EFFECTS OF VOLTAGE SAGS IN PROCESS INDUSTRY APPLICATIONS

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Abstract This paper describes the causes of voltage sags in affecting process industries, their impacts on equipment operation, and possible solutions. The definition proposed focuses on system faults as the major cause of voltage sags. The sensitivity of different types of process industry equipment; including adjustable speed drive controls, programmable logic controllers, and motor contactors; is analyzed. Available methods of power conditioning for this sensitive equipment are described.

INTRODUCTION

A voltage sag is a momentary (i.e. 0.5-60 cycles) decrease in the rms voltage magnitude [1,2], usually caused by a remote fault somewhere on the power system (Figure 1). Voltage sags are the most important power quality problem facing many process industry customers. Equipment used in modern industrial plants (process controllers, programmable logic controllers, adjustable speed drives, robotics) is actually becoming more sensitive to voltage sags as the complexity of the equipment increases and the equipment is interconnected in sophisticated processes. Even relays and contactors in motor starters can be sensitive to voltage sags, resulting in shut down of a process when they drop out.

It is important to understand the difference between an interruption (complete loss of voltage) and a voltage sag. Interruptions occur when a protective device actually interrupts the circuit serving a particular customer. This will normally only occur if there is a fault on that circuit. Voltage sags occur during the period of a fault for faults over a wide part of the power system. Faults on parallel feeder circuits or on the transmission system will cause voltage sags but will not result in actual interruptions. Therefore, voltage sags are much more frequent than interruptions. If equipment is sensitive to these voltage sags, the frequency of problems will be much greater than if the equipment was only sensitive to interruptions.

This paper describes the voltage sag characteristics and the sensitivity of equipment. With this information, the range of fault locations on the power system that can cause problems can be estimated (area of vulnerability). Options for improving equipment performance in the presence of voltage sags include power conditioning or equipment design modifications. Both of these options are described.

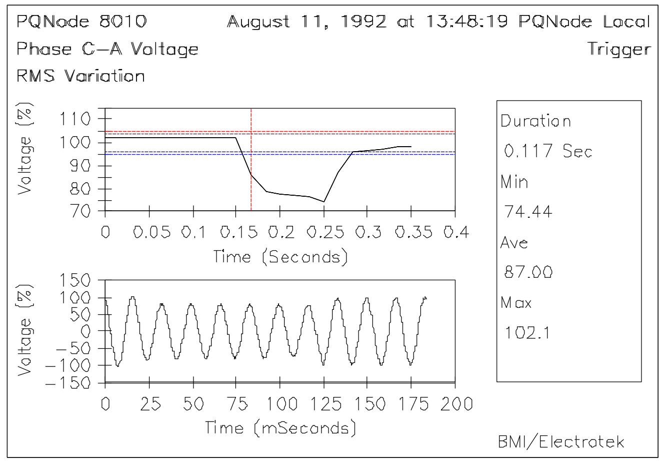


Figure 1. Voltage sag waveform caused by a remote fault condition (7 cycles)

CAUSES OF VOLTAGE SAGS

Voltage sags are typically caused by fault conditions. Motor starting can also result in undervoltages, but these are typically longer in duration than 60 cycles and the associated voltage magnitudes are not as low. Motor starting voltage variations are often referred to as "voltage flicker", especially if the motor starting can occur frequently.

Faults resulting in voltage sags can occur within the plant or on the utility system. The voltage sag condition lasts until the fault is cleared by a protective device. In the plant, this will typically be a fuse or a plant feeder breaker. On the utility system, the fault could be cleared by a branch fuse or a substation breaker. If reclosing is used by the utility, the voltage sag condition can occur multiple times, with varying durations (Figure 3). Also, faults on the distribution system can result in voltage sags that are difficult to characterize with simple magnitude/duration information because the fault characteristics change with time (Figure 4).

Figure 2. Typical distribution system one line diagram illustrating types of protection devices.

