The Impact of Voltage Sags on Industrial Plant Loads

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Customer PQ Concerns
CVT/Ferroresonant Transformer
Lightning Fault
Other Faults
Sag/Swell
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Introduction
This paper describes voltage sag characteristics, the sensitivity of equipment to voltage sags, and possible measures to make equipment less sensitive. Test results are presented showing the voltage sag ride through capability of typical industrial plant loads. Characteristics and limitations of ferroresonant transformers to enhance voltage sag ride through capability are also presented. A discussion of important equipment specification considerations is included.

The ability of modern industrial plant equipment to ride through voltage sags is becoming more and more important. As plant operations and processes become more automated, the need to keep this equipment operating is readily apparent. Any down time can be directly correlated to lost revenue and profits. The equipment used in industrial plants, such as process controllers, programmable logic controllers, relays, and contactors, is becoming more and more complex and can be more sensitive to voltage sags than earlier equipment.

For purposes of this paper, a voltage sag is defined as a decrease in the rms voltage magnitude that lasts between 1/2 and 30 cycles. Figure 1 shows a measured 6 cycle voltage sag. This paper describes the characteristics and causes of voltage sags. Using a disturbance simulator, the ride through capability of several different 120 V loads was investigated and compared to manufacturer's data.

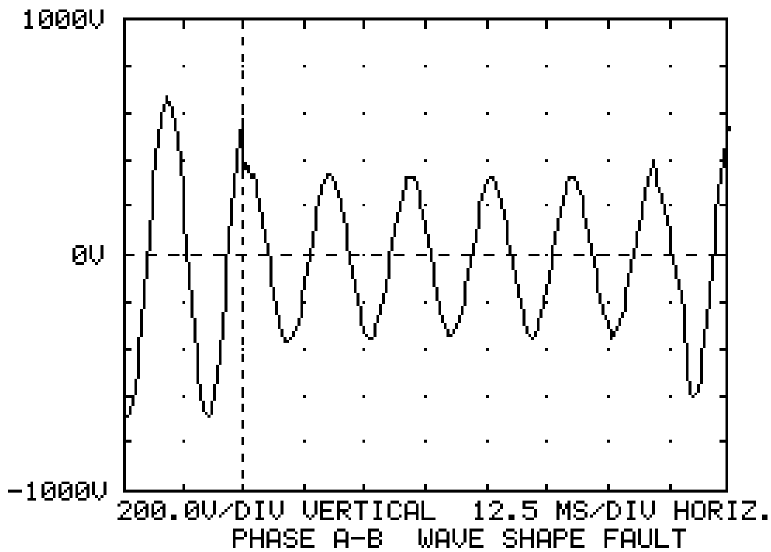

Figure 1: Measured Voltage Sag Waveform

One method of improving ride through capability is with ferroresonant transformers. The sensitive equipment was tested when powered through two different ferroresonant transformers. The characteristics and limitations of the ferroresonant transformers were also tested and documented.

Another method of improving ride through capability is through the use of equipment procurement specifications. Only equipment with acceptable ride through characteristics would then be used in the plant.

Causes and Characteristics of Voltage Sags

Voltage sags are different than interruptions in that voltage sags are momentary reductions in voltage, while an interruption is a complete loss of voltage. Most voltage sags are caused by fault conditions on the power system. Faults can be caused by lighting, tree limbs contacting a phase wire, animal contact, accidents, or any other action which results in large amounts of current flowing through the system source impedance. Voltage sags can also be caused by motor starting, but these are typically longer in duration (> 30 cycles) and are often referred to as short term undervoltage.

Figure 2 is an example of a typical distribution system which will be used to explain how voltage sags occur. The feeders are all supplied from a common bus. A fault on feeder F1 will cause an interruption on that feeder because the substation recloser on F1 will open to allow the fault to clear. However, all the customers on the other three parallel feeders will experience a voltage sag while the fault is on the system. Therefore, voltage sags are much more frequent than interruptions because customers a great distance from the fault location can still experience a voltage sag. The substation reclosing breaker can cause as many as four voltage sags in succession on the parallel feeders. The voltage sags can last anywhere from a couple cycles to more than ten cycles. A typical reclosing sequence is shown in Figure 3 and a customer voltage profile resulting from two reclosing operations on a parallel feeder is shown in Figure 4.

