

## Voltage Regulators and Sag Correctors (Voltage Compensation Devices)

### Questions & Answers

This document contains three sections:

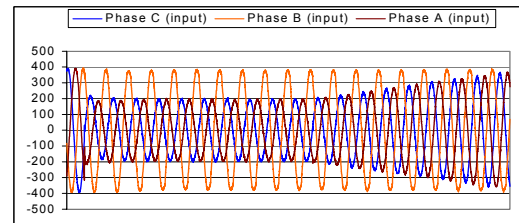
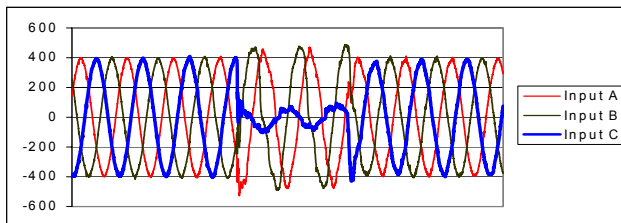
- A. Questions about sags including, how often they occur, what causes them and their impact on equipment
- B. Questions about Cutler-Hammer's Sag Ride Through (SRT)
- C. Overview of technologies

### A. Questions about Sags

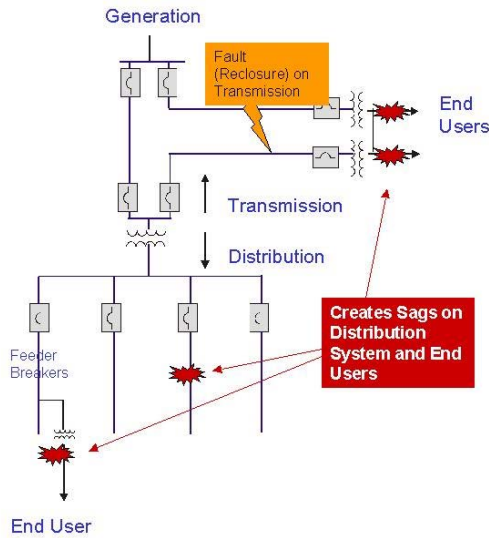
#### 1. What are voltage sags, voltage regulation and interruptions?

**Voltage sags** are a 10% to 90% reduction in the supply voltage (of nominal voltage). These deep voltage sags are often called **dips**. These events are short in duration, often lasting between  $\frac{1}{2}$  a cycle to a few seconds. A sag is a deep voltage decrease and is shorter in duration than a voltage regulation problem (brownout). In addition, sags are often accompanied by voltage distortion, transients, and phase shifts.

Two different sags are illustrated below.



The most severe sags are caused by faults on the utility distribution or transmission system. Faults can be caused by storms, lightning, falling tree branches, animal contact, human accidents, insulation failures or motor starting. Customers located close to a fault will experience a deep sag and possibly an interruption while the breaker or fuse operates. The vast majority of customers connected to the transmission system or other distribution feeders will experience some level of voltage sag. The diagram below illustrates that all the customers on the system will experience a sag.



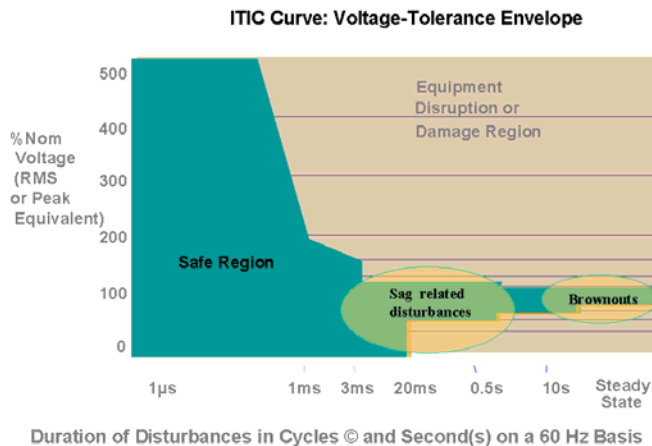
Research data indicates that the majority of sags are single phase line to ground (SLG) or line to line (L-L) faults. Three phase, line to ground sags and long duration interruptions are rare. Power Quality monitors capture and record sag events. Key parameters of the sag include voltage magnitude,

duration and phase distortion. A number of studies, by utilities and facility managers, have concluded that sags are the most common disturbance encountered at an industrial or commercial facility. The average facility will experience 45 sags per year and many of them will result in equipment shutdown.

