Voltage Sag Analysis Case Studies

Jeff Lamoree
Member, IEEE
Electrotek Concepts, Inc.
Knoxville, Tennessee

Dave Mueller
Member, IEEE
Electrotek Concepts, Inc.
Knoxville, Tennessee

Paul Vinett
Senior Member, IEEE
Central Hudson Gas & Electric Corp.
Poughkeepsie, New York

William Jones
Member, IEEE
Public Service Company of New Mexico
Albuquerque, New Mexico

Abstract - This paper summarizes the results from a number of different voltage sag investigations. These investigations involve characterizing the voltage sag performance at a customer facility and evaluating equipment sensitivity to different voltage sag magnitudes and durations. Possible solutions to voltage sag sensitivity problems are also described.

INTRODUCTION

Voltage sags and momentary power interruptions are probably the most important power quality problems affecting industrial and large commercial customers. These events are usually associated with a fault somewhere on the supplying power system. Actual interruptions occur when the fault is on the circuit supplying the customer. Voltage sags are much more common since they can be associated with faults remote from the customer. Even voltage sags lasting only 4-5 cycles can cause a wide range of sensitive customer equipment to drop out.

Analysis of voltage sag concerns requires a knowledge of the voltage sag characteristics, statistical information describing the likelihood of a voltage sag occurring, and information describing the sensitivity of important loads within the facility. Developing this knowledge base requires close cooperation between the utility, the customer, and equipment manufacturers.

In order to develop a better understanding in all of these areas, the Electric Power Research Institute (EPRI) and a number of individual electric utilities have been sponsoring case studies to investigate voltage sag concerns and available solutions. This paper summarizes some of the important results from these case studies.

CHARACTERISTICS OF VOLTAGE SAGS

Voltage sags which can cause equipment impacts are usually caused by faults on the power system. Motor starting also results in voltage sags but the magnitudes are usually not severe enough to cause equipment misoperation. The simplified one line diagram in Figure 1 can be used to explain how a fault results in a voltage sag at a customer facility.

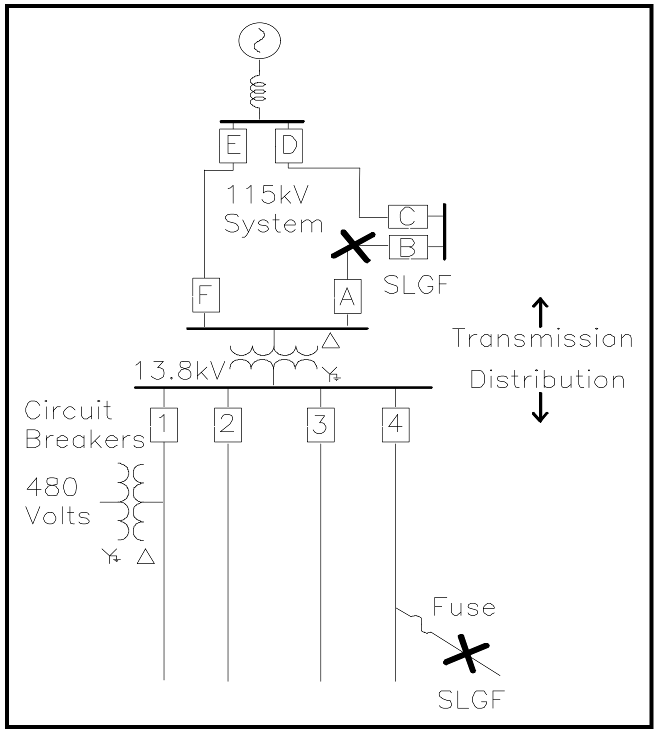

Figure 1. Example Power System

Consider a customer that is supplied from the feeder designated with breaker 1 on the diagram. If there is a fault on this feeder, the customer will experience a voltage sag during the fault and then an interruption when the breaker opens to clear the fault. If the fault is temporary in nature, a reclosing operation on the breaker may be successful and the interruption will only be temporary. Regardless, sensitive equipment will almost surely trip during this interruption.

