists 7 specific purposes centered about promoting understanding, establishing uniform nomenclature, promoting coordination between systems and equipment, and giving guidance for the future. It establishes a system of voltage drop allocation and preferred voltage ranges to ensure that ultimate users of electricity can enjoy safe and reliable operation of their electrical equipment. Utilities know what voltage range they should deliver, building designers know the allowable voltage drop in building wiring systems, and product manufacturers know what voltage range to expect. C84.1 implies that manufacturers will likely design and test their equipment for proper operation within the specified voltage ranges.

Another important aspect of C84.1 is the definition of two voltage ranges, preferred Range A and infrequent Range B shown in the table below. These two voltage ranges are prescribed for Medium Voltage (MV) distribution systems, Low Voltage (LV) service entrance, and LV utilization. The service voltage is most often measured near the electric meter. Utilization voltage is normally measured where equipment is connected to the building wiring such as the duplex receptacle where the television is plugged in the wall. Range A service voltage is for electric suppliers and is most often measured near the residential electric meter. Quoting from C84.1, “Electric supply systems shall be so designed and operated that most service voltages will be within the limits specified for Range A. The occurrence of service voltages outside these limits should be infrequent.”

Range B allows infrequent operation “above and below Range A limits that necessarily result from practical design and operating conditions on supply or user systems, or both.” When voltages are in Range B, “corrective measures shall be taken within a reasonable time to improve voltages to meet Range A requirements.” Also, “Insofar as practicable, utilization equipment shall be designed to give acceptable performance in the extremes of the range of utilization voltages, although not necessarily as good performance as in Range A.” Therefore, some degradation in performance might be expected for Range B voltages. Range B for service voltage is 110 –127 volts and is 106-127 volts at the point of utilization. There is more language to say once you go outside Range B, equipment may not work satisfactorily and prompt corrective action is necessary.

Allowable Range of Voltages – On a 120 V Nominal Base

	Range A (Preferred)	*Range B (Infrequent)*
Service Voltage	114 – 126	110 – 127
Utilization Voltage	110 – 125	106 - 127

This standard assumes voltage regulation will be applied to the Medium Voltage (MV) systems, often referred to as distribution lines. Except for underground distribution systems, these lines would be supported by wooden or concrete poles along local streets and alleys. These lines operate at voltage levels generally ranging from 4 kV to 35 kV. C84.1 allocates 9 volts drop (on a 120 volt basis) for utility MV lines mostly because of the long distances involved. Fixed tap distribution transformers convert MV to Low Voltage (LV) for delivery to homes and businesses. LV wires, often referred to secondary and service conductors, carry electric power from the distribution transformers to the interface with customer owned wiring. C84.1 allocates a total of three volts drop for the distribution transformer, secondary and service. Utilities have followed this practice with some variation in voltage drop allocation in their system. However, these variations still produce proper Range A voltage at the utility-customer interface.

Finally, C84.1 allocates 4 V drop in the building LV wiring systems. Unfortunately, it is important to note a difference or incompatibility between National Electrical Code (NEC) and C84.1 with regard to voltage drop in buildings. The NEC has footnotes in sections 210 and 215 that encourage building designers to limit voltage drop to 5% (6 V on a 120 V system) compared to 4 V in C84.1. This creates a bias for problems because it suggests voltages in buildings may be two more volts lower than the C84.1 standard. The voltage drop allocation between utilities and building owners provides for reasonable, and generally cost-effective electric supply systems. Taking away voltage drop allocation from either party generally forces greater infrastructure investments. Building owners would generally install more and larger conductors to reduce voltage drop. Utilities would generally build additional substations, add more power lines, or use larger conductors to minimize voltage drop. Requiring equipment to tolerate wider voltage ranges may increase product costs to consumers.

UPSs resulting from battery end-of-life associated with an excessive number of attempts to restore the pre-CVR voltage (see sidebar “What Do UPSs Do?”).