Utilities and consultants recommend mitigating devices to prevent equipment disruption due to sags. Cutler-Hammer's Sag Ride Through (SRT), is an effective device that is installed at the service entrance or branch panel, feeding a critical process.

**Voltage Regulation**, often called a brownout, occurs when voltage deviates from +10% to -20% of the nominal amount for a long period of time.

In the United States, most facilities have sufficient voltage regulation. However, in some US locations and many developing countries, regulation problems occur because of overstressed utility distribution systems. In some cases, due to the excessive demand on the utility system, voltage may be below 8% of nominal (-8%) during the day. This condition is called a **voltage regulation** or **brownout**. Customers may notice dim lights and reduced power. During the evening, voltage may rise above 10% of nominal (+10%) because large facilities and loads are shutdown. This shutdown reduces the power demand on the grid and results in a voltage increase.



The IEEE defines voltage regulation as over voltage or under voltage. Voltage regulation events last from a **few minutes to many hours** with voltage varying by +/- 20%. Long term regulation problems differ from short duration sags and dips, which are much deeper voltage drops. The figure to the left shows the difference in duration and magnitude between sag and brownout condition. Electrical devices are sensitive to

voltage fluctuations. In countries that experience voltage fluctuations, customers require **Electronic Voltage Regulators (EVRs)** on home appliances, office and industrial loads. EVRs prevent failed components. Cutler-Hammer manufactures Electronic Voltage Regulators from 10 kVA to over 700 kVA. This technology employs an electronic tap changing transformer that corrects voltage from +15 to -27% and quickly adjusts the output voltage to within +/-3% of the nominal.

Prior to installing voltage regulators, Cutler-Hammer encourages customers to monitor incoming voltage to determine if voltage regulation is a problem. The local utility may also be able to provide information on voltage expected at the facility. In most cases, regulation may not be the problem, voltage sags may be the problem.

**Interruptions**, also called outages, are the complete loss of three-phase voltage. The load can not operate as intended. It may last from a few cycles to several hours.

Long term outages are rare in North America. Studies by utilities indicate that long-term outages only represent 2% to 5% of all power quality events. Interruptions are almost non-existent for customers fed directly from a utility transmission system. Remaining power quality events are typically sags or transient disturbances.

## **2. What is the “cost” of voltage sags and other power quality events?**

The “cost” of poor power quality depends on many factors; however, it generally varies from \$50 to \$400 per kVA of total load. For example, a 10 MVA automotive plant can expect to pay between \$500,000 and \$4,000,000 per year. These annual costs can be eliminated, or significantly reduced, by implementing a power quality improvement strategy.

When an industrial or commercial process is shutdown or interrupted, it is costly and may take significant effort to restart. For example, a two-cycle sag may cripple a textile or paper process for hours. The line has to be cleaned up, scrap must be removed and the process restarted. These lost hours of production negatively affect plant productivity, customer service and financial profitability.

Documented cases, from many different industries, indicate that each voltage sag costs between three to thirty thousand dollars. The higher costs are associated with petrochemical, telecommunication, semiconductor, and other critical processes.