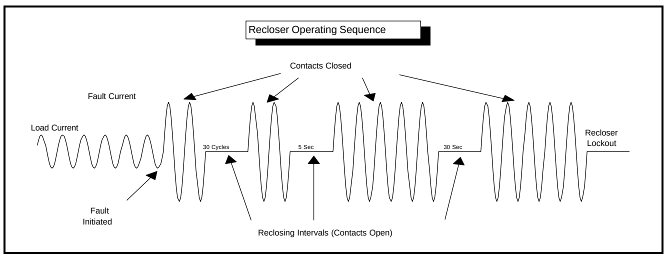


Figure 3. Typical recloser operating sequence.

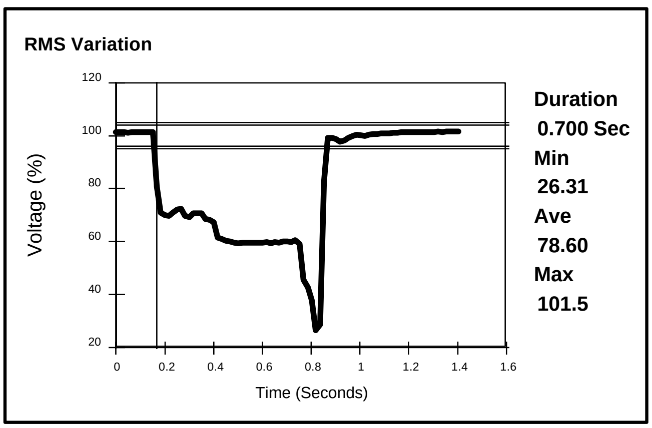


Figure 4. Example of voltage sag caused by a distribution system fault.

Faults on the transmission system can affect even more customers. Customers hundreds of miles from the fault location can still experience a voltage sag resulting in equipment misoperation when the fault is on the transmission system.

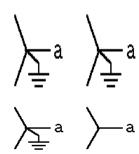
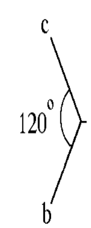
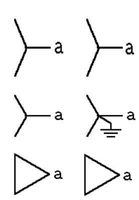
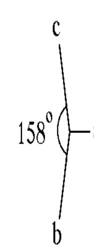
The large majority of faults on a utility system are single line-to-ground faults (SLGF). Three phase faults are more severe, but much less common. SLGFs often result from weather conditions such as lightning, wind, and ice. Contamination of insulators, animal contact, and accidents involving construction or transportation activities also cause faults. Although utilities go to great lengths to prevent faults on the system, they cannot be eliminated completely. Usually, these faults are temporary, which means that they will not reinitiate after they have been cleared and the line is reclosed. Since faults (and, therefore, voltage sags) are inevitable, it is important for customers to make sure that critical equipment sensitive to voltage sags is adequately protected.

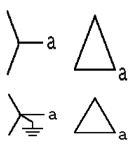
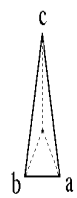
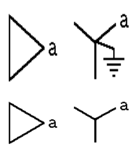
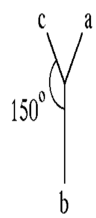
PLANT VOLTAGE DURING SINGLE LINE-TO-GROUND FAULTS ON THE UTILITY SYSTEM

Single line-to-ground faults (SLGFs) on the utility system are the most common cause of voltage sags in an industrial plant. The voltage on the faulted phase goes to zero at the fault location. The voltage at the substation and on parallel feeders will depend on the distance of the fault from the substation. On transmission systems, the faulted phase voltage at a remote location depends on the overall network impedances.

The important quantities for equipment sensitivity are the voltages at the customer bus. These voltages will depend on the transformer connections between the faulted system and the customer bus. For a distribution system fault, the worst case occurs when the fault is close to the substation bus. Effectively, this is the same as a fault near the customer transformer primary. The voltages on the customer bus will then be a function of the customer transformer connections, as indicated in Table 1.

Table 1. Transformer secondary voltages with a SLGF on the primary.