High-Intensity Discharge Lamps

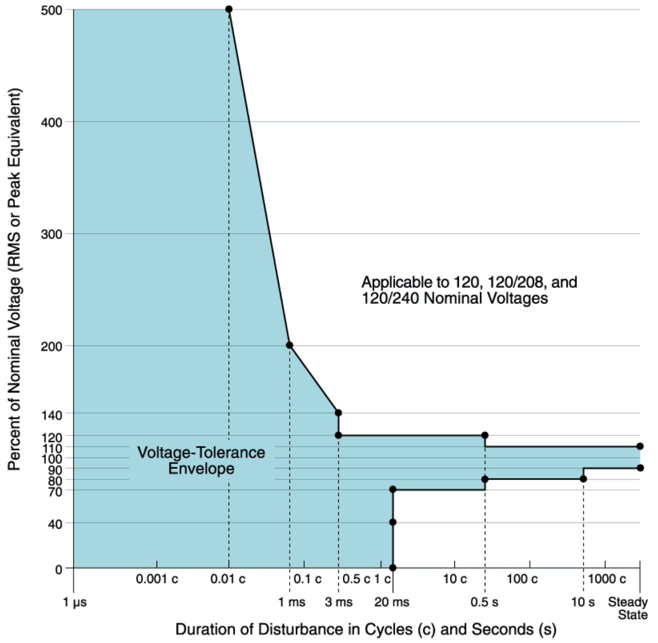
One of the most visible cases of equipment misoperation during a sag is high-intensity discharge lighting, particularly when the bulbs have a high number of operating hours and are used with non-regulating ballasts. It is rather common during storms to find an entire plant floor in total darkness while the process equipment continues to operate. The severity of the sag (depth and duration) was sufficient to extinguish the lamps while the manufacturing equipment was unaffected. If the HID lighting did not require a cool down and restrike period, there would be no problem. This undesirable situation becomes more likely to occur with lamp aging over time and depending on ballast type, as illustrated by Figure 2.

Consider the curves for the various types of ballasts used in conjunction with HID lamps. A sag that reduces the voltage at the fixture to less than 80% of nominal is sufficient to extinguish even a new bulb operating with a non-regulating ballast. As the bulb ages, it becomes even less tolerant of sags. If the bulb were rated at 120 volts, a sag to 96 volts would cause it to be extinguished. The margin between operating and extinction is 24 volts. This represents a sag of 20%, a not uncommon occurrence.

Consider now periods where CVR would be used as a means of load curtailment, and a nominal 5% reduction in voltage is applied. The “new” nominal voltage is 114 volts. The characteristics have not changed – they will still extinguish at the same point. This means that a sag of approximately 15% versus the previous 20% will drop out the lamp, requiring a new restrike cycle. If the plant normally operated at 115 volts, the 5% CVR would lower this to 109 volts. The sag would under this condition need only be 12% to cause lamp drop out. The sensitivity only worsens as the bulbs age.

The “CBEMA Curve”

For the past twenty years the CBEMA (Computer Business Equipment Manufacturers Association) curve for voltage tolerance has been widely used and published as a guideline for voltage tolerance and a susceptibility curve for end-use equipment. After several years of careful consideration, the Information Technology Industry Council (ITIC) ESC-3 working group agreed upon a new revision to the widely quoted CBEMA curve in 1996. This new CBEMA curve (now known as ITIC curve) is more reflective of the performance that can be expected from typical single-phase computers, computer peripherals, and other types of information-technology equipment such as copiers, fax machines, and point-of-sale terminals. The figure shows the revised CBEMA curve now known as the ITIC curve.



The New CBEMA (ITIC) Curve (1996)

While the ITIC curve serves as a benchmark for equipment susceptibility, it is only applicable to Information Technology equipment. It does not address the wide range of equipment such as adjustable speed drives, DC drives, programmable logic controllers, relays, and contactors. These are extensively used in process industries and are often the most sensitive elements impacted by voltage sags. Meeting the ITIC requirement alone does not guarantee that critical loads will be unaffected by events associated with disturbances occurring under “normal” steady-state conditions, and even less when a CVR has become the new steady state condition. Standards-developing groups, supported by test results, are working on expanding the concept of the CBEMA curve to the specific types of equipment listed above.

Impact of CVR on Voltage-Sag Sensitivity of End-Use Equipment

The most important power quality variation for customers is the voltage sag. Although these events are relatively infrequent, they are important because of their substantial economic impact on certain class of end users, primarily industrial customers with continuous process and sensitive equipment. A voltage sag event is primarily characterized by magnitude and duration. Figure A shows a voltage sag event that can be classified as voltage sag down to 70% of nominal for 0.10 second (6 cycles for a 60 Hz power system).

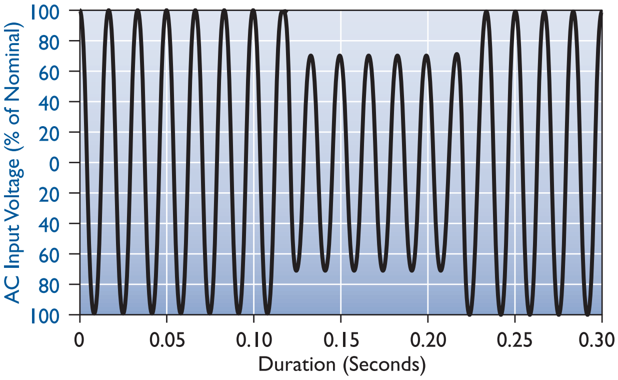


Figure A

A rectangular envelope that identifies the voltage sag ride-through duration and the magnitude is often used to characterize the sensitivity of end-use equipment to voltage sags. For example, Figure B shows the sag sensitivity of a typical programmable logic controller – the heart of process automation and control – that is sensitive to voltage sags deeper than 55% of nominal voltage with durations of more than 0.7 seconds. By superimposing the voltage sag event of Figure A in the equipment sensitivity envelope, it can be seen that such an event will cause the programmable logic controller to trip.