## **3. What industries or equipment/processes are sensitive to sags?**

Industries that often have equipment upsets due to sags include:

- telecommunication systems
- semiconductor manufacturers
- steel mills
- petroleum & chemical processes
- pharmaceuticals
- automotive
- textile
- printing processes
- plastic injection manufacturers
- paper mills

Equipment used in commercial buildings or industrial plants are sensitive to voltage sags. Examples of equipment particularly sensitive to sags include:

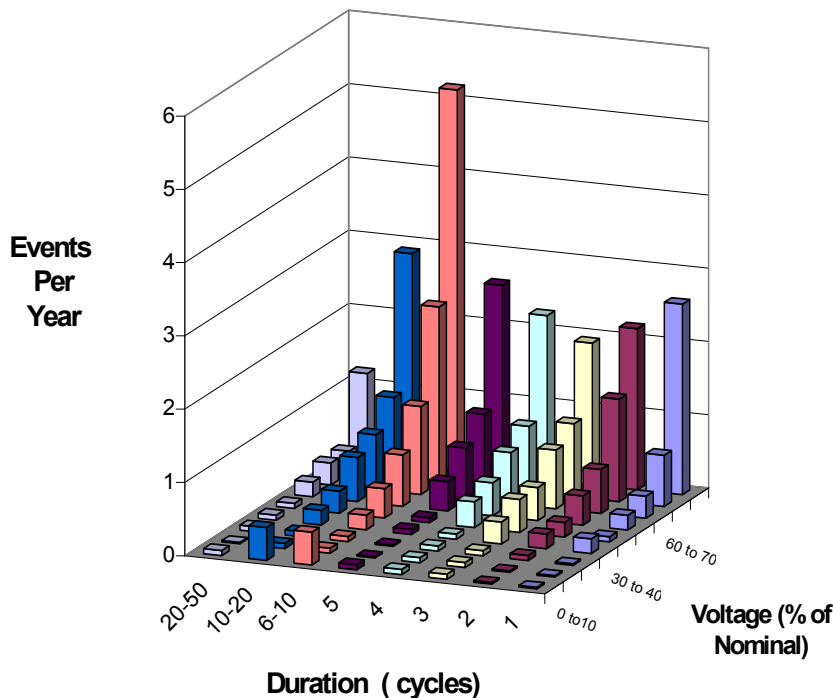
- AC and DC adjustable speed drives
- Communication Systems
- Robotics
- Relays & Motor contactors
- HID lighting
- HVAC controls

#### 4. How often do sags occur?

Voltage sags and momentary interruptions are the most costly power quality problem for industrial and commercial customers. Depending on the location, a facility can expect to experience 30 to 50 sag events per year.

Utilities and customers have published many studies, articles and case studies, which discuss the costly problem of sags. One large baseline research project was the Distribution Power Quality (DPQ) study sponsored by the Electric Power Research Institute (EPRI), which was supported by twenty-four utilities.

Between 1993 and 1995, data was captured on power quality disturbances from 300 monitors located across the United States. The data indicated that 92% of all events are sags. Interruptions between 2 seconds and 10 minutes only accounted for 4% of events. Other disturbances accounted for the remaining 4% of events. Sags accounted for almost all recorded events for customers connected directly to the transmission line.



The diagram above presents average utility data from the DPQ study. The number of sags per year is the average per voltage magnitude and duration. Adding up all the data results in the total

sags per year at the site. For a list of articles and website addresses please contact Cutler-Hammer's Surge Protection and Power Conditioning line.

## 5. What does Cutler Hammer offer to solve voltage sag or voltage disturbance problems?

Cutler-Hammer has two power conditioning products for these disturbances:

- **Sag Ride Through (SRT)** device corrects deep sags in sub-cycle time. Input voltages of -63%, including phase shifts, distortion, and transient surges are corrected using a series compensation transformer with dual-conversion voltage injection. This product is recommended for facilities affected by sags.
- **Electronic Voltage Regulator (EVR)** is a fast acting tap changer with an isolation transformer. Input voltage (+10/-26%) is tightly regulated to +/-3% output voltage. This is applicable for international locations or domestic facilities that suffer from brownouts and long duration under/over voltages.