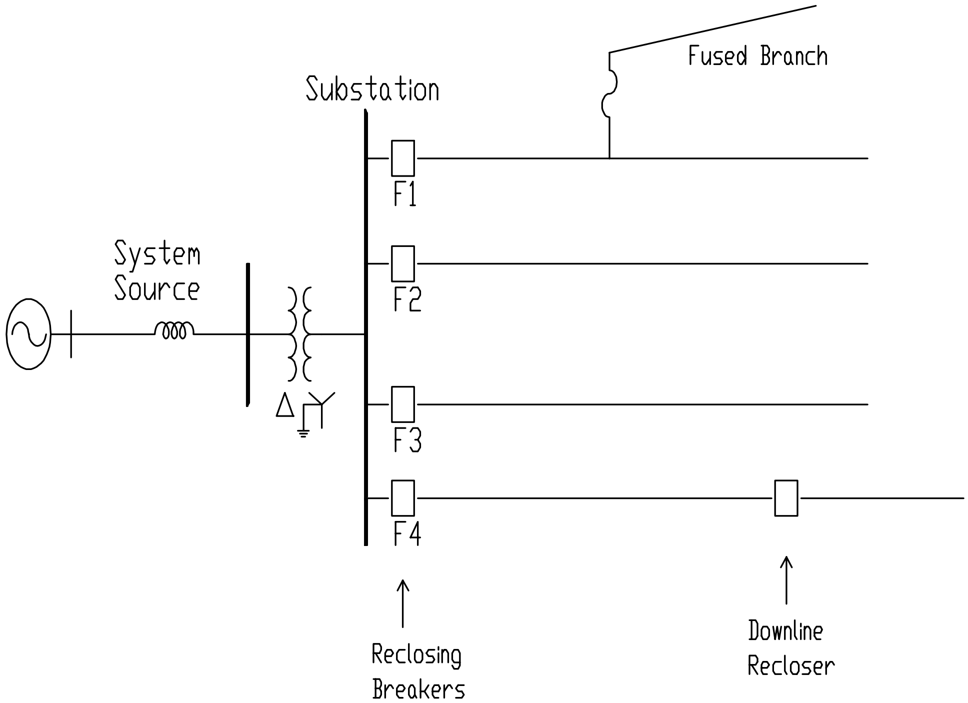

Figure 2: Typical Distribution System

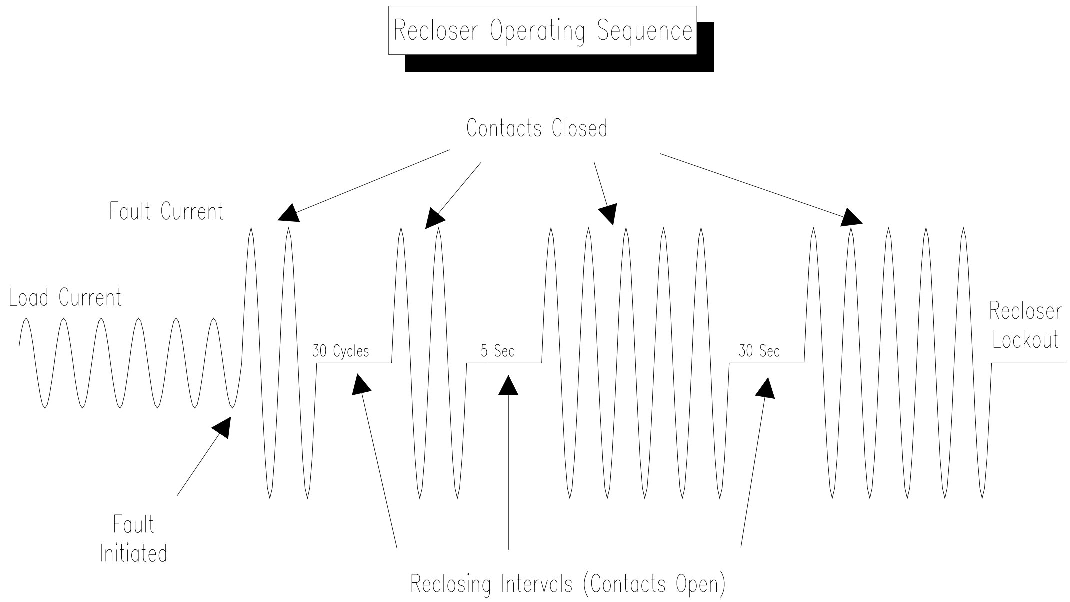

Figure 3: Typical Recloser Operating Sequence

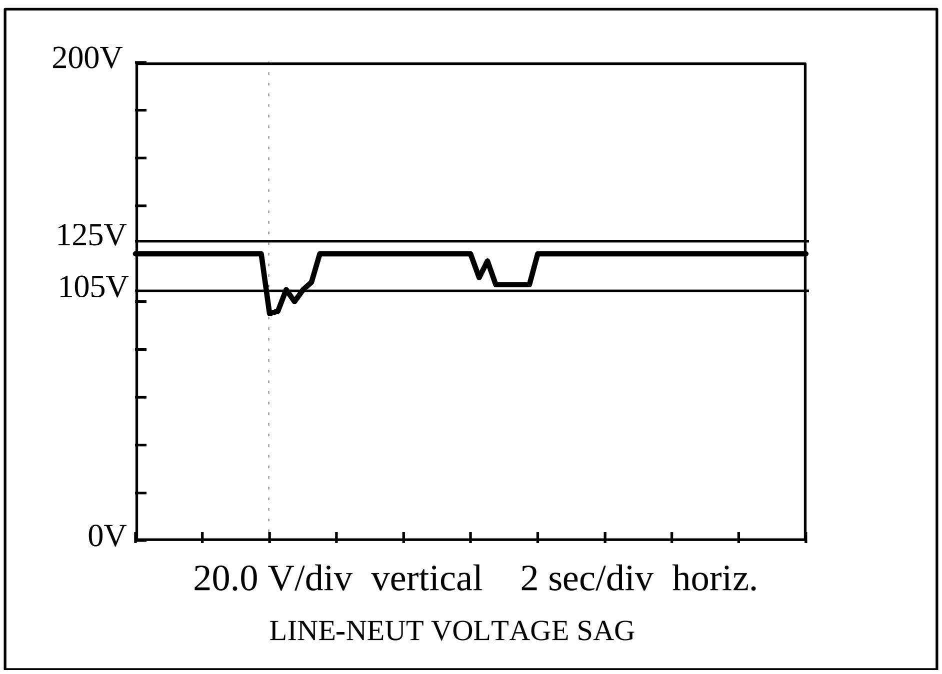

Figure 4: Voltage Sag at Customer Location with Two Recloser Operations

Fault Type and Location:
The type of fault and location on the feeder relative to the customer have an important impact on the severity of the voltage sag at the customer bus. Three-phase faults result in much more severe voltage sags than single-line-to-ground faults, but occur very infrequently. The large majority of faults on a utility system are single-line-to-ground faults. Figure 5 illustrates the difference in voltage sag severity for three-phase and single-line-to-ground faults. Faults were applied along feeder F1 of the typical distribution system shown in Figure 2, and the resulting lowest phase-to-phase percent voltage at the customer bus (service entrance) was obtained for a customer located near the substation on feeder F4. Notice how the voltage sag severity is reduced as the fault location is moved out along feeder F1.

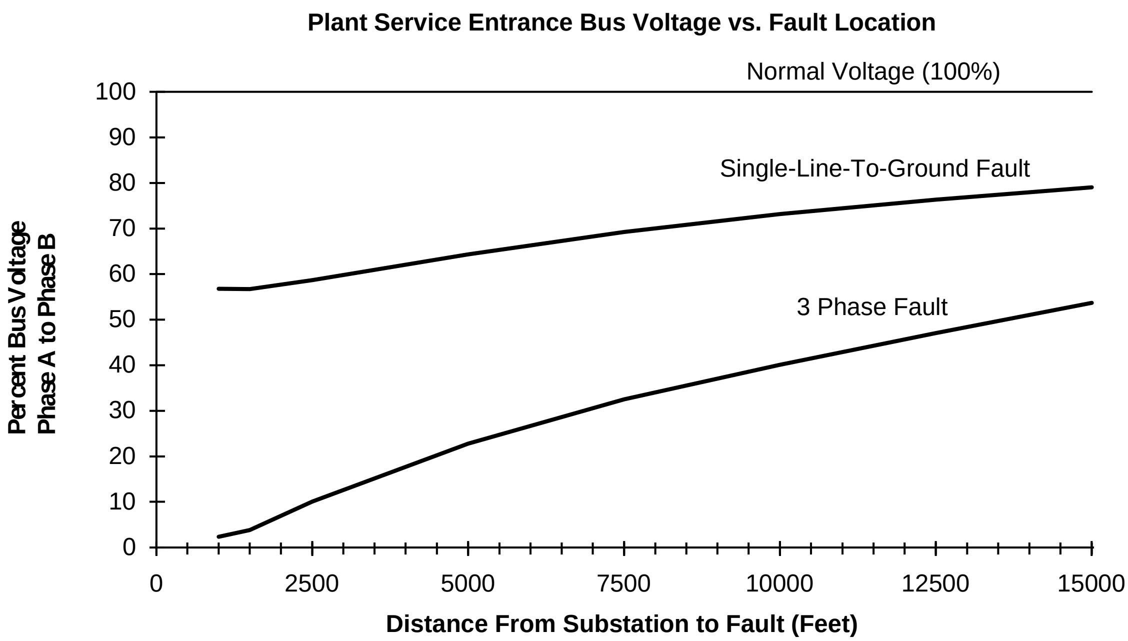

Figure 5: Voltage Sag Severity vs. Fault Location and Type

Customer Stepdown Transformer Connections:
The important quantities for equipment sensitivity are the voltages in the customer plant. The 120 V equipment tested is normally connected through 480 to 120 V control power transformers as shown in Figure 6. Therefore, since the control power transformer is connected line-to-line across two phases, the 120 V supply will see the same magnitude voltage sag as its phase-to-phase supply.

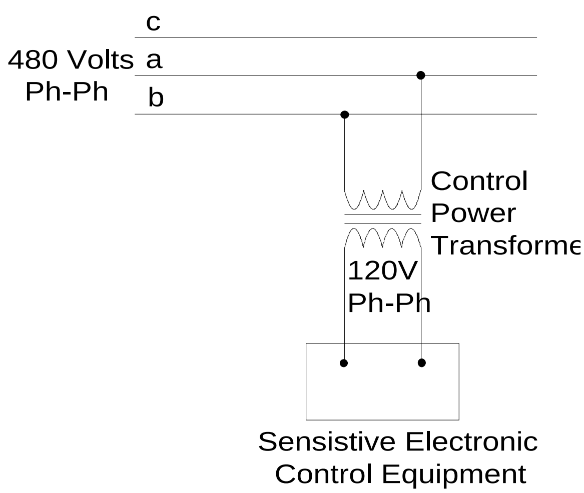

Figure 6: Typical 120 Volt Electronic Control Equipment Installation

For three-phase faults, the phase-to-phase voltages in the plant are essentially the same as at the service entrance. However, for a single-line-to-ground fault, the phase-to-phase voltages in the plant are a function of the stepdown transformer connection. For a distribution system fault, the worst case occurs when the fault is close to the customer bus. Effectively, this is the same as a fault near the customer transformer primary as shown in Figure 7. Table 1 summarizes plant voltage levels with various transformer connections due to a single-line-to-ground fault on the customer transformer primary.

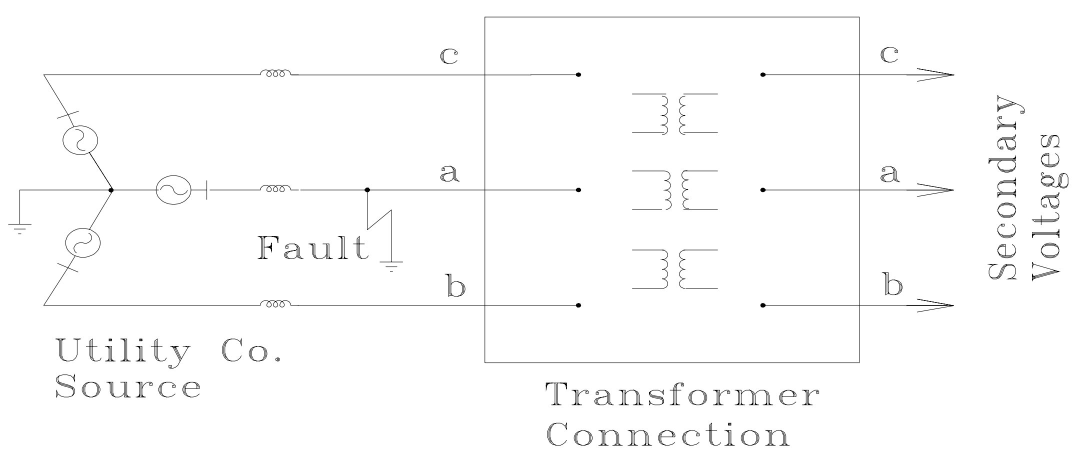

Figure 7: Single-Line-To-Ground Fault Near Transformer Primary

Transformer Connection	Vab	Vbc	Vca	Van	Vbn	Vcn
Wye-Gr to Wye-Gr	0.58	1.00	0.58	0.00	1.00	1.00
Wye-Gr to Wye	0.58	1.00	0.58	0.00	1.00	1.00
Wye to Wye	0.58	1.00	0.58	0.33	0.88	0.88
Wye to Wye-Gr	0.58	1.00	0.58	0.33	0.88	0.88
Delta to Delta	0.58	1.00	0.58	0.33	0.88	0.88
Wye to Delta	0.33	0.88	0.88	----	----	----
Wye-Gr to Delta	0.33	0.88	0.88	----	----	----
Delta to Wye-Gr	0.88	0.88	0.33	0.58	1.00	0.58
Delta to Wye	0.88	0.88	0.33	0.58	1.00	0.58