The common understanding is that a 5% reduction in voltage will cause a similar decrease in voltage sag ride-through capability of end-use equipment. For example, if equipment is characterized as being sensitive to a voltage sag down to 80% of nominal voltage based on a 120 V nominal, then the actual undervoltage trip point of the equipment is 96 V. A 5% voltage reduction causes the nominal voltage to fall to 114 V. The voltage sag sensitivity threshold would then be increased to 84.2% (96/114 x 100%). This means that in essence the undervoltage trip point has increased from 80% to 84.2%, thereby making the equipment more susceptible to voltage sag events. However, this simplified understanding ignores the voltage sag response of power supplies, which are the heart of all digital loads from personal computers to programmable logic controllers. The voltage sag ride-through capability of power supplies is primarily a function of the energy stored in the DC bus of the power supply, which is proportional to the square of the voltage. A voltage reduction will cause the energy stored in the DC bus to reduce in square proportion instead of linear proportion.

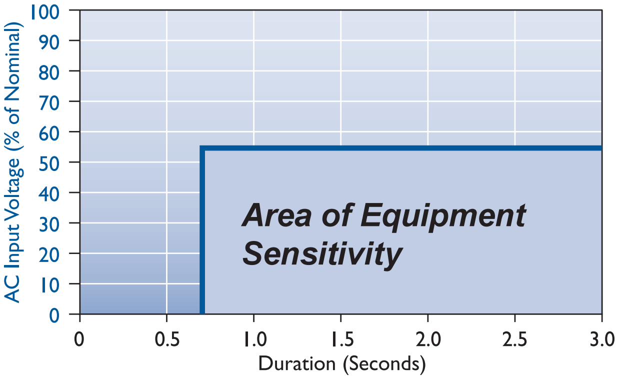


Figure B

Consider the voltage sag ride-through of the power supply of a personal computer characterized by a rectangular sensitivity envelope (72%, 0.12 second) as shown in Figure C. Based on this sensitivity, any voltage sag that causes the voltage to drop below 72% of nominal for more than 0.12 second will cause the equipment to trip. Applying the square relationship gives a new ride-through duration = $(0.95^2 - 0.7^2)/(1 - 0.7^2)$ x 0.12 seconds = 0.0971 seconds instead of 0.12 seconds, *a decrease of almost 18% for a 5% voltage reduction.* New voltage threshold = 0.7/0.95 = 0.737.

Figure C also shows the new sensitivity of the power supply as a result of the voltage reduction. The shaded area in the curve shows the increased area of vulnerability of the equipment due to the voltage reduction. From such an analysis, it could be possible to estimate the increase in sag incidents experienced by a particular customer, taking into consideration the frequency and severity of voltage sag events at the specific location of the customer and taking into consideration the voltage drop between the service entrance and the point of connection of the equipment.

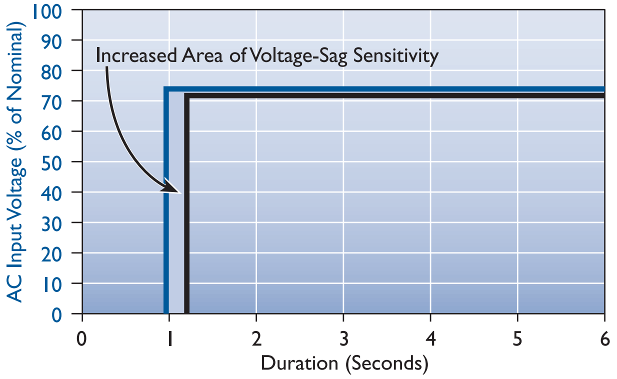


Figure C

Motors

When considering the impact of low system voltage on motor operation, it is necessary to examine the connected load. Just as the regulated power supply or the gold melting furnace will maintain a fixed output power over a range of input voltages, a motor connected to a fixed mechanical load will draw a fixed amount of power. As the voltage is lowered, the current will increase. A more immediate concern is the ability of motors to start when connected to high inertial loads. Torque, like the power drawn by a resistance heater, is proportional to the voltage squared. Torque defines the ability of the motor to change power when required. This is analogous to accelerating through a red light. If additional power is not supplied while engaging the clutch, the engine will stall. The steeper the hill when going up, the more torque is required. Conversely, when going downhill, no torque may be required.