A much more common event would be a fault on one of the other feeders from the substation or a fault somewhere on the transmission system (see fault locations shown on the figure). In either of these cases, the customer will experience a voltage sag during the period that the fault is actually on the system. As soon as breakers open to clear the fault, normal voltage will be restored at the customer. Figure 2 is a plot of the rms voltage vs. time and the waveform characteristic at the customer location for one of these fault conditions.

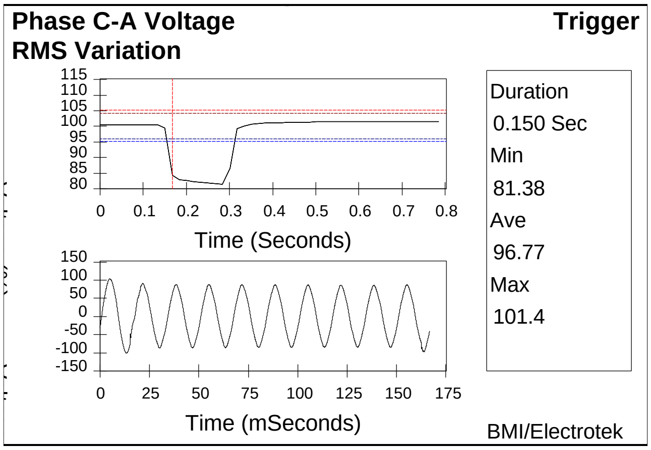

Figure 2. Example Voltage Sag Characteristic During a Fault on a Parallel Feeder Circuit

The waveform given in Figure 2 is typical of the customer voltage during a fault on a parallel feeder circuit that is cleared quickly by the substation breaker. The total duration of the fault is 150 msec, or about nine cycles. The voltage during a fault on a parallel feeder will depend on the distance from the substation to the fault location. A fault close to the substation will result in a much more significant sag than a fault near the end of the feeder. Figure 3 shows the voltage sag magnitude at the plant bus as a function of fault location for an example system. Note that a single line-to-ground fault condition results in a much less severe voltage sag than a three phase fault condition due to a delta-wye transformer connection at the plant.

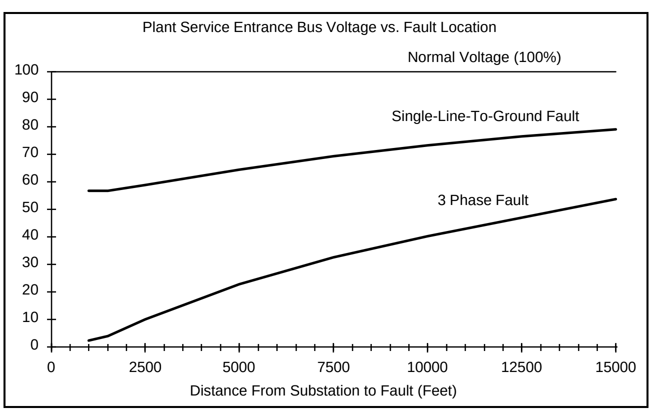

Figure 3. Plant Phase-to-Phase Bus Voltage (%) as a Function of Fault Location on a Parallel Feeder

Transmission related voltage sags are normally much more consistent in duration than distribution voltage sags. Because of the large amounts of energy associated with transmission faults, they are cleared as soon as possible. This normally corresponds to 3-6 cycles, which is the total time for fault detection and breaker operation.

Normally, customers do not experience an interruption for a transmission system fault. Transmission systems are looped or networked, as opposed to distribution systems which are radial. This means that if a single line trips, or is out of service, the remaining system supplies the load. If a fault occurs as shown on the 115 kV system, the protective relaying will sense the faults and breakers A and B will open to clear the fault. While the fault is on the transmission system, the entire power system, **including the distribution system**, will experience a voltage sag.

Figure 4 shows the magnitude of measured voltage sags at an industrial plant supplied from a 115 kV system. Most of the voltage sags were 10-30% below nominal voltage, and no momentary interruptions were measured at the plant during the monitoring period (almost one year).