Table 1: Transformer Secondary Voltages with a Single-Line-To-Ground Fault on the Primary

It is clear from the table that a tradeoff exists regarding transformer connections. For wye-wye and delta-delta connections two phase-to-phase voltages will drop to 58% of nominal while the other phase-to-phase voltage is unaffected. However, for delta-wye and wye-delta connections, one phase-to-phase voltage will be as low as 33% of nominal, while the other two voltages will be 88% of nominal. These relationships are very important. One might think that a single-line-to-ground fault on the primary of a wye-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. Therefore, even with a single-line-to-ground fault on the primary of the transformer, the lowest phase-to-phase voltage in the plant will be about 33% of normal value.

Both wye-wye and delta-wye transformers were added at the customer bus on feeder F4. Single-line-to-ground faults were again applied along feeder F1. Now the corresponding lowest phase-to-phase percent voltage in the plant was obtained. This data is shown graphically in Figure 8.

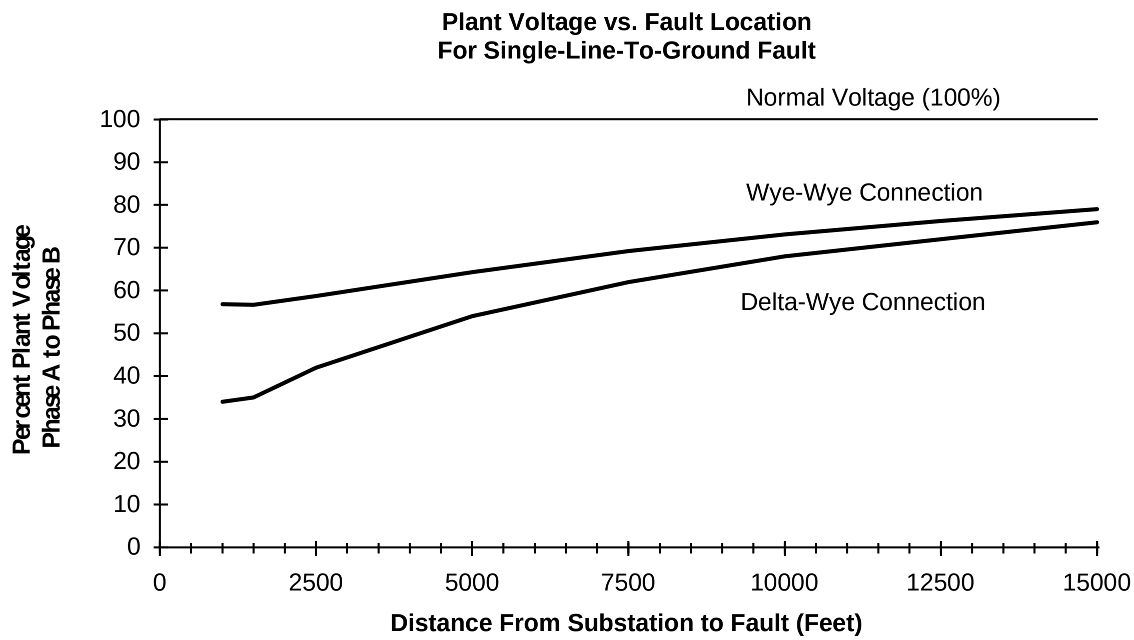

Figure 8: Voltage Sag Severity vs. Transformer Connection and Fault Location

Equipment Sensitivity to Voltage Sags

With an understanding of voltage sag characteristics, the sensitivity, or ride through capability of various types of equipment was investigated. This was done by first identifying different sensitive equipment categories, obtaining examples of equipment in each category, reviewing manufacturer's data, and then testing the actual ride through capability of the sensitive equipment using a disturbance simulator.

The following categories of equipment were tested:

1. Process controllers - two types

2. Programmable logic controllers - two types

3. Control relays - three types

4. Personal computer - one type

Each controller/relay was connected to the 120 V output of the disturbance simulator and subjected to voltage sags of various magnitudes and durations. For each cycle duration, the voltage magnitude was reduced until controller/relay outage or tripping. The cycle durations were 0.5, 1, 3, 6, 10, 30, 60, 100, 1000. Figure 9 is a disturbance simulator example showing a sag down to zero volts for 3 cycles. All sags were initiated at a zero crossing of the voltage waveform.

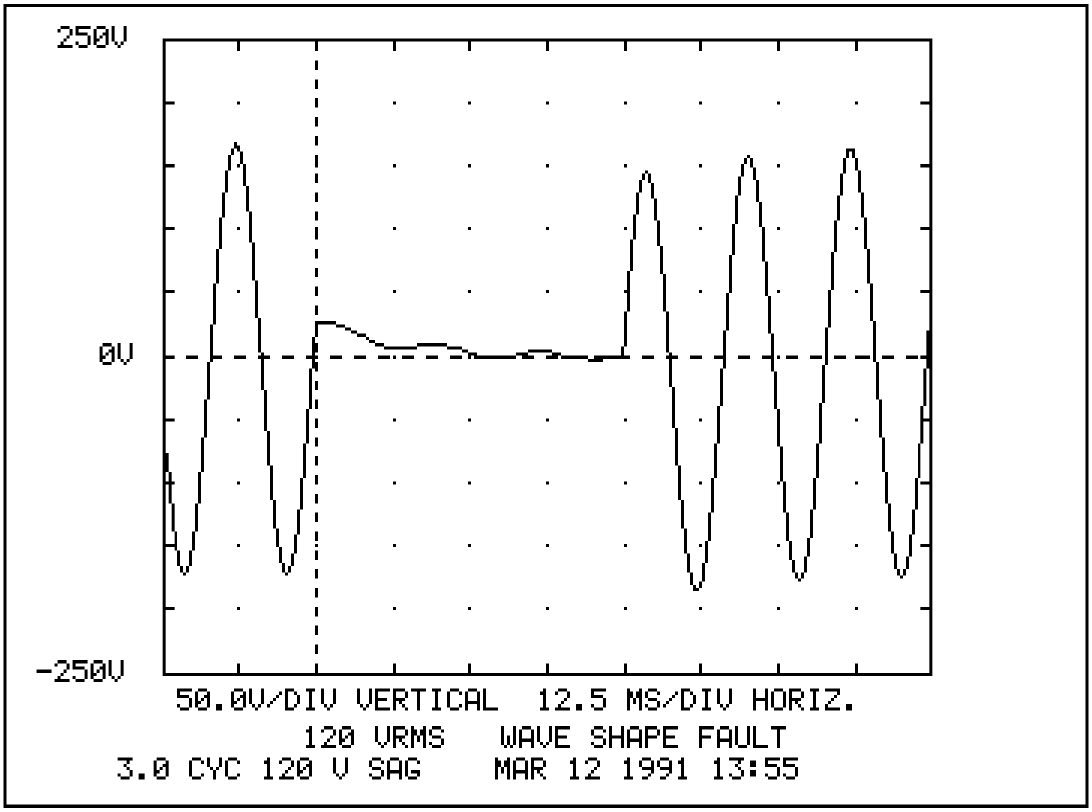

Figure 9: Disturbance Simulator Sample Output

This method of testing was done in order to construct a CBEMA-like curve for each piece of equipment. The CBEMA curve is a standard developed by computer manufacturers outlining minimum overvoltage and undervoltage ride through capability for computers [1]. The curve covers events from 0-1000 cycles in duration, and is shown in Figure 10. On the horizontal axis is the duration of the event in cycles, while the vertical axis plots minimum percent voltage as well as maximum percent voltage for each duration. For example, for a 0.5 cycle event, a computer should be able to withstand a sag to zero volts, and at 100 cycles, the computer should be able to withstand a sag to 87% of rated voltage. The CBEMA curve was used as a starting reference point for the equipment testing because it is the only available benchmark.