The starting torque, pull-up torque, and pullout torque of induction motors, all change based on the applied voltage squared. Thus, a 5% reduction from nameplate voltage (100% to 95%, 230 volts to 219 volts) would reduce the starting torque, pull-up torque, and pullout torque by a factor of 0.95 x 0.95. The resulting values would be 90% of the full voltage values. Under this condition, the starting current (locked rotor current) might be limited to the point that the motor could fail to break the load loose. This would result in rapid overheating and unless properly coordinated protection is provided, would certainly cause motor failure. A unique situation occurs when the electric motor is connected to the load through a gear, pivot or cam system where the effort to start depends on where in the cycle the load was last left. A shear type cutter would be an example. If the blade

Voltage-Sag Sensitivity of the Petrochemical and Semiconductor Industries

"The key needs at Pennzoil are clean and reliable power. Many manufacturing processes in the petroleum industry are highly sensitive to voltage sags and harmonics. A 30-cycle-sag for example, can throw an entire process off-spec, so the product is ruined. Not only do these power disturbances impact production they can damage equipment…."

--Rob Stephens, Pennzoil, EPRI Signature Newsletter, Fall 1998, Volume 8, Number 3

Both the petrochemical and the semiconductor industries are vulnerable to electrical disturbances. In this age of embedded microprocessors, no one industry has impacted the digital revolution more than the semiconductor industry. It is also true that no one industry is more impacted by voltage sags than the semiconductor industry. Voltage sags down to 70% of nominal can cause process disruptions. Voltage-sag tests conducted by EPRI PEAC Corporation on 33 tools that are commonly used in the production line of a semiconductor-fabrication plant revealed that the process line is as strong as its "weakest link." These weak links can shut down a complete process line, costing more than one million U.S. dollars in some cases. The table below shows some weak links that are not only common in the semiconductor industry but also common in other automated-process industries, such as those found in petrochemical plants.

Susceptibility Ranking	*Voltage-Sensitive Device in Critical Process*
1 (47%)	EMO Circuit: Pilot Relay and Main Contactor
2 (19%)	DC Power Supplies: PC, Controller, I/O
3 (12%)	3-Phase Power Supplies: Magnetron, RF, Ion
4 (12%)	Vacuum Pumps
5 (7%)	Turbo Pumps
6 (2%)	AC Inverter Drives

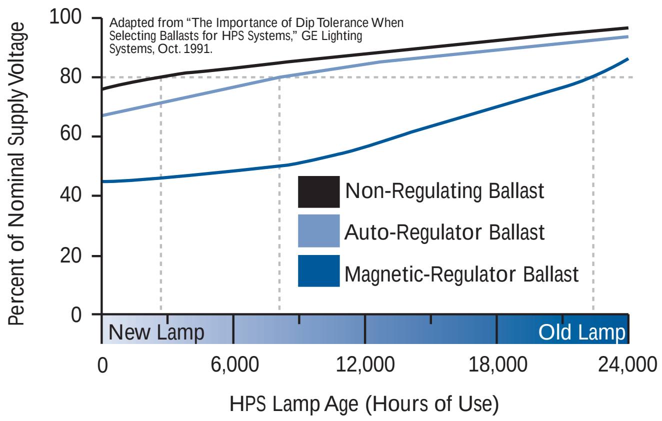

Adapted from "The Importance of Dip Tolerance When Selecting Ballasts for HPS Systems," GE Lighting Systems, Oct. 1991.

Figure 2. Dropout Voltage of HID Lamps as a Function of Age

What Do UPSs Do ?

When connected to a computer load, the primary function of an Uninterruptible Power Supply (UPS) is to supply voltage during loss of utility power. UPS are generally sized to operate the computer until electrical service is restored. During this period, the power to operate the load is provided by batteries. These batteries can be internal for smaller UPSs or in a separate self-contained cabinet for larger systems. Unfortunately, these essential batteries are the weak element of all UPSs. UPS come in three flavors:

- Inexpensive UPS, known as off-line units, normally provide no interaction with the load unless a deviation from normal is sensed. At this point, the UPS will alarm and transfer the computer to an internal inverter supplying the entire load from the battery. Interestingly, the majority of less expensive and smaller UPSs actually interrupt the load for a brief instant while transferring to their internal inverter.
- A more sophisticated level of UPS is termed line-interactive. These UPSs are able to accommodate a wider range of input voltage while correcting their output without the use of battery power. To accomplish this, the output is maintained by drawing more input current.
- The most expensive UPS units, those used to protect the most important and largest systems are termed dual-conversion. These units always convert the incoming AC to an intermediate DC link and then invert this DC to the AC level required to maintain computer operation. The battery is in parallel with the DC link and thus the loss of input power is a non-event for the connected load.