Transformer Connection	Phase to Phase V_{ab}	V_{bc}	V_{ca}	Phase to Neutral V_{an}	V_{bn}	V_{cn}	Phasor Diagram
	0.58	1.00	0.58	0.00	1.00	1.00	
	0.58	1.00	0.58	0.33	0.88	0.88	

	0.33 0.88 0.88	---- ---- ----	
	0.88 0.88 0.33	0.58 1.00 0.58	

The relationships in Table 1 are very important. One might think that a SLGF on the primary of a wye grounded/delta transformer could result in zero voltage across one of the secondary windings. Instead, circulating fault current in the delta secondary windings results in a voltage on each winding. The magnitude of the lowest secondary voltage depends upon the relationship:

$$\alpha = \frac{X_T}{X_T + X_S}$$
$$0 < \alpha < 1$$

where: X_T - Transformer short circuit reactance
X_S - Source equivalent reactance

For industrial power distribution, the ratio α will usually be very close to unity and the relationships in Table 1 are for this case.

Even with a SLGF on the primary of the transformer, the voltage sag at the customer bus will be no lower than 33% normal value. These faults account for the great majority of faults on the power system.

SENSITIVITY OF EQUIPMENT TO VOLTAGE SAGS

Process industry equipment can be particularly susceptible to problems with voltage sags because the equipment is interconnected and a trip of any component in the process can cause the whole plant to shut down. Examples of these industries include plastics, petrochemicals, textiles, paper, semiconductor, and rubber). Important loads that can be impacted include the following:

- Motors, heating elements, and other 3-phase loads can be connected directly to the LV bus.
- Adjustable speed drive and other power electronic devices that use 3-phase power will be connected directly to the LV bus, or through an isolation transformer.
- Lighting often utilizes single-phase connections from phase-to-neutral.
- Control devices such as computers, contactors, and programmable logic controllers are often supplied through a single phase control transformer.

The voltages experienced during a voltage sag condition will depend on the equipment connection. Table 1 showed that the individual phase voltages and phase-to-phase voltages are quite different during a SLGF condition on the transformer primary. Some single phase loads will be unaffected and other single phase loads may drop out, even though their sensitivities to voltage sags may be identical

Voltage unbalance is also a concern for motor heating. However, the durations of the unbalanced voltages during fault conditions are so short that motor heating is not a significant concern. Adjustable speed drives, however, may have controls that trip very quickly during unbalanced conditions.

Different categories of equipment and even different brands of equipment within a category (e.g. two different models of adjustable speed drives) have significantly different sensitivities to voltage sags. This makes it difficult to develop a single standard that defines the sensitivity of industrial process equipment.

The closest document to a standard is the CBEMA curve given in Figure 5, which was developed by the Computer Business Manufacturers Association [3]. This applies primarily to data processing equipment. The curve shows that the load sensitivity is very dependent on the duration of the sag. Allowable sags range from 0% voltage for 1/2 cycle to only 87% voltage for 30 cycles.

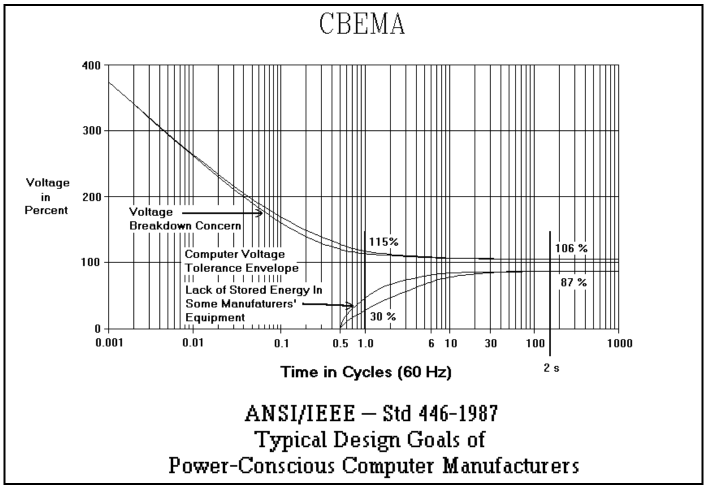


Figure 5. CBEMA operating voltage envelope.

While the CBEMA limits suggest a "standard" sensitivity to voltage sags, actual plant equipment has a variety of operational characteristics during voltage sags. A few examples are listed here.