Both the SRT and EVR are three phase units. The SRT is available in sizes from 25 kVA to 6000 kVA and the EVR is available in sizes from 10 kVA to 1250 kVA. Contact factory for larger sizes. These units can be installed at the service entrance, branch locations, or at critical loads.

## 6. What can a utility do to reduce sags?

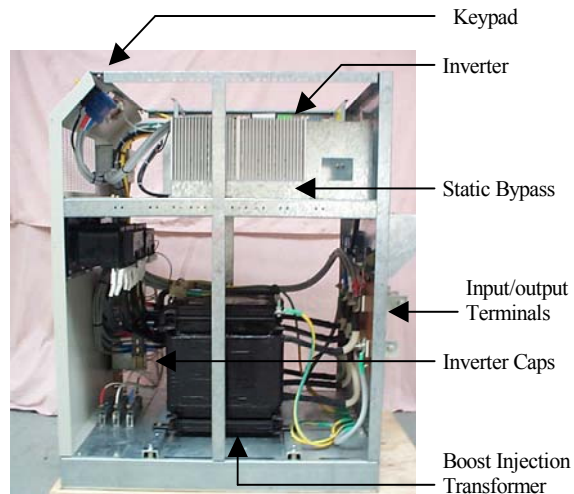
Utilities can reduce voltage sags, by adding line arrestors, animal guards and by trimming trees. Additional precautions can be taken by implementing line reclosers, eliminating fast tripping, adding loop schemes and modifying feeder design. These practices may reduce the number and/or duration of momentary interruptions and voltage sags. However, utility faults can never be eliminated completely.

Many utilities now recommend mitigating solutions, such as the SRT, to their customers. Others are even financing these solutions and generating the payments by charging after each sag event, or by administering an annual fee.

## B. Questions about the SRT

### 7. How does the SRT work?

The SRT power conditioner is a series connected active voltage compensation device. The unit normally operates in an online, a high efficiency (~99%) mode continuously monitoring input voltage. When a sag disturbance is detected, the unit reacts in under 2 milliseconds (sub-cycle), injecting the voltage required to correct the sag or provide momentary outage ride-through. The series connected transformer produces a clean stabilized voltage output. The device is able to correct even the deepest sags. Input voltage can vary by as much as -63%.



SRT power conditioners are installed in the distribution system and in front of critical loads to stop sags. Normally the device is only required to provide correction for 3 to 15 cycles while the sag

persists. However, the SRT's rugged construction enables continuous correction if necessary: a significant performance advantage over other technologies.

No minimum load is required to operate the SRT and there are no restrictions on the system's available fault current. The SRT's unique design accommodates nonlinear loads and applications with high inrush current or momentary overloads.

The SRT provides a significant return on investment. It ensures improved operating productivity not commonly experienced with traditional tap switching or ferroresonant technologies. UPSs are significantly more expensive, however, they may be used in conjunction with the Cutler-Hammer SRT for facility-wide protection. UPSs are not considered for branch/service entrance locations protecting industrial processes and electrical loads.

### **8. Is response time important?**

Yes. Response time is the total elapsed time between the initiation of the sag and the correction of the output. In the case of all power conditioners, time is required to recognize the sag and take action, either by activating the desired electronic tap or engaging the inverter section to provide correction.

Due to its unique patented design, the SRT has a sub-cycle response time. Total correction time is approximately 1/4 cycle (less than 4 milliseconds), significantly faster than traditional power conditioners and UPS devices. The following are typical response times for power conditioning technologies:

- Ferroresonant transformer: 8 - 16 milliseconds
- Solid state Tap Changer: 16 - 160 milliseconds
- UPS: less than 16 milliseconds
- Micro SMES: less than 5 milliseconds
- Cutler-Hammer SRT (Sag Ride Through): 4 milliseconds
- Cutler-Hammer EVR (Electronic Voltage Regulator): 16 milliseconds

Generally, a response time of less than 1/2 a cycle is required to provide protection to sensitive loads such as relays, contactors and HID lighting loads.