A critical factor involved with each of these three UPS designs is at what voltage level they require energy from the battery. The manufacturers of off-line UPS often provide a user adjustment of the set point where the input voltage level is deemed unacceptable. When this point is reached, battery discharge will begin. The most adverse situation would result if the CVR lowered the input voltage to a point one volt below the acceptable level. The UPS would attempt to supply the entire computer load from the battery, and because the deliberate CVR, by definition, is longer than the capacity of the battery, it would merely drain the battery until the point where the UPS shuts down, totally interrupting the computer power source. Beware that UPS batteries are the most immediate casualties of voltage reductions and that their later inability to furnish energy during actual interruptions would cause havoc with computer installations.

The factory setting of the operating range is generally much more conservative than actually required. If the CVR condition causes the UPS to transfer to internal operation, the set point should be lowered. Note that the line-interactive UPS will be less affected by lowered input voltage than the off-line units. The effect on dual-conversion will be more design specific than that of the less sophisticated units. If the AC-DC conversion portion of the UPS (charger) is unable to maintain an adequate DC voltage level, the battery will be discharged.

An insidious and latent problem that all IT personnel must be aware of is the battery degradation that occurs every time the UPS requires energy from the battery. Batteries are electrochemical devices, and particularly those supplied with the majority of smaller off-the-shelf UPS, are limited in the number of discharge/recharge cycles they will accept over their lifetime. The life of the typical sealed cell lead-acid battery, under the best circumstances is 5 to 7 years, provided that the battery is not fully discharged. If the battery were subjected to daily, prolonged discharges as the result of CVR, it would be better described by the number of discharge cycles or days of life.

Except under very tightly controlled maintenance routines, the battery is given very little consideration. As a result, although the effects of the CVR could appear inconsequential, when a later site interruption occurs (and it will) the battery could be useless due to the number of discharges associated with the voltage reductions, and the computer will be interrupted at that time.

rested at the maximum distance above the product being cut, the starting torque would be minimal. On the other hand, if the cutter were started just when the blade was in contact with the product being sheared, the necessary starting torque would be greatest.

The starting of a motor driving a high-inertia load is often a stressful event even without the complication of an intentional voltage reduction. Figure 3 shows the effect on the electrical service to a very large hospital during chiller starting. Most sags appearing in this chart clearly coincide with periods of very large motor inrush currents. This identifies the event as an internal motor start. Due to the industrial nature of the area, the starting of another large motor(s) by other customers (sags without any increase in the current used by the hospital) also results in severe voltage events. Given the importance and expense of modern diagnostic and customer support equipment, it is quite understandable that great effort was expended to reduce the severity of these events. The ability of a motor to start high inertia loads depends on the voltage at the motor terminals during the start. The system voltage drop shown on this graph is entirely the result of inrush current, but would be compounded by a pre-existing low voltage condition.

Motors driving impeller pumps are not high-inertia loads. The required torque depends on the rotational speed so that the starting torque problem just discussed would not be a problem. However, operation at reduced voltage can impact the ability of the pump to deliver rated flow.

Words from NEMA

NEMA Lamp and Ballast Section Technical Experts have this to say about VR conservation and the potential impact on lighting systems—

“From a lighting perspective, line voltage reduction is not preferred as an ongoing conservation measure. Line voltage reduction might be used if needed to avoid an imminent blackout situation, rather than as an energy conservation strategy. Here’s why –

Under reduced voltage conditions, some lighting products are more seriously impacted than others. The main issue with incandescent or tungsten halogen sources is one of reduced light output and reduced task effectiveness. A 10% drop in line voltage will cause approximately a 30% drop in light output. Lower wattage tungsten halogen lamps, which are widely used in commercial retail establishments, may experience premature lamp blackening and short life since operation at reduced voltage can disrupt the halogen cycle.

Compact fluorescent, linear fluorescent, and high-intensity discharge (HID) systems become even more susceptible to low line voltage since erratic or unreliable ignition (lamp starting) can occur. When poor, erratic, or unreliable lamp starting occurs, lamps that normally start on a given system will experience damage to the lamp cathodes that may drastically shorten lamp life. Poor starting can have other unintended consequences such as increased electromagnetic interference and severe lamp flicker. HID lamps will be more susceptible to drop out. It is impossible to accurately predict the severity of the situation as the line voltage is reduced below the normal intended ballast operating range since many other factors come into play that interact with the line voltage: ambient temperature, age of the lamp(s), distance between the lamp(s) and fixture starting or ground plane, humidity, as well as the specific ballast type and output circuit configuration.