<u>Motor Contactors and Electromechanical Relays</u>
One manufacturer has provided data that indicates their line of motor contactors will drop out at 50% voltage if the condition lasts for longer than one cycle. This data should be expected to vary among manufacturers, and some contactors can drop out at 70% normal voltage or even higher.[4]

<u>High-Intensity Discharge (HID) Lamps</u>
Mercury lamps are extinguished at around 80% normal voltage and require time to restrike [5]. A voltage sag that extinguishes HID lighting is often mistaken as a longer outage by plant personnel.

<u>Adjustable Speed Motor Drives (ASDs)</u>
Some drives are designed to ride through voltage sags. The ride through time can be anywhere from 0.05 sec to 0.5 sec, obviously depending on the manufacturer and model. Some models of one manufacturer monitor the ac line and trip after a voltage sag to 90% of normal voltage is detected for 50 ms.

<u>Programmable Logic Controllers (PLC's)</u>
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 [8].

The sensitivity range for these types of equipment is shown in Figure 6 with the durations of fault induced voltage sags also indicated. The wide range of sensitivities underlines the importance of working with the manufacturer to make sure the equipment can work in the environment where it will be used and to develop specifications based on realistic power system conditions.

It is important to recognize that the entire process in an industrial plant can depend on the sensitivity of a single piece of equipment. The overall process involves controls, drives, motor contactors, robotics, etc. that are all integral to the plant operation. This can also make it difficult to identify the sensitive piece of equipment after the entire process shuts down.

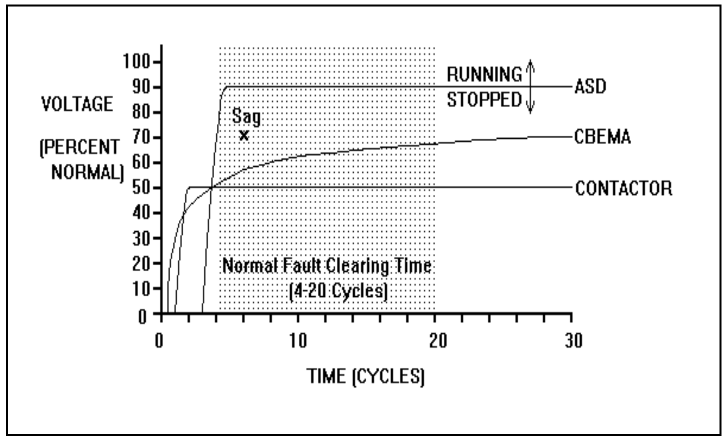


Figure 6. Range of equipment sensitivity to voltage sags.

ESTIMATING THE PROBABILITY OF A VOLTAGE SAG PROBLEM

Voltage sags and momentary interruptions are caused by faults on the power system. Therefore, determining voltage sag performance characteristics involves calculation of fault performance characteristics for the power system supplying a particular customer of interest. Faults over a wide area of the power system can affect the operation of a facility that has sensitive equipment. Faults can occur on the transmission system or on the distribution system. For most facilities, both cases need to be evaluated to estimate the overall performance expected. Figure 7 illustrates the breakdown of events that caused equipment disruption for one process industry customer.

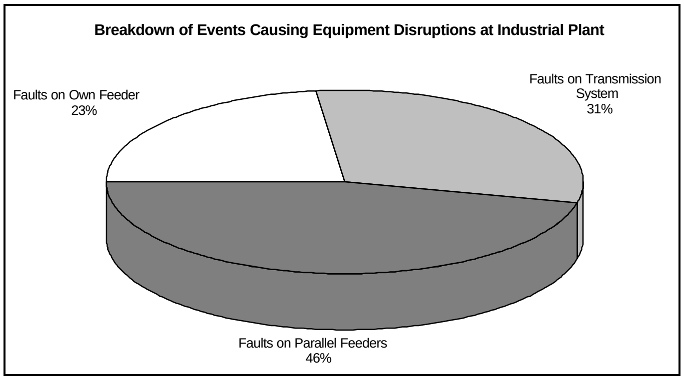


Figure 7. Breakdown of utility fault events that caused equipment disruption at a MV customer.

For facilities that are supplied directly from the transmission level, only transmission faults usually need to be considered.