### **9. Is phase shift/distortion important to sag correction?**

Most power quality distribution problems have phase shifting associated with them, especially in cases of line to line faults. Phase shifting is the variance between magnitude and power factor. Line-to-line and line-to-ground faults are often accompanied by voltage distortion. This voltage distortion is caused by arcing faults, and phase shifts, due to wye-delta service entrance transformer connections. Thyristor-based power supplies (such as in DC drives) need accurate zero-crossing information. As a result, maintaining phase consistency and wave shape is important to reliable operation.

Ferroresonant transformers and tap changers do **not** correct phase shifts. Often they aggravate the problem, resulting in a more severe disturbance. For optimal performance, a sag corrector device should inject the voltage required for any expected disturbance and with appropriate phase shift. The Cutler-Hammer SRT electronically synthesizes the voltage to the required AC voltage magnitude and corrects the phase shift to a balanced 3-phase output.

### **10. Why is operating efficiency an important specification?**

Efficiency is the ratio of input power divided by output power. This is a key element in making an economical decision for a voltage sag solution.

The total cost of owning a power quality mitigating device includes the purchase price and all operating costs. Operating costs include maintenance and efficiency (energy losses). For UPS and other sensitive equipment, cooling costs must also be included.

The following Losses and Efficiency table compares efficiency and maintenance costs of three different power conditioners: ferroresonant transformers, tap changers and voltage compensation devices (SRT technology).

<b>Losses and Efficiency</b>			
<b>50 KVA Device</b>	<b>No Load (Watts)</b>	<b>Load (Watts)</b>	<b>Efficiency</b>
Electronic Tap Changer	1050	1700	95.0%
Ferroresonant Transformer	6000	2500	83.0%
Voltage Compensation Device ( SRT)	50	600	99.0%

The Approximate Annual Operating Costs table below illustrates the annual operating cost of these three technologies. Note that ferroresonant transformers are very expensive to operate compared to voltage compensation devices. The efficiency costs should be included in the economic analysis when choosing mitigation solutions.

<b>Approximate Annual Operating Costs (Energy)</b> <b>\$ per kW of unit size @ .08/kWh</b>			
<b>50 KVA Device</b>	<b>No Load</b>	<b>Load</b>	<b>Typical \$/Year</b>
Electronic Tap Changer	\$880.00	\$1200.00	\$1120.00
Ferroresonant Transformer	\$4200.00	\$5950.00	\$5500.00
Voltage Compensation Device (SRT)	\$35.00	\$455.00	\$350.00

Although UPS devices are relatively efficient (~93%), they are costly due to battery maintenance, testing and regular replacement. In addition UPS systems require air conditioning systems.

### **11. How long can the SRT correct sags?**

The SRT can correct sags on a continuous basis. It does not require charging time between operations: a significant advantage over other designs that must recharge between events. Other devices may be able to respond to the first and second sags, but do not have the capacity to correct multiple events.

### **12. What is the minimum load required by the SRT?**

None. This significantly reduces the complexity of ordering the appropriate SRT device. Tap changers, ferroresonant transformers and other devices require a minimum load to operate properly. Without a minimum load, other devices will drop out.

### **13. What about inrush current? What will happen to the SRT if there is a downstream fault?**

A power conditioning device should be able to support inrush current demands during load startup and cycling without loss or degradation of available power to the load.

### **14. What are key parameters required for a SRT?**

- Input voltage: -63% single phase
- kVA rating: 25 to 6000 kVA (contact factory for larger sizes)
- Response time: sub-cycle (1/4 cycle)
- Technology: dual conversion sag protection with series compensated transformer
- Phase shift: restores balanced 3 phase load
- Minimum Load: none
- Inrush: 150% for 30 seconds
- Efficiency: 99%
- Maintenance: battery free – no maintenance

## **C. Overview of Ferroresonant, UPS, and other Technologies**

There are several products that mitigate problems caused by sags and momentary interruptions. The following discusses these products, their capabilities and their limitations.