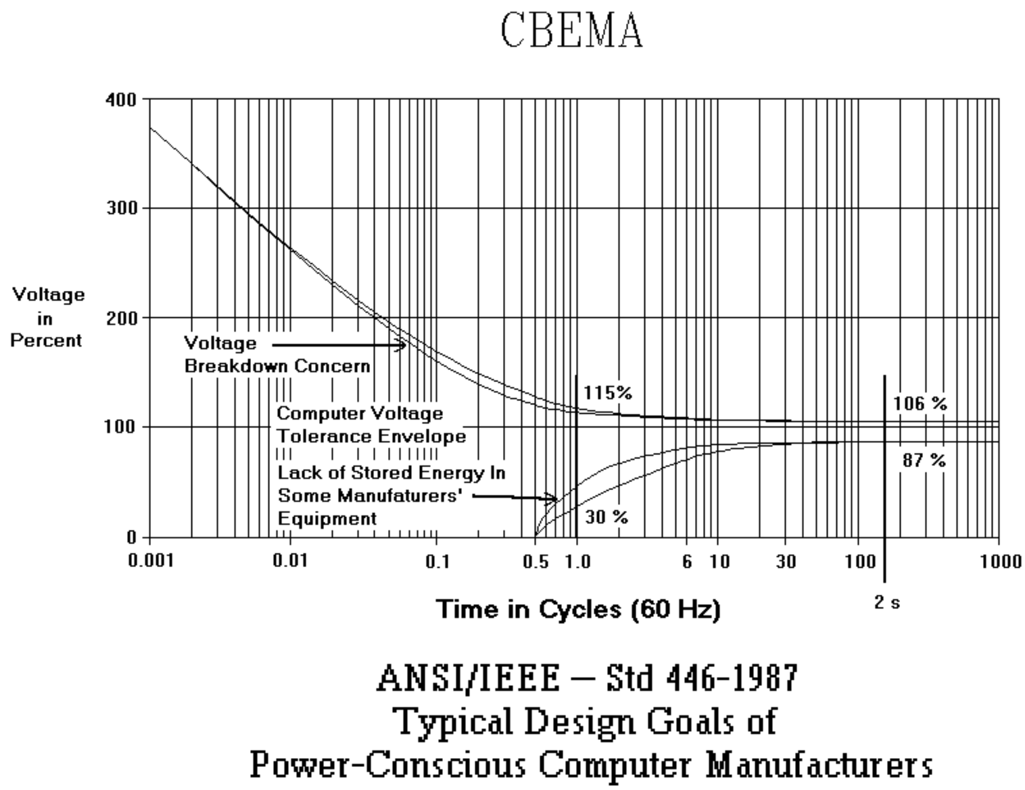

Figure 10: CBEMA Curve

The equipment was first tested without any power conditioning devices installed. This was done in order to get an accurate picture of the sensitivity of the equipment. In all graphs that follow, the vertical axis is the percent voltage at which the equipment shut off or relay opened. The horizontal axis is the sag duration in cycles. Also on each graph is the CBEMA curve for reference. Whenever possible, multiple units were tested to verify the results.

Process Controllers:
Two different process controllers were tested. Type 1 is a fairly common device used for process heating applications such as controlling water temperature. Type 2 can be used to provide many control strategies such as pressure/temperature compensation of flow.

Figure 11 shows the results of the process controller testing. As can be seen from the figure, Type 1 is much worse than Type 2 for short cycle sags, tripping out at around 80% of rated voltage. This is slightly better than the manufacturer's claim of 85%, but still worse than the CBEMA limit. Type 2, on the other hand, was much better, operating at zero voltage for 10 cycles. This is better than the manufacturer's claim of zero voltage ride through for 6 cycles. For long duration sags, however, Type 2's ride through capability decreases to about 75% of rated voltage, but is still below the CBEMA limit.

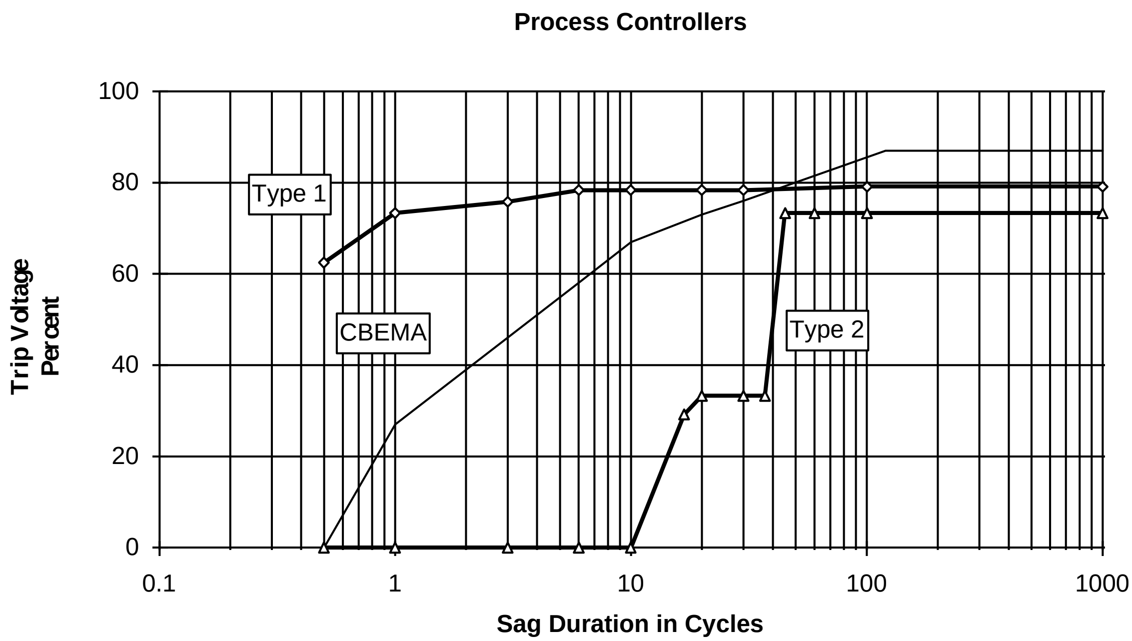

Figure 11: Process Controller Voltage Sag Ride Through Capability

Programmable Logic Controllers:
Two different programmable logic controllers were tested. Both are manufactured by the same company. Both are used to control important processes. Type 1 is the newer, more advanced version of Type 2.

Figure 12 shows the results of the voltage sag testing. It is interesting to note that Type 1, the newer model, is much more sensitive than Type 2. Type 2 can withstand zero voltage for almost 11 cycles, then jumps quickly to about 68%. Type 1 has a fairly constant ride through capability curve between 55 and 60%, which is worse than the CBEMA curve for short duration sags.

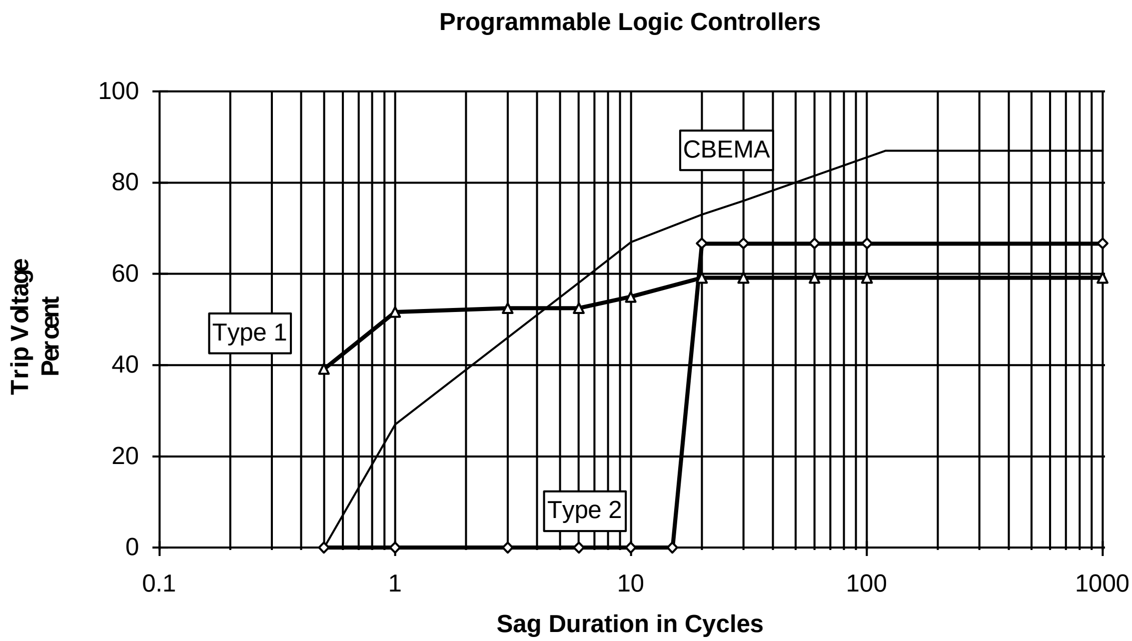

Figure 12: Programmable Logic Controller Voltage Sag Ride Through Capability

Control Relays:
Three different control relays were tested. Type 1 and Type 2 are both manufactured by the same company and are commonly called 'ice cube' relays. They are used to power important equipment. Type 3 is commonly called a motor contactor and is used to power motors.