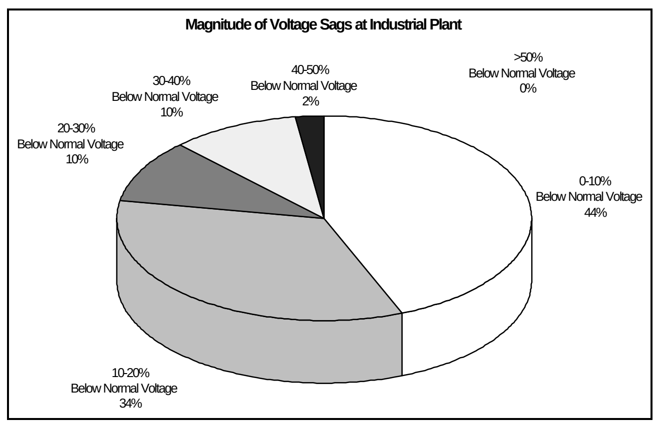

Figure 4. Industrial Plant Sag Magnitude Data (magnitudes are in % below nominal voltage)

Figure 5 gives a three dimensional plot illustrating the number of sags experienced as a function of both the voltage sag magnitude and the duration. This is a convenient way to completely characterize the actual or expected voltage sag conditions at a site. Evaluating the impact of voltage sags at a customer plant involves estimating the number of voltage sags that can be expected as a function of the voltage sag magnitude and then comparing this with the equipment sensitivity.

The estimates of voltage sag performance are developed by performing short circuit simulations to determine the plant voltage as a function of fault location throughout the power system. Total circuit miles of line exposure that can affect the plant (area of vulnerability) are determined for a particular voltage sag level. Historical fault performance (faults per year per 100 miles) can then be used to estimate the number of sags per year that can be expected below that magnitude. Finally, a chart such as the one in Figure 6 can be constructed breaking down the expected voltage sags by magnitude and cause (voltage level of faulted line). This information can be used directly by the customer to determine the need for power conditioning equipment at sensitive loads in the plant.

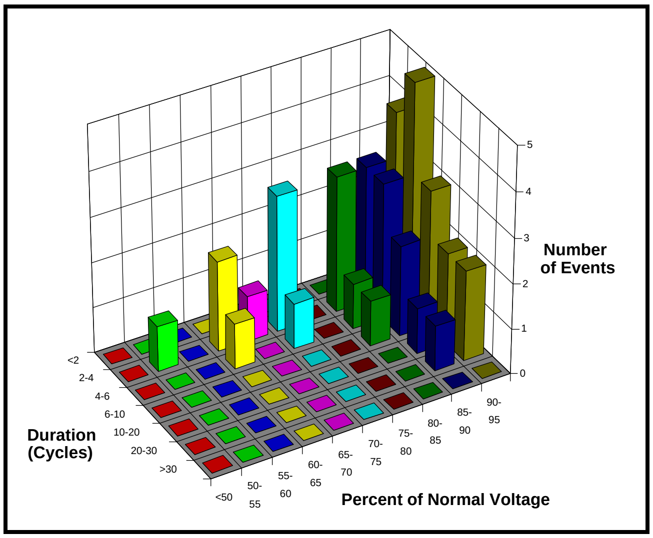

Figure 5. Voltage Sag Events
as a Function of Magnitude and Duration

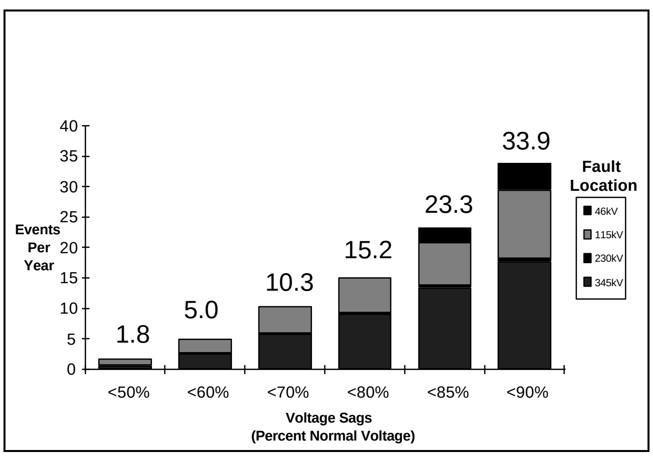

Figure 6. Estimated Voltage Sag Performance
at Customer Site as a Function of Faulted Line Voltage
and Voltage Sag Level

EXAMPLES OF EQUIPMENT SENSITIVITY

Determining equipment sensitivity can be the most difficult task when analyzing voltage sag concerns. The sensitivity of equipment presented here was determined as part of EPRI Power Quality Case Studies that dealt specifically with voltage sag problems.