Operation outside the normal design range for ballasts is not consistent nor well defined. Some fluorescent electronic ballasts will attempt to maintain a constant power, actually negating the intent of reducing line voltage for energy conservation, since such ballasts will draw additional current from the power distribution system. This type of ballast, which is becoming more common, will operate at higher temperatures in this mode and can experience as much as a 50% decrease in ballast life.

(Note: Line voltage design ranges for fluorescent and HID lighting ballasts can be found in ANSI C82.11 and ANSI C82.4. These ranges apply to the voltage when measured at the connection point to the ballast, which will always be lower in practice than at the service entrance for a building.)”

Historical Perspective

Looking back

Peak power shaving by voltage reduction is not a new strategy. Utilities have applied it to preserve system stability during disturbances and periods of high demand. After the energy conservation concerns of the 1970s, there was increasing interest on the part of utilities to assess the benefits (see Table 2) as well as among end users in search of remedial measures to deal with brownouts (see bibliography for some examples).

The results shown in the table were concerned with demand reduction and do not provide information on possible side

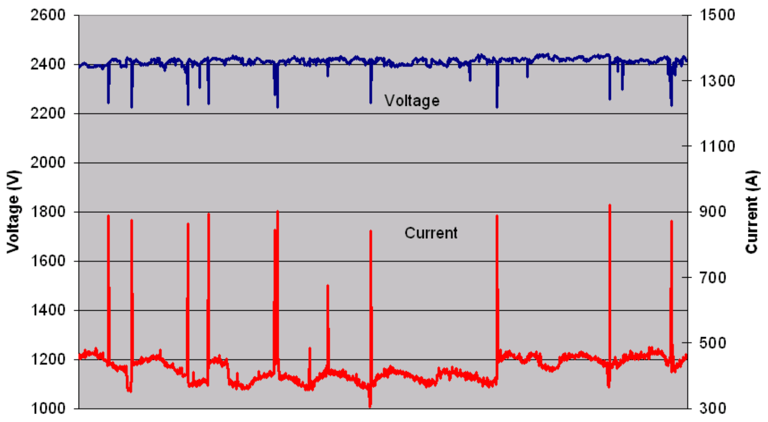


Figure 3. Hospital Chiller Starting Current and Voltage Drops

effects on power quality. However, the unexplained differences among utilities between residential and commercial loads illustrate the complexity of responses of power systems to CVR and the need for better understanding of the effects of CVR initiatives.

Looking into the Future

The recent energy crisis that occurred in California rekindled interest in applying a moderate voltage reduction as a remedial approach, either as a temporary relief for short periods of time, or as a permanent strategy. Thus, three different motivations have been offered to justify voltage reductions:

1. Emergency measure to forestall system collapse
2. Steady-state for short periods to avoid rolling blackouts
3. Long-term peak power shaving

It is difficult to argue against the first measure. Avoiding rolling blackouts is also an emergency measure that has been applied recently and attracted considerable attention. However, the side effects of systematically supplying loads with reduced voltage have not been fully evaluated. End users with critical loads that might already be sensitive to sags would be well advised to assess their risks under such voltage reductions, including appropriate tests to reconcile manufacturers specifications and utilities conditions.

The exposure of a plant or facility to sags will vary from location to location, the weather in the area and sensitivity of the installed devices to sags. When continued plant operation is the paramount concern, external voltage support devices such as ferroresonant transformers or UPSs are often installed. Their need is readily justified, based on the expense of a process shutdown as well as the number of times the process is affected by sags.

Operating the equipment at the upper range of their normal limits is one solution that has often and readily been applied (see sidebar “Boosting Voltage to Mitigate Sag Effects”). This allows greater tolerance for a large majority of sags that are not particularly severe, but are the most frequent. However, the reduced margin between the new nominal established by the voltage reduction and the fixed misoperation point of equipment can be expected to result in more Power Quality problems than otherwise would be seen. Again, this illustrates the point that more information is needed before a blanket acceptance of CVR as a means to reduce energy consumption and shave peak power demands.

A typical and inexpensive solution to a permanent low voltage situation would be to change the fixed taps on transformers feeding the final load or in the absence of transformer taps, the installation of a boosting transformer to raise the voltage to the upper end of the acceptable range. However, when the supply voltage is altered regularly, as might be seen during CVR conditions, this is less practical, due to the possibility of overvoltage when the CVR is lifted. The constant voltage transformer (ferroresonant) has proven extremely effective to reducing process sensitivity to sags when properly sized and coordinated with the loads which it supports. Be aware that determining specifically those loads requiring support during sags to prevent misoperation usually involves significant expertise in the area of equipment voltage sensitivity, the nature of sags, device interaction and also specialized test equipment for both confirming the tentative assumptions and the performance of the installed remedies.