Figure 13 shows the results for the three different control relays tested. Notice the disparity in the Type 1 and Type 2 relays. One has a fairly constant ride through capability at 65% of nominal, while the other has a much better ride through capability, down to 20% of rated voltage. The Type 3 contactor also has a fairly constant ride through capability of around 60%, which is fairly close to the manufacturer's claims.

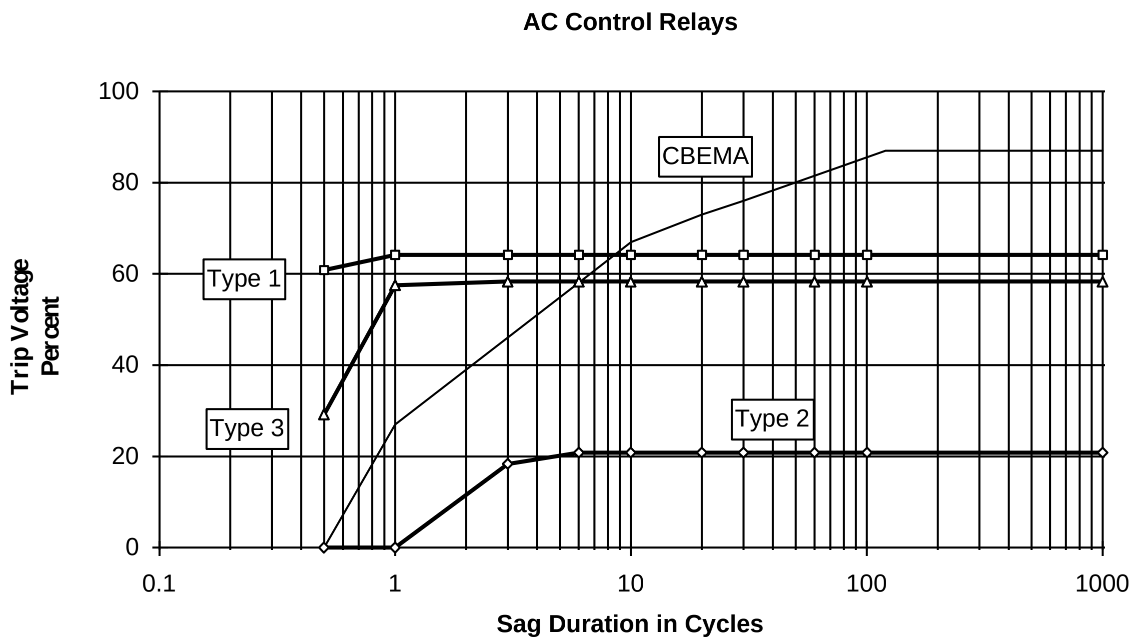

Figure 13: AC Control Relay Voltage Sag Ride Through Capability

Personal Computers:
A laptop computer was also tested and the results are shown in Figure 14. As can be seen from the figure, the computer is well below the CBEMA limit, and can ride through zero voltage for 6 cycles, then levels out with a voltage sag ride through capability at around 50% of rated voltage. The laptop's ride through capability did not change even when it was accessing the hard drive.

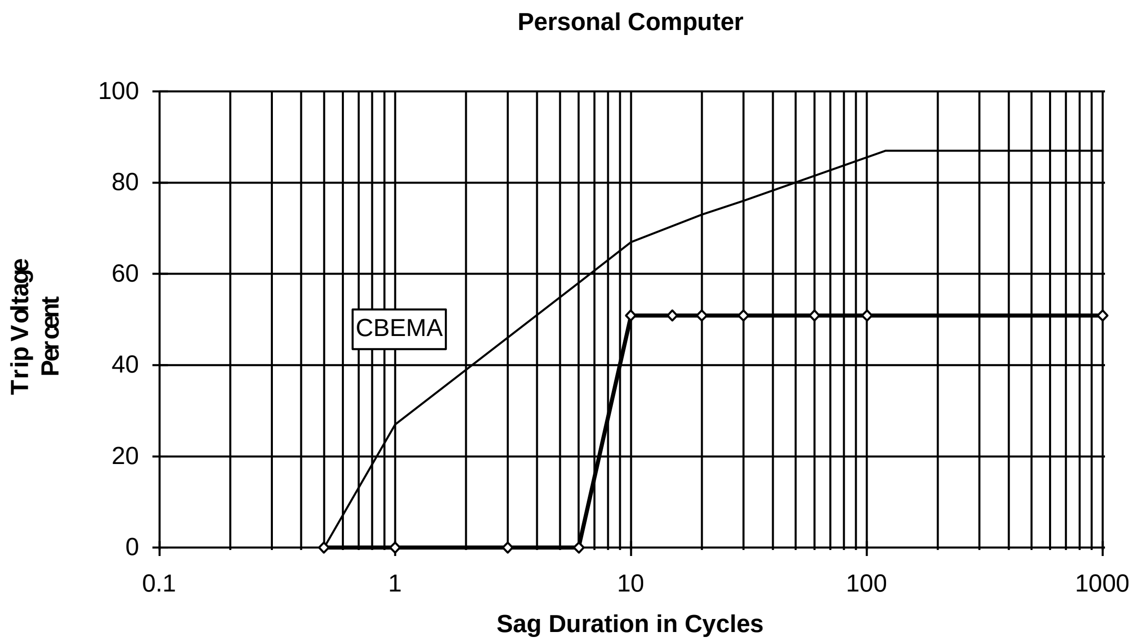

Figure 14: Personal Computer Voltage Sag Ride Through Capability

Since the lowest phase-to-phase voltage in the plant would not be less than 33% of rated voltage for single-line-to-ground faults, it is clear from the equipment testing that the Type 1 process controller will trip for faults a great distance from the plant. The Type 1 programmable logic controller, and Type 1 and 3 control relays will trip for close-in faults. However, the Type 2 process controller and Type 2 programmable logic controller do not have any problems with sags less than 10 cycles in duration, which are the most prevalent.

Improving Voltage Sag Ride Through With Ferroresonant Transformers

One popular method of increasing the voltage sag ride through capability of sensitive equipment is to apply power conditioning equipment such as ferroresonant transformers. Two different ferroresonant transformers, a 120 VA and a 1000 VA, were tested.

Most voltage sags can be handled by ferroresonant transformers, also called constant voltage transformers (CVTs). CVTs are especially attractive for constant, low power loads. Variable loads present more of a problem because of the tuned circuit on the output. Ferroresonant transformers have a nonlinear response similar to a transformer excited high on its saturation curve, thus the output voltage is not significantly affected by input variations. A typical ferroresonant circuit is shown in Figure 15. The equipment was then retested with the CVTs. Figure 16, Figure 17, Figure 19 and Figure 19 show the results of this testing.