Chiller Controls

Process controllers can be very sensitive to voltage sags. An electronic component manufacturer was experiencing problems with large chiller motors tripping off-line during voltage sag conditions. The chillers supply water to an entire chip manufacturing and testing facility. During extreme voltage sags, enough chillers may trip to affect manufacturing, causing large monetary losses.

A 120 V, 15 VA process controller which regulates water temperature was thought to be causing individual chillers to trip. This controller was tested using a voltage sag simulator for voltage sags from 0.5-1000 cycles in duration. The controller was found to be very sensitive to voltage sags, tripping at around 80% voltage, regardless of the duration. The results of this test is shown in Figure 7.

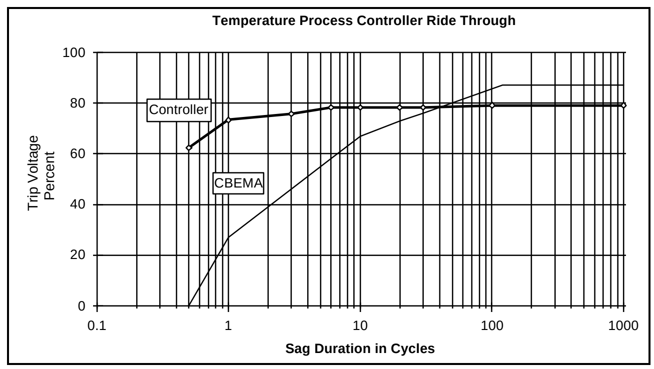

Figure 7. Process Controller Ride-Through Capability

Chip Testers

Electronic chip testers are very sensitive to voltage variations, and because of the complexity involved, often require 30 minutes or more to restart. In addition, the chips involved in the testing process can be damaged, and several days later, internal electronic circuit boards in the testers may fail. A chip tester consists of a collection of electronic loads, printers, computers, monitors, etc. If any one component of the total package goes down, the entire testing process is disrupted. The chip testers can be 50 kVA and larger in size.

There were 17 voltage sags causing a loss of load in IBM's sensitive tester room during the 12 months April 1, 1991 through March 31, 1992. The testers are located in a facility fed from a 13.2 kV distribution system. Of the 17 total events, 13 were on the 13.2 kV distribution system and 4 were on the 115 kV system. The sags ranged in magnitude from 14-100% below nominal. The testers typically dropped out if the voltage fell below 85% of nominal.

The following figure is a summary of all the disturbances recorded during that time period. As can be seen from the figure, most voltage sags recorded fell very close to the trip setting of the chip testers (80-85%) and are less than 100 cycles in duration.

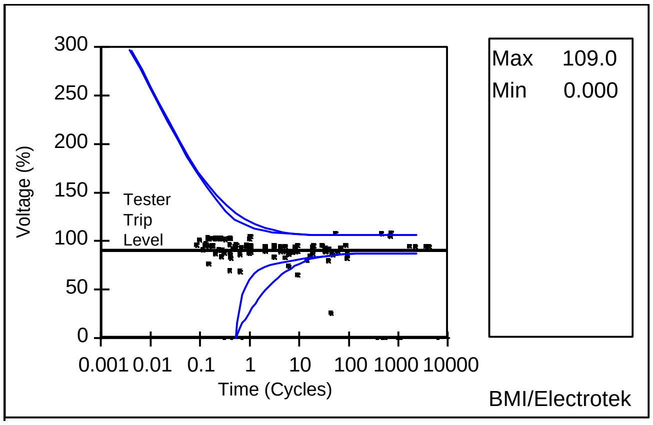

Figure 8. Summary of Voltage Sag Events at Chip Tester Location

DC Drives

DC drives are used in many industrial processes, including printing presses and plastics manufacturing. The plastics extrusion process is one of the common applications where voltage sags can be particularly important. The extruders melt and grind plastic pellets into liquid plastic. The liquid plastic may then be blown up into a bag or processed in some other way before a winder winds the plastic on to spools.