Table 2. Voltage reduction test results among four utilities (Source: Power System Voltage Stability by C.W. Taylor, McGraw-Hill, Inc.)

Utility	*Percent Demand Reduction for 1% Voltage Reduction*	
	Residential	Commercial
American Electric Power 1	0.80	0.78
American Electric Power 2	0.90	0.86
Consumers Power Company	0.83	1.38
San Diego Gas & Electric Co.	1.14	0.08

Boosting Voltage to Mitigate Sag Effects

A buck-boost transformer can be used to boost voltage to certain equipment to mitigate the effects of minor voltage sags. The ability of sensitive equipment to ride through even minor voltage sags is greatly compromised when the voltage at the equipment terminals is near the low end of the nominal voltage range in ANSI Standard C84.1. Increasing the utilization voltage to the upper end of the ANSI standard may be an effective way to increase equipment sag tolerance. Consider using a buck-boost transformer when one of the following symptoms exists:

- Equipment nameplate voltage does not match a supply voltage available at the point of use. For example, a 230-volt motor is connected to a 208-volt supply.
- Equipment such as high-intensity discharge (HID) lighting, motor contactors, and other process controllers drop out during minor voltage sags while other equipment and devices ride through the sags.
- Equipment that is powered by long cables shut down during voltage sags.
- The utilization voltage at equipment is near the low end of the ANSI C84.1 range. For example, the voltage at the terminals of a 120-volt motor-control center is measured at 108 volts.

The following benefits can be achieved by using a buck-boost transformer in the boost mode:

- Prevent costly process and equipment shutdowns.
- Increase equipment reliability.
- Save money by treating only the equipment that needs voltage matching or enhanced sag tolerance instead of treating an entire facility.
- Save space by using a transformer that is typically smaller than an equivalently sized isolation transformer.

Specifying a Buck-Boost Transformer to Increase Sag Tolerance

To select a buck-boost transformer to increase sag tolerance of equipment, follow these three steps:

Step 1. Install a voltage monitor at the point of utilization to record the voltage during normal operation, including during any voltage sags that cause the equipment to drop out or malfunction.

Step 2. Determine the amount of voltage boost to achieve a utilization voltage at or slightly above the rated voltage of equipment but lower than the allowable maximum utilization voltage. Consider the following example. HID lighting designed to operate at 208 V (200 V utilization) in a process facility is known to be sensitive to voltage sags that do not upset other facility equipment. The voltage measured at the HID lighting panel is 195 V during normal conditions and 172 V during the startup of a large compressor motor, which causes the lights to go out. The voltage at the panel can be increased by 16 V and still be within the ANSI C84.1 range for a 208-V circuit. This voltage boost will prevent the lights from going out during the startup of the motor.

Step 3. From equipment nameplates, determine the voltage and current ratings of all loads to be connected to the transformer. If such data cannot be gathered, measure the current of all loads to be connected to the transformer. Add the current ratings or current measurements together, then calculate the load kVA by multiplying the nominal load voltage by the load current.

Summary

This brief examination of some common loads and their response to CVR does raise concerns on power quality issues. Undeniably, there are instances where -peak power reduction with some total system energy consumption can be obtained. However, a closer examination raises questions regarding the effectiveness of voltage reduction as a broad conservation strategy. While peak power demand can be reduced, the net effect on integrated energy consumption will be reduced by the automatic compensation performed by control circuits. Some of these controls simply maintain constant power output, others increase the duration of operation until the targeted task is accomplished.

For many types of load equipment, a CVR might not produce a reduction of power consumption and their sensitivity to power quality events occurring during the CVR can produce unexpected adverse side effects. A very significant negative impact of CVR is the resulting increase in the frequency of occurrence and severity of sags that can disrupt manufacturing operations and information technology activities. There are solutions to this problem, but they require a careful assessment of the situation, perhaps even on a case-by-case basis.

Conclusion

While there are instances where peak power reduction with some energy consumption reduction can be obtained by conservation voltage reduction (CVR), the response of some loads to CVR can include adverse side effects, in particular for those loads that are already susceptible to voltage sags. Because the parameters of this response have not been sufficiently quantified, it is necessary to identify and quantify them by comprehensive tests of equipment compatibility under CVR conditions.

Bibliography

A comprehensive bibliography of technical and trade publications on the subject of conservation voltage reduction ("brownouts") would take several pages and require acquiring a large number of publications. Some of these might not directly address the scope of this PQ Commentary – the importance of objectively assessing the efficacy and side effects of systematic CVR. The following is only a sampling, illustrating the range of such publications. Listings are classified under the respective subject headings and publication chronological order. The range of dates of publication is also an indication that the subject has a long history.