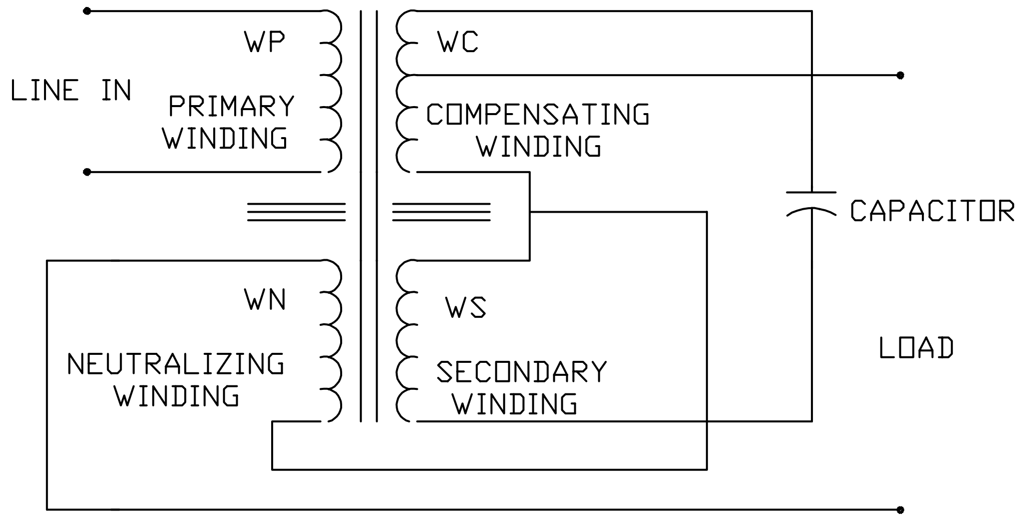

Figure 15: Typical Circuit for a Ferroresonant Transformer

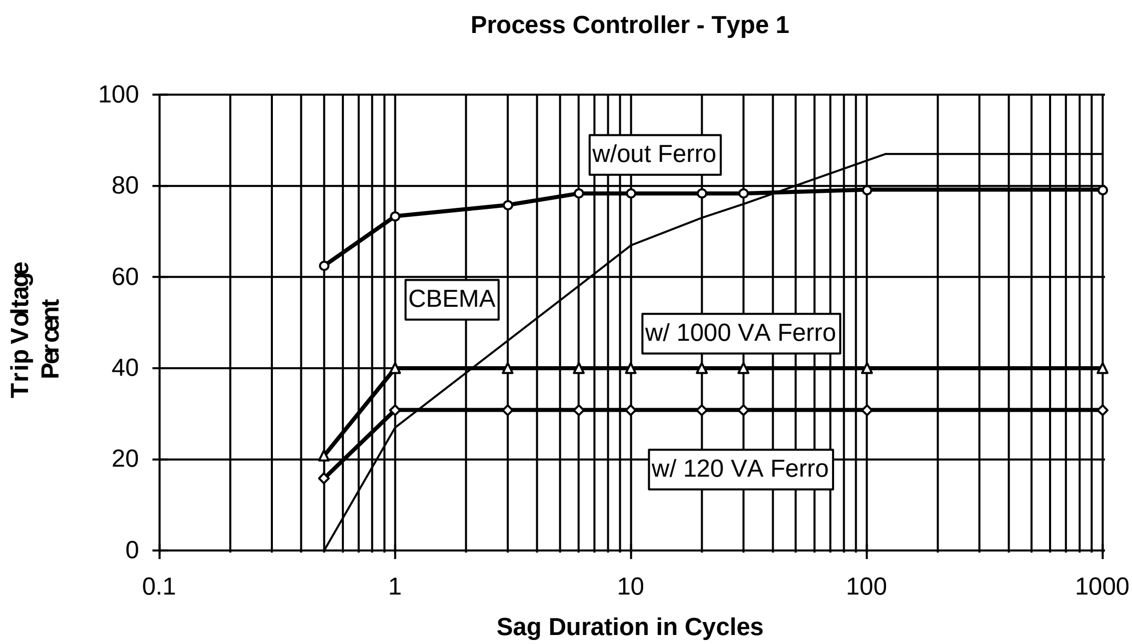

Figure 16: Process Controller - Type 1 with CVTs

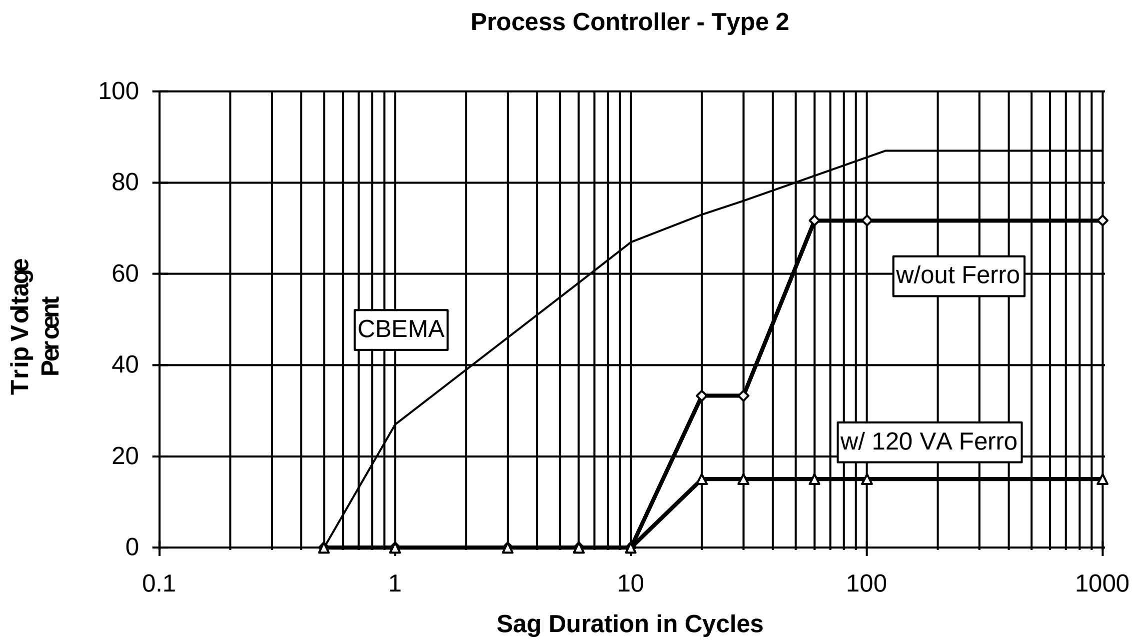

Figure 17: Process Controller - Type 2 with CVT

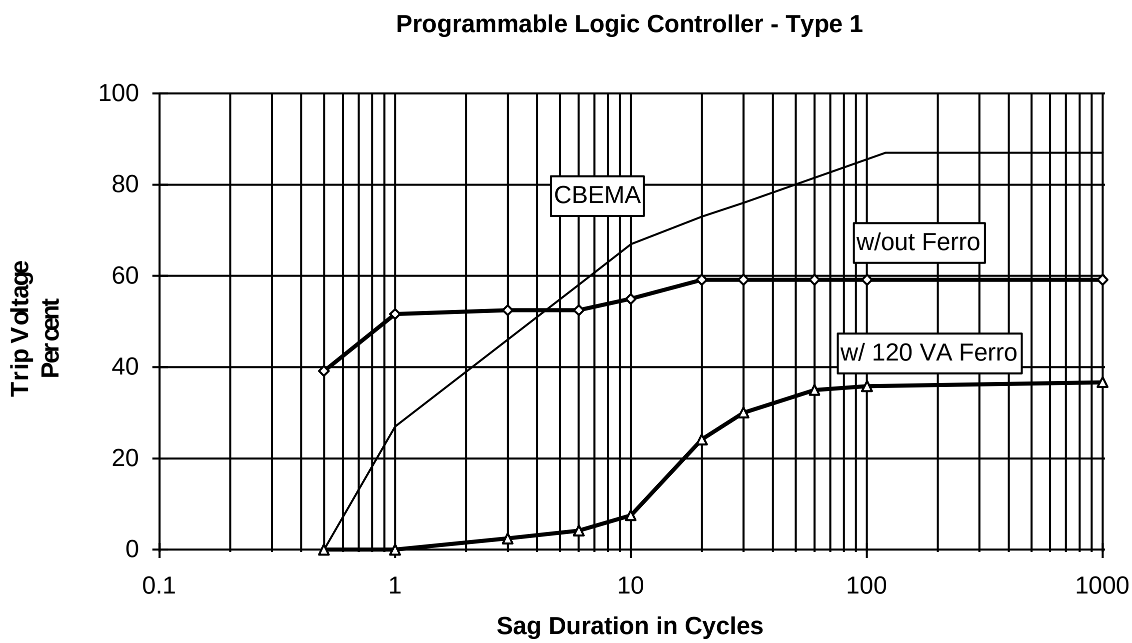

Figure 18: Programmable Logic Controller - Type 1 with CVT

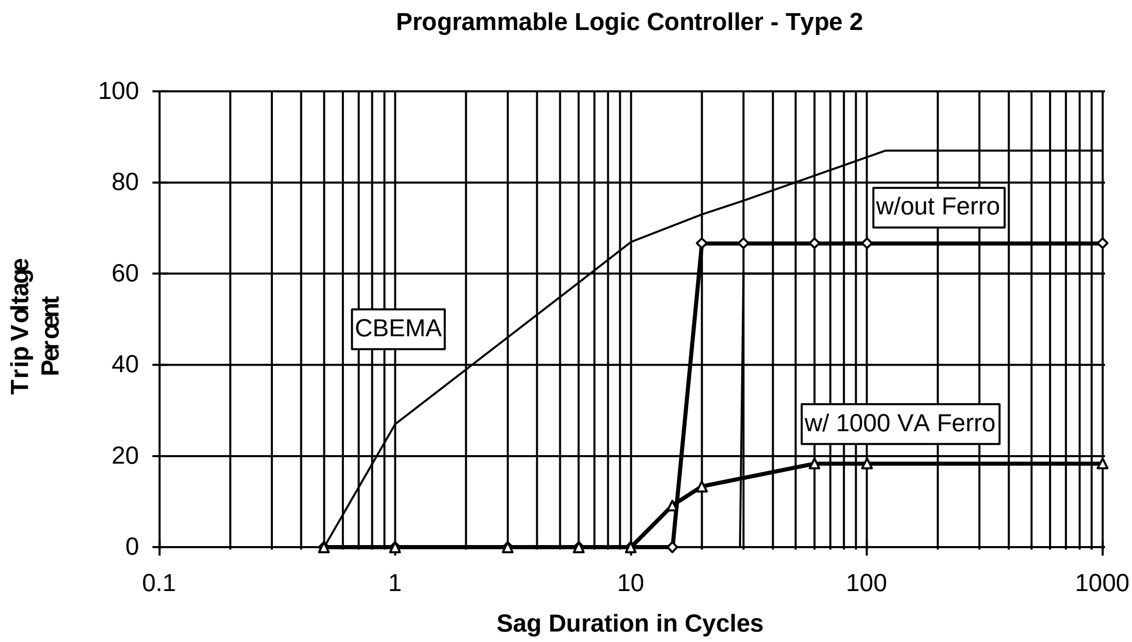

Figure 19: Programmable Logic Controller - Type 2 with CVT

The figures show the marked improvement in the capability of the equipment to ride through voltage sags. Figure 16 shows that the most sensitive process controller, Type 1, can now ride through a voltage sag down to 40% of nominal with the 1000 VA CVT, and down to 30% with the 120 VA CVT. Notice how the ride through capability is held constant at a certain level. The reason for this is the small power requirement of the Type 1 process controller, only 15 VA.

The Type 2 process controller's ride through capability also increased as shown in Figure 17. The figure shows that the original ride through capability is not jeopardized with the use of a ferroresonant transformer. With and without a CVT, the Type 2 process controller can withstand zero voltage for 10 cycles, and for sags greater than 10 cycles in duration, the voltage sag ride through capability increases to less than 20% with the addition of the CVT.

Figure 18 and Figure 19 also show great improvement with the use of CVTs. Both the 1000 VA and 120 VA CVTs performed well. In Figure 18, the voltage sag ride through curve, with the 120 VA CVT, ramps upward, unlike Figure 16 and Figure 17, from zero to about 35%. This is due to the fact that in this test the 120 VA CVT was almost fully loaded with the Type 1 programmable logic controller, about 110 VA.