During a voltage sag, the controls to the dc drives and winders may trip. These extrusion operations are typically completely automated and an interruption can cause very expensive cleanups and restarting requirements. Losses can be on the order of $10,000 per event and a plant fed from a distribution system may experience 20-25 events per year.

From preliminary monitoring results, it has been determined that the extruders begin to have problems when the voltage sags to only 88% of nominal which indicates a very high level of sensitivity. Faults many miles away from the plant will cause voltage sags down to the 88% level.

Even protecting only the winders and controls does not help all the time. When the controls and winders are protected and a voltage sag occurs, the controls and winders continue to operate properly. However, the dc drives slow down. If the voltage sag is severe enough, the dc drives slow down too much, causing the bag to break, resulting in the same problem as before. Therefore, the dc drives also need to be protected to ride through all voltage sags.

The following figure is a disturbance measured at the plant that caused a number of the dc drives to trip. As can be seen from the figure, the event was less than a cycle. This illustrates the sensitivity of the equipment.

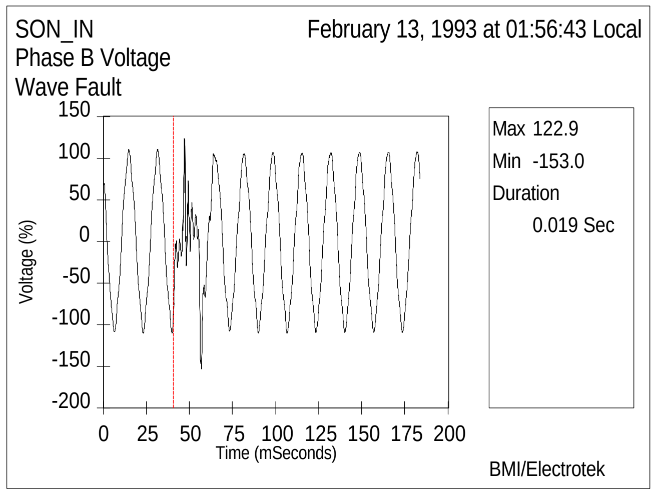

Figure 9. Measured Voltage Sag Disturbance Causing Extruders to Trip

Programmable Logic Controllers

This is an important category of equipment for industrial processes because the entire process is often under the control of these devices. The sensitivity to voltage sags varies greatly but portions of an overall PLC system have been found to be very sensitive. The remote I/O units, for instance, have been found to trip for voltages as high as 90% for a few cycles. The following figure shows the results of voltage sag ride through testing on two different programmable logic controllers. The figure shows the difference between an old and new version of the same PLC. The newer, Type 1 controller is sensitive at 50-60% of nominal voltage, while the older, Type 2 PLC could ride through zero voltage for 15 cycles. This illustrates how electronic equipment is becoming more sensitive to voltage variations.

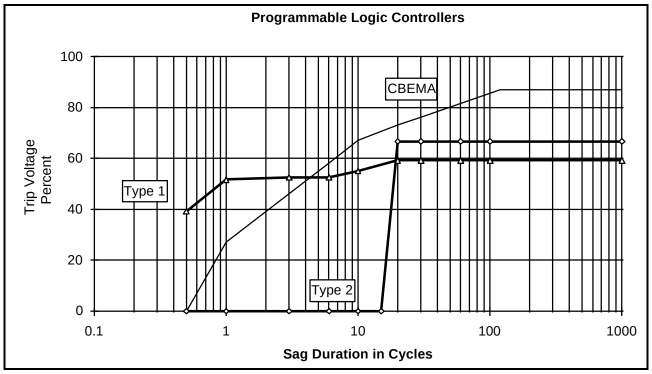

Figure 10. Programmable Logic Controller Ride Through Capability

Machine Tools

Machine tools can be very sensitive to voltage variations. Often, robots or complicated machines are used in the cutting, drilling, and metal processing that is required when specialized parts are produced. Any variation in voltage can affect the quality of the part that is being machined.