The first task is estimating the expected voltage sag and momentary interruption performance. This analysis will result in information that describes the expected number of voltage sags per month where the voltage goes below a specified threshold. Then this performance is compared to equipment to determine the expected performance of the process or the overall facility. Finally, methods for improving the performance can be evaluated at the different levels of the system. The overall flow chart for the evaluation is given in Figure 8.

Transmission System Performance Evaluation

This evaluation must be performed, regardless of the end user facility location. For facilities supplied from MV systems, the performance of the transmission system determines the expected number of voltage sags and interruptions due to transmission faults. This is measured as the voltage at the supplying substation.

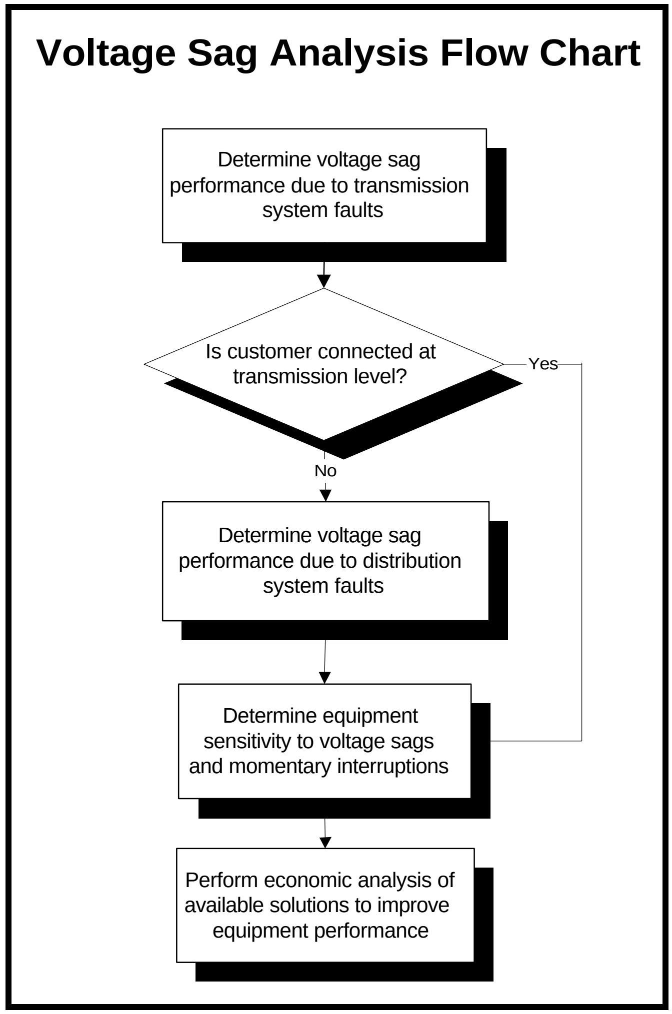


Figure 8. Voltage sag evaluation procedure.

A standardized procedure can be used to calculate expected performance. The result of the calculation is the expected voltage sag performance at a selected bus on the system.

1. Build and maintain a transmission line data table for reference. This table will include the historical performance information and expected performance for each line section in terms of number of faults expected per year for at least single line-to-ground and three phase faults.

2. Perform short circuit analyses to determine the **Area of Vulnerability** for different voltage sag severities. This gives the total circuit miles where a fault will result in a voltage sag below a specified threshold. This analysis must be performed for at least single line-to-ground and three phase fault conditions.

3. Convert the area of vulnerability data to actual expected events per month at the specified location. This is done using the area of exposure and the expected

performance for three phase and single line-to-ground faults over that area.

The *momentary interruption performance* for an end user due to transmission system faults should be calculated if the customer is supplied as a tap from a switched transmission line. In this case, the expected number of momentary interruptions per year due to transmission events is the expected number of faults on that line. This should be calculated separately from the voltage sag performance.

4. Perform the above calculations for different voltage sag severities and for momentary interruptions. The results can be presented as a histogram for use by the end use facility (Figure 9).