For maximum improvement of voltage sag ride through capability, ferroresonant transformers should be sized about four times greater than the load. Figure 20 shows the allowable voltage sags as a percentage of nominal voltage versus ferroresonant transformer loading as specified by one manufacturer. At 25% of loading, the allowable voltage sag is 30% of nominal, which means that the CVT will output over 90% normal voltage as long as the input voltage is above 30%. This is important since it is virtually impossible for a single-line-to-ground fault to cause a voltage sag below 30% at the sensitive equipment. As the loading is increased, the corresponding ride through capability is reduced, and when the ferroresonant transformer is overloaded (e.g. 150% loading), the voltage will collapse to zero. Figure 21 shows the effect of loading on the 120 VA CVT. An extra 30 VA load was added to the CVT and the ride through capability was reduced 10%.

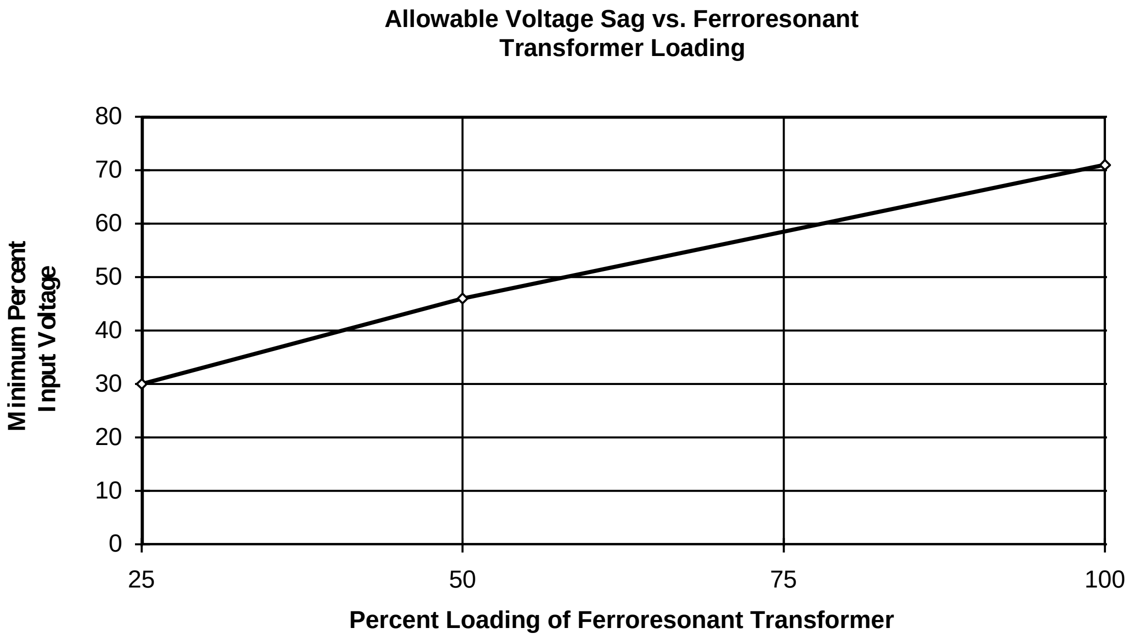

Figure 20: Allowable Voltage Sag vs. Ferroresonant Transformer Loading

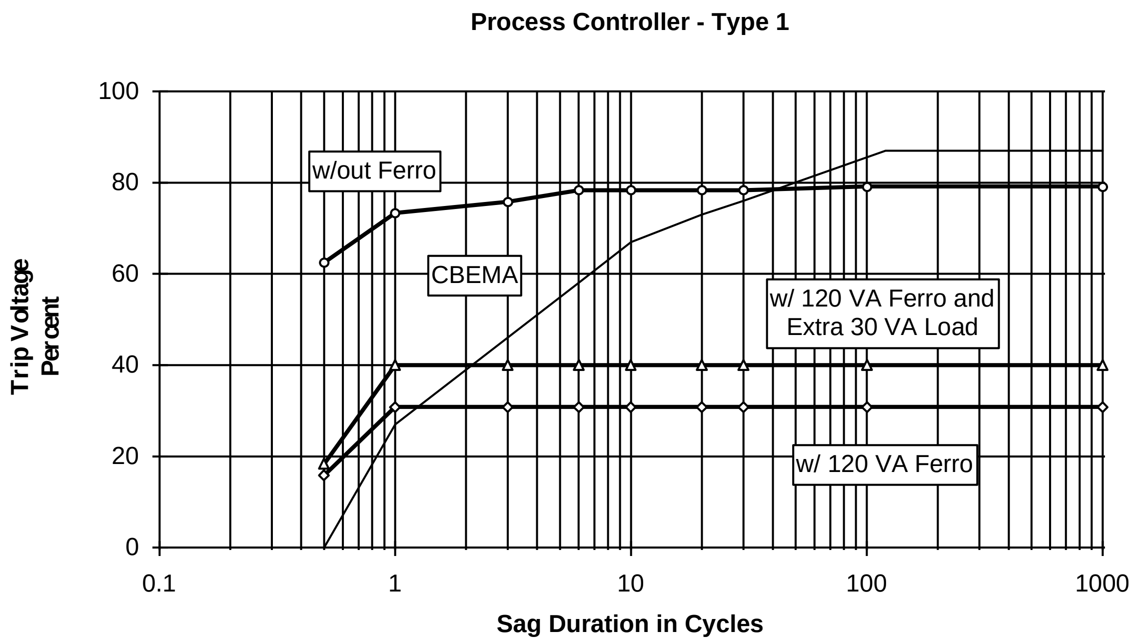

Figure 21: Effect of Load on the Capability of a 120 VA CVT

The steady-state operating characteristics of the 1000 VA and 120 VA ferroresonant transformers were also tested. Figure 22 and Figure 23 show that for both CVTs, as the input voltage is lowered, the voltage remains steady at about 120 V. The output voltage of the 120 VA CVT begins to break down at about 20 V. In addition, as the voltage is reduced, the current that the CVTs draw rises considerably. The 1000 VA CVT was only tested down to 50 V because the disturbance simulator was exceeding its current output rating. For both tests, the ferroresonant transformers were loaded with the Type 1 process controller.

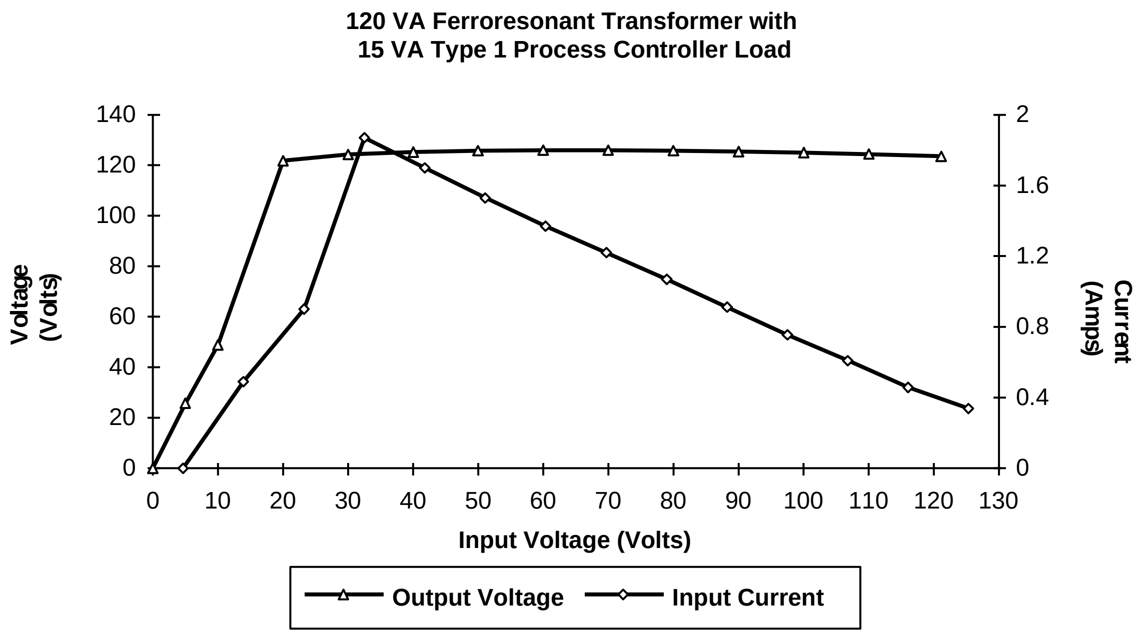

Figure 22: Steady-State Characteristics of 120 VA CVT

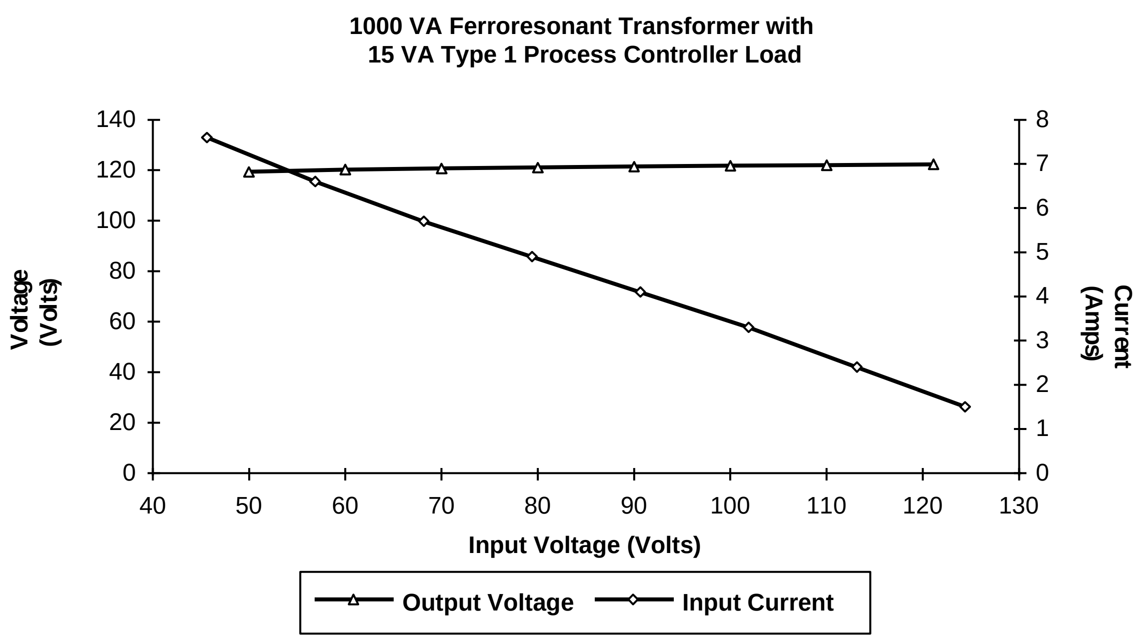

Figure 23: Steady-State Characteristics of 1000 VA CVT

The 120 VA CVT was then loaded with an additional 30 VA load and the steady-state characteristics were again tested. The results are shown in Figure 24. The voltage, along with the voltage shown in Figure 22, are compared in Figure 25. Figure 25 shows that the performance of the CVT is not as good when the loading is increased from 15 to 45 VA. The output voltage breaks down sooner.

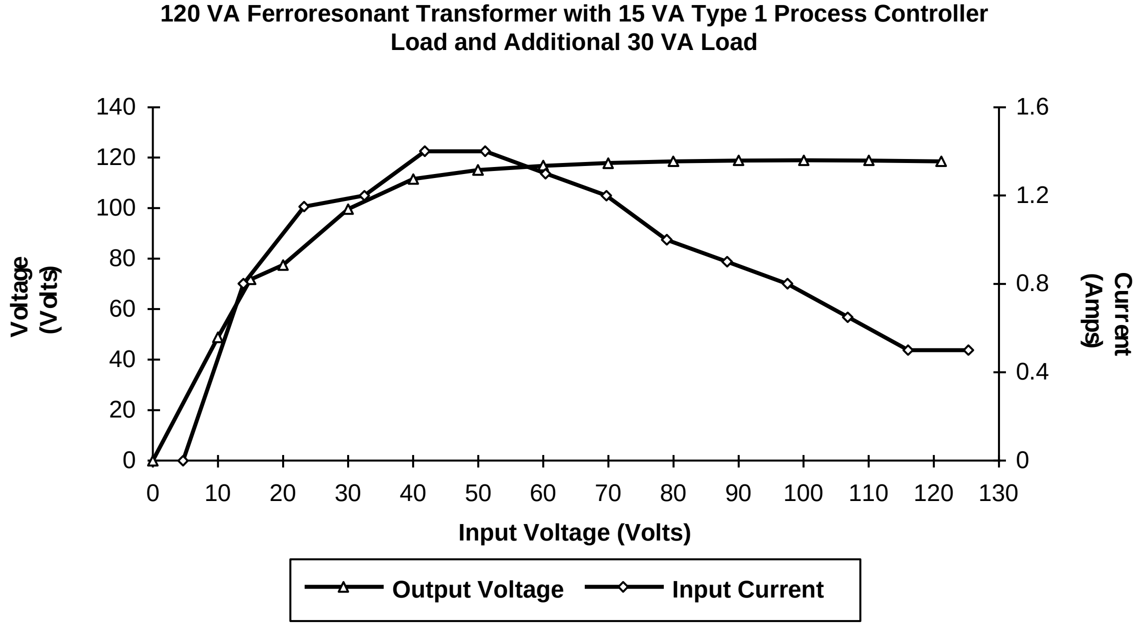

Figure 24: Steady-State Characteristics of 120 VA CVT with Additional 30 VA Load