Another reason machine tools are sensitive to voltage variations is for safety reasons. Robots generally need very constant voltage to operate properly and safely. Any voltage fluctuations, especially sags, may cause unsafe operation of the robot or machine. Therefore, these types of machines are often set to trip at voltage levels of only 90%.

SOLUTIONS TO VOLTAGE SAG PROBLEMS

Several things can be done by both the utility and customer to reduce the number and severity of voltage sags and to reduce the sensitivity of equipment to voltage sags.

Utility Solutions

Utilities derive important benefits from activities that prevent faults. These activities not only result in improved customer satisfaction, but prevent costly damage to power system equipment. Utilities have two basic options to continue to reduce the number and severity of faults on their system:

1. Prevent faults
2. Modify fault clearing practices

Fault prevention activities include tree trimming, adding line arresters, insulator washing, and adding animal guards. Insulation on any transmission system cannot withstand the most severe lightning strokes, but any line that shows a trend toward lightning-induced faults is usually investigated. Tower footing resistance is an important factor in back flashovers from static wire to a phase wire. If the tower footing resistance is high, the surge energy from a lightning stroke will not be absorbed by the ground as quickly. Tower footing resistances should be as low as possible especially in high lightning areas.

Improved fault clearing practices may include adding 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 but utility faults can never be eliminated completely.

Customer Solutions

Customer solutions usually involve power conditioning for sensitive loads. Proper application of power conditioning equipment requires an understanding of the capabilities of the device. Also important is a definition of the requirements of sensitive or critical loads. The figure below is a schematic of the general approach used. Power conditioning equipment is used to isolate equipment from high frequency noise and transient power disturbances, or to provide voltage sag ride through capability, or both.

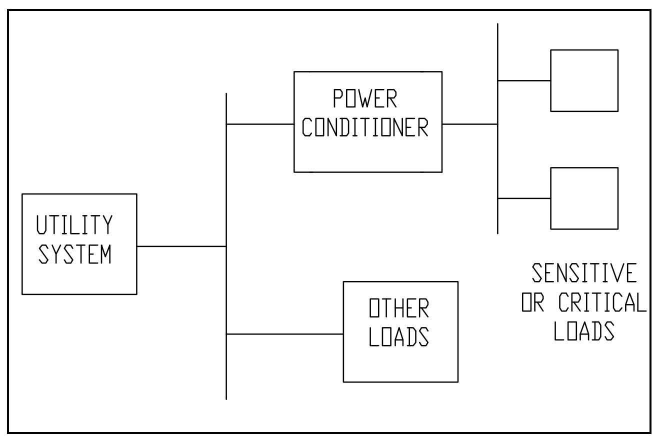

Figure 11. General Approach for the Application of Power Conditioning Equipment

There are several solutions currently available that will provide ride through capability to critical loads.

- Motor-Generator Sets (M-G Sets)
- Uninterruptible Power Supplies (UPSs)
- Ferroresonant, Constant Voltage Transformers (CVTs)
- Magnetic Synthesizers

- Superconducting Storage Devices (SSDs)

M-G Sets usually utilize flywheels for energy storage. They completely decouple the load from the electric power system. Rotational energy in the flywheel provides voltage regulation and voltage support during undervoltage conditions. M-G sets have relatively high efficiency and low initial capital cost.