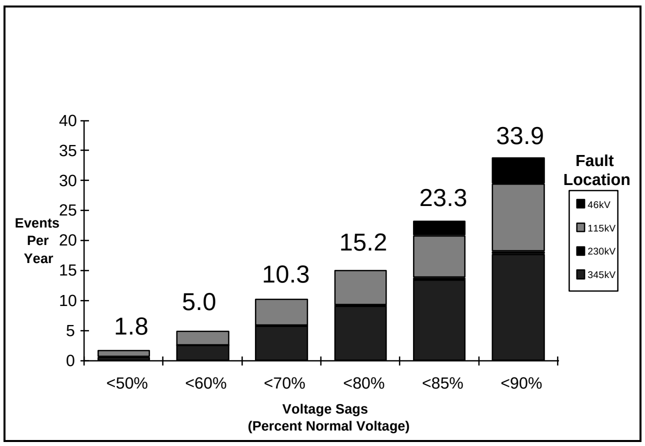


Figure 9. Example of expected voltage sag performance at a customer site due to transmission system faults.

Distribution System Performance Evaluation

For end users that are supplied from the distribution system, the voltage sag and momentary interruption performance due to distribution system events must be calculated in a similar manner. Faults on parallel feeders and fused branches will result in voltage sags while faults on the same part of the feeder as the end user will result in at least momentary interruptions. The total performance at the customer is a combination of the performance due to transmission events and the performance due to distribution events.

EVALUATING SOLUTIONS FOR VOLTAGE SAG PROBLEMS

The interruption of an industrial process due to a voltage sag can result in very substantial costs to the operation. These costs include lost productivity, labor costs for clean-up and restart, damaged product, reduced product quality, delays in delivery, and reduced customer satisfaction.

Proper evaluation of alternatives to improve plant equipment and the power distribution network requires a cost vs. benefit comparison. For example, once the costs of retrofitting sensitive process equipment with some method of improving voltage sag ride through are determined, the benefits of recovering lost production, material, product quality, and customer responsiveness must be determined. Experience by the industrial plant will provide data on production losses for a given occurrence following a voltage sag. There may even be a record of the number of disruptions due to voltage sags in the past calendar months or years. If the necessary data exists, the cost of implementing a solution can be evaluated against the expected cash flow of recovered production losses.

Solutions can be implemented at different levels of the system for an end user that has equipment or a process that is sensitive to voltage sags and momentary interruptions. For instance, the individual sensitive equipment can be protected with power conditioning with ride through support, a whole portion of the facility could be protected, or measures could be implemented on the utility system to improve performance. The individual solutions must be identified and a system perspective used to evaluate the economics. The most economic alternative usually involves protection closest to the sensitive equipment or within the design of the equipment itself (Figure 10).

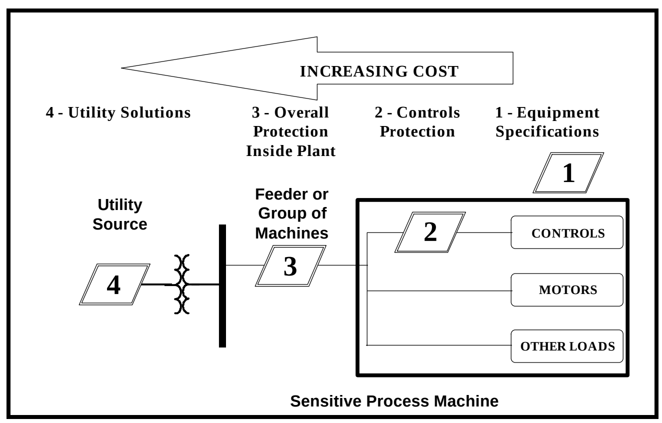


Figure 10. Economics of voltage sag ride through support at different levels of the system.

In the long run, the best solution to voltage sag problems will be to purchase equipment that has the necessary ride through capability. As manufacturers become increasingly aware of the need for this capability, it will become more and more standard in industrial process equipment. Even now, manufacturers offer new models or simple modifications that permit extended ride through capability.

Until equipment can handle voltage sags directly, it will often be necessary to apply power conditioning equipment for particular sensitive loads. Most voltage sag conditions can be handled by ferroresonant, or constant voltage, transformers (CVTs). CVTs are especially attractive for loads with relatively low power requirements and loads which are constant. Variable loads are more of a problem for CVTs because of the tuned circuit on the output.