### **Ferroresonant or Constant Voltage Transformer (CVT)**

Ferroresonant provides sag ride for –30% voltage sags (voltage down to 70% of nominal). CVTs are used for constant loads. Variable loads, especially those with high inrush currents, present more of a problem for CVTs because of the tuned circuit on the output. CVTs are 1:1 transformers which are excited high on their saturation curves, providing output voltage which is not significantly affected by input voltage variations. The efficiency of ferroresonant devices is poor. They produce significant losses even with no load. The annual cost of losses is on the order of the initial purchase cost, making them unattractive solutions at large power levels. The physical size of these devices also limits their application.

In order to provide sufficient sag protection at full load, the CVT transformer is usually larger than the nominal full load kVA. This over-sizing is required to improve ride-through capability, however, it reduces efficiency which makes ferroresonant transformers an expensive operating solution. CVTs are commonly used for small single-phase loads (<10 kVA).

### **Uninterrupted Power Supply (UPS)**

The UPS has been the most popular device used to mitigate sags and interruptions. During normal operation the load is supplied from the source and a bank of batteries is maintained in charged standby mode. When a sag or interruption occurs, the UPS supplies power from the batteries. This is accomplished by inverting the DC battery power and converting it into the needed AC. An advantage of the UPS is that it provides interruption ride-through capability during brief power outages.

The UPS is an expensive solution for sag correction. During each event, the batteries degrade, which leads to a reduced life expectancy. Maintenance costs are high due to the need for regular inspection and the replacement of batteries.



UPSs cannot provide long-term outage protection. For large three phase loads, the UPS can provide protection from a few cycles to approximately 20 minutes. To obtain 100% protection for critical processes it is necessary to provide back-up generation for the UPS. The cost of such systems is higher (\$750-\$1000 per kVA), and the operating and maintenance costs are significant. The large footprint of UPS units is a considerable disadvantage at high power levels.

UPS systems are often used on computer systems, but are not economical solutions for drives, HID lighting, contractors/relays, robotics and other industrial loads. Sag correctors, using voltage compensation, are becoming the preferred solution for these loads.

### **Static Transfer Switch**

The strategy of a static transfer switch is to supply the load from one system while having a second (and independent) supply available in case there is a problem on the first. The load is normally transferred from one source to an alternate source within one-half cycle. The cost of a static transfer switch also includes additional costs associated with supplying an independent backup feeder. The efficiency can be as high as 99%.

### **Tap Changing Regulator**

Multi-tap transformers are configured with electronic switches at each tap and can be used to provide a degree of regulation in voltage output for varying input voltages. Devices on the market react in a minimum of one cycle, although, some versions require up to 10 cycles to correct the voltage. These devices can regulate incoming voltage variations of +10/-20% of nominal. They provide limited protection against deep sags and do not correct phase shifts.

Cutler-Hammer's Electronic Voltage Regulators are ideal for applications where long duration under/over voltage (brownouts) occur, but are only marginally successful at addressing deep sags.

### **Sag Correction Voltage Compensator**

The static voltage compensator is often referred to as a Dynamic Voltage Restorer (DVR) or SSVR. The device operates in by-pass, directly supplying the load from the source. When a sag is detected, the unit is activated and synthesizes the required voltage deficiency to a balanced three phase, which is the desired output. This compensation voltage is injected into the line through a series connected transformer, while capacitors are used for energy storage. This device is designed to mitigate voltage sags, however, the capacitor energy storage provides a modest level of interruption ride-through capability.

This technology is applied at the service entrance or branch locations (low voltage). The solution addresses 92% to 95% of typical events at a fraction of the cost of UPS solutions. However, the unit is not able to provide back-up power for outages. To provide 100% protection, a generator, UPS and other devices would be required. To achieve the remaining 5% to 8% of protection, a significant incremental cost (>1000% of the Cutler-Hammer SRT solution) would be required.