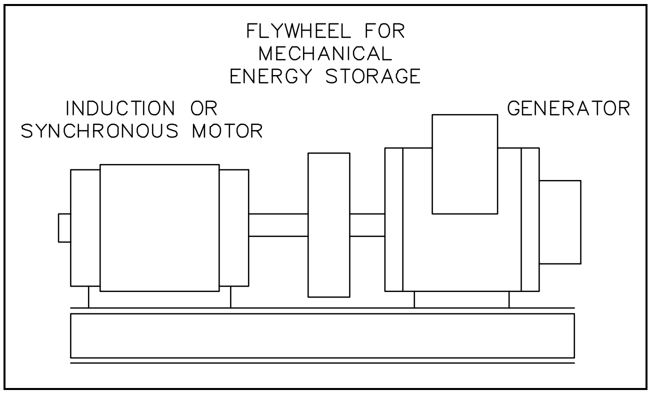

Figure 12. Motor-Generator Set

UPSs utilize batteries to store energy that is converted to a usable form during an outage or voltage sag. UPS technology is well established and there are many different UPS configurations to choose from.

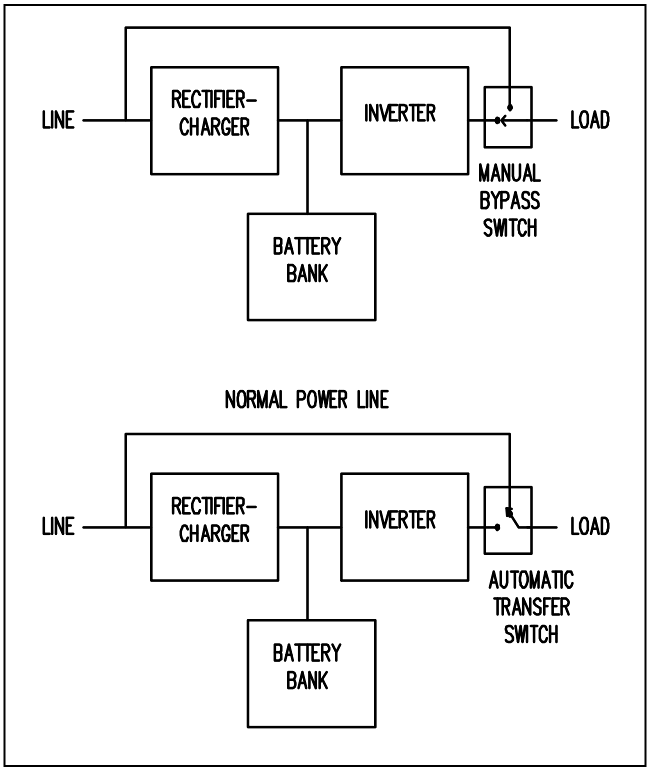

Figure 13. UPS Configurations

CVTs can be used to improve voltage sag ride through capability. CVTs are especially attractive for constant, low power loads. Variable loads, especially with high inrush currents, present more of a problem for CVTs because of the tuned circuit on the output. CVTs are basically 1:1 transformers which are excited high on their saturation curves, thereby providing output voltage which is not significantly affected by input voltage variations.

The following figure shows the voltage sag ride through improvement of a process controller fed from a 120 VA CVT.

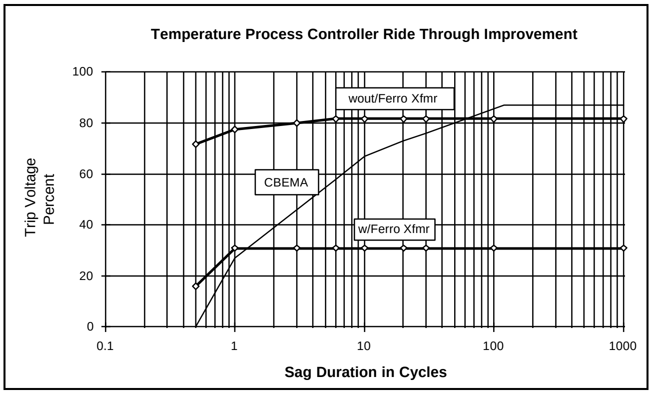

Figure 14. Voltage Sag Improvement with CVT

Magnetic Synthesizers are generally used for larger loads. A load of at least several kVA is needed to make these units cost effective. They are often used to protect large computers and other sensitive electronic equipment.

The magnetic synthesizer is an electromagnetic device which takes incoming power and regenerates a clean, three-phase ac output waveform, regardless of input power quality. A block diagram of the process is shown in the figure below.