These power conditioners work similar to a transformer being excited high on its saturation curve, so that the output voltage is not significantly affected by input voltage variations. The actual design and construction is more complicated. A typical ferroresonant circuit is shown in Figure 11.

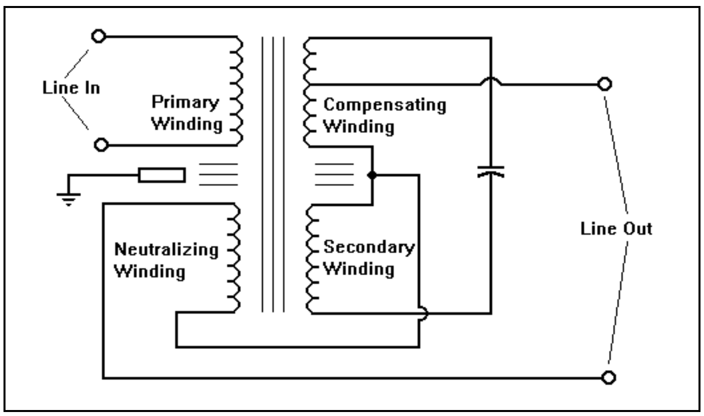


Figure 11. Typical circuit for a ferroresonant transformer.

Ferroresonant transformers output over 90% normal voltage as long as the input voltage is above a minimum value, at which the output collapses to zero voltage. Voltage support during voltage sags can be very good if the CVT is oversized for the load. Figure 12 illustrates the sensitivity of a chiller control with and without an oversized CVT for protection. With ride through down to almost 30% of normal voltage, the chiller should never trip due to remote single line-to-ground faults on the power system.

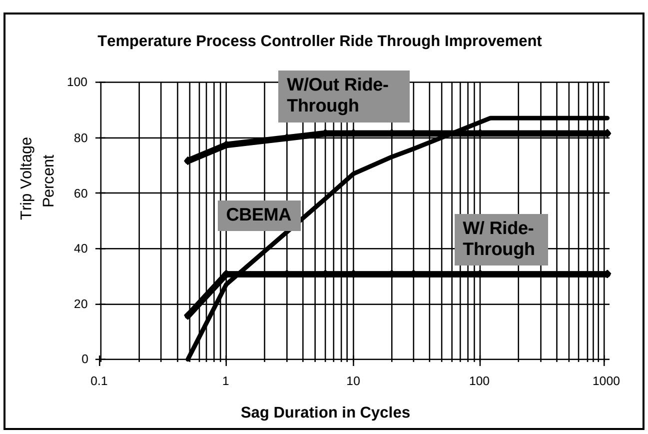


Figure 11. Voltage sag ride through for a process controller with and without a CVT.

CVTs will handle the majority of voltage sag conditions. If voltage sags which are too severe for CVTs or if the loads are too large for protection with CVTs, some type of energy storage technology will have to be used for ride through support. Protection for extremely critical loads, such as life safety systems and critical data processing equipment, should include UPS systems or the equivalent for complete backup capability. New energy storage technologies that can provide short duration backup for large portions of a facility are now becoming available. These include superconducting magnetic energy storage [10], flywheels, and advanced battery systems.

CONCLUSIONS

1. Voltage sags are becoming an increasing concern for process industries due to increasing automation. Automated facilities are more difficult to restart, and the electronic controllers used are sometimes more sensitive to voltage sags than other loads.

2. Single-line-to-ground faults on the utility distribution or transmission system are often the cause of voltage sags. Lightning is a frequent cause. Evaluation of the fault performance of transmission and distribution lines can be used to predict the voltage sag performance at a customer facility.

3. A single-line-to-ground fault on the primary side of a distribution transformer will result in a voltage sag to no lower than 33% of normal voltage on any phase-to-phase connection.

4. The sensitivity of industrial equipment to voltage sags varies greatly. The more sensitive equipment widens a plant's area of vulnerability to disruptive voltage sags.

5. Constant Voltage Transformers can be applied economically at constant loads to handle the great majority of voltage sag conditions. If needed, increased protection for voltage sags or actual interruptions can be provided in the form of UPS systems or other energy storage technologies.

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