Research Papers

Butler, J.W. and Concordia, C., "Analysis of Series Capacitor Application Problems," *AIEE Transactions Vol 56,* No. 8, 1937.

Betancourt, R. and Lin, M.S., *A Study of the Effects of Transient Voltage Drop on Power System Stability,* San Diego State University, January 1986.

Warnock, V.J. and Kirkpatrick, T.L., "Impact of Voltage Reduction on Energy and Demand," *IEEE Transactions PAS-3* No.2, May 1986.

Archer and Ritchie, W.M., "Brownout Voltage Stability – System Measurements and Simulations," *Proceedings, 5 th International Conference on AC and DC Power Transmission*, London, 1991.

Tutorial Publications

Lamoree, J., "How Utility Faults Impact Sensitive Customer Loads," *Electrical World,* April 1992.

Kundur, P., *Power System Stability and Control*, McGraw Hill, 1993

Taylor, C.W., *Power System Stability*, McGraw Hill, Inc., 1994.

Performance of AC Motor Drives During Voltage Sags and Momentary Interruptions, EPRI PQ Commentary No.3, December 1998.

Standards

IEEE Std 141, *IEEE Recommended Practice for Electric Power Distribution for Industrial Plants* (IEEE Red Book)

IEEE Std 446, *IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications* (IEEE Orange Book).

IEEE Std 493, *IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems* (IEEE Gold Book).

IEEE STD 1100, *IEEE Recommended Practice for Powering and Grounding Electronic Equipment* (IEEE Emerald Book)

Public Utilities Commission, State of California, *Ruling on Voltage Reduction Issue*, (R.) 00-10-002, September 21, 2001.

Application Notes

Avoiding Temporary Blackouts of Metal Halide Lamps, PQTN Application Note No.3, September 1995.

Using Buck-Boost Transformers to Match Equipment Voltage and Increase Sag Tolerance, PQTN Application Note No.11, December 1997.

Matching Utilization Voltages to Motor Nameplates, PQTN Application Note No.12, December 1997.

Performance of a Hold-In Device for Relays, Contactors, and Motor Starters, EPRI PQ Brief No.46, October 1998.

Case Histories

University of Texas at Arlington, *Effects of Reduced Voltage on the Operation and Efficiency of Electric Loads*, EPRI Reports EL-2036(1981) and EL-3591 (1984).

Kyrita, A. and Sakurai, T., “The Power System Failure on July 23, 1987 in Tokyo,” *Proceedings of the 27th IEEE Conference on Decision and Control*, Austin TX, December 1988.

Elevator Drive Control Card Failures Caused by Voltage Sags, Application Materials, EPRI PEAC, August 1997.

Chiller Shutdowns Caused by See Insensitivity of Control Relays to Voltage Sags, EPRI Case Study No.3, July 1998.

Trade Articles

Leonard, M. “Brownout-proofing Your Product,” *Machine Design*, June 13, 1974.

Tucker,R.G., “When Emergency Generators And UPS Are Not Enough,” *Actual Specifying Magazine*, July 1975.

Magazine Editor “One chip guards against overvoltage, line loss, and brownout,” *Electronic Design*, November 1981.

McGowan, K.J., “Make the Smartest Blackout Protection Choice by Assessing the Benefits of a UPS vs. an SPS,” *PCIM Magazine*, November 1985.

McSwain, D., “Conservation voltage reduction is coming,” *North County Times*, July 7, 2001.

Acknowledgment

This work was sponsored by EPRI Power Quality target members and the Consortium for Energy Infrastructure for Digital Society (CEIDS). The information presented in this PQ Commentary was obtained from many sources and edited by François Martzloff of the National Institute of Standards and Technology. Larry Conrad of Cinergy Corp., Thomas Key and Arshad Mansoor of EPRI PEAC, and Edward Yandek of GE Lighting contributed source material and comments.

Key Terms:

EPRI PEAC Corporation supports electric utilities and their customers in their efforts to understand and resolve power quality problems and system compatibility issues; help utilities solidify durable, beneficial relationships with their customers, manufacturers, and standards organizations; and empower utilities with knowledge via power quality training and publications.

For information about EPRI PEAC, call 865-218-8000. To order EPRI publications, call the EPRI Customer Assistance Center at 800-313-3774 or, if outside the U.S., 1-650-855-2121.

Commentary Number 4, December 2001

ID ??????????

Printed on recycled paper in the United States of America.

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304
PO Box 10412, Palo Alto, California 94303 USA
askepri@epri.com • www.epri.com