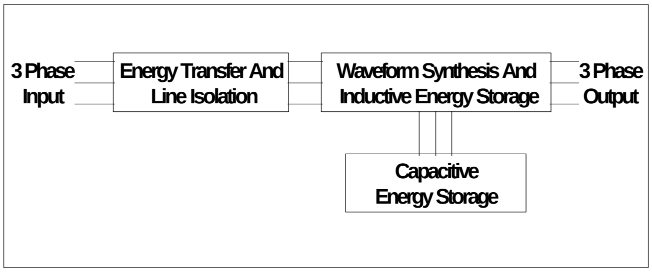

Figure 15. Block Diagram of Magnetic Synthesizer

The following figure shows a magnetic synthesizer's voltage sag ride through capability as compared to the CBEMA curve, as specified by one manufacturer.

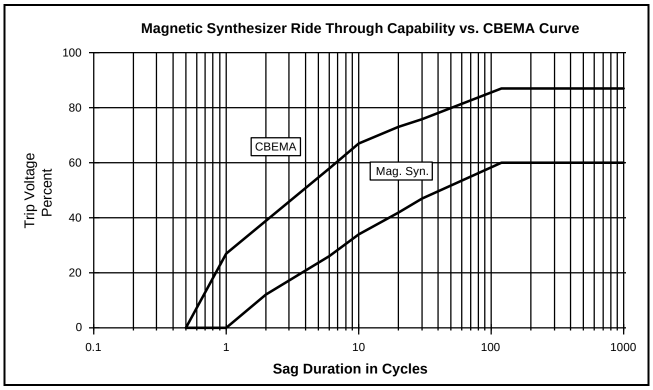

Figure 16. Magnetic Synthesizer Voltage Sag Ride Through Capability

SSDs utilize a superconducting magnet (Figure 17) to store energy in the same way a UPS uses batteries to store energy. The main advantage of the SSD is the greatly reduced physical space needed for the magnet as compared to batteries. There are also a lot less electrical connections involved with SSDs as compared to UPSs so the reliability should be greater and the maintenance requirements less. Initial SSD designs are currently being tested in several locations with favorable results. The projected future costs of an SSD should be competitive with UPSs.

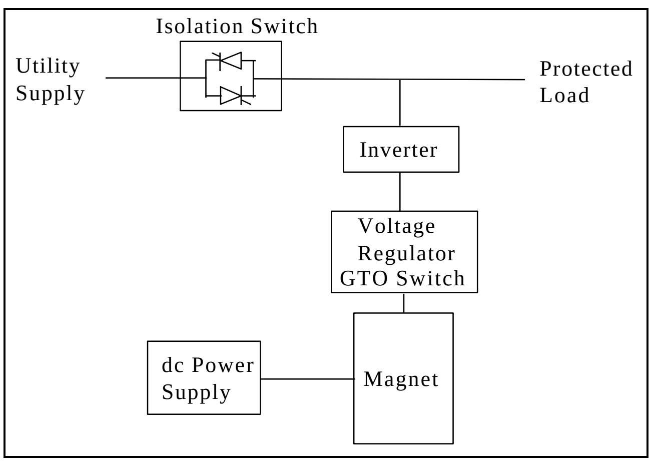

Figure 17. SSD One-Line

SUMMARY/CONCLUSIONS

Voltage sags are one of the most important power quality problems affecting industrial and commercial customers. Industrial processes are particularly sensitive to relatively minor voltage sags.

Utilities can improve system fault performance but it is not possible to completely eliminate faults on the system. Therefore, customers will have improve the ride through capability of the sensitive equipment in their facilities. This can be accomplished with power conditioning or in the equipment itself.

Power conditioning to improve voltage sag ride through can be very expensive. Solutions often require protection of virtually the entire process. Very large UPS systems or newer superconducting storage devices must be used in these cases.

It will be much more economical in the long term to improve the voltage sag ride through capability of the actual process equipment. Adjustable speed drives are a good example. Some manufacturers now have the capability to resynchronize the ASD output into a spinning motor. This allows use of the motors inertia to ride through most voltage sag events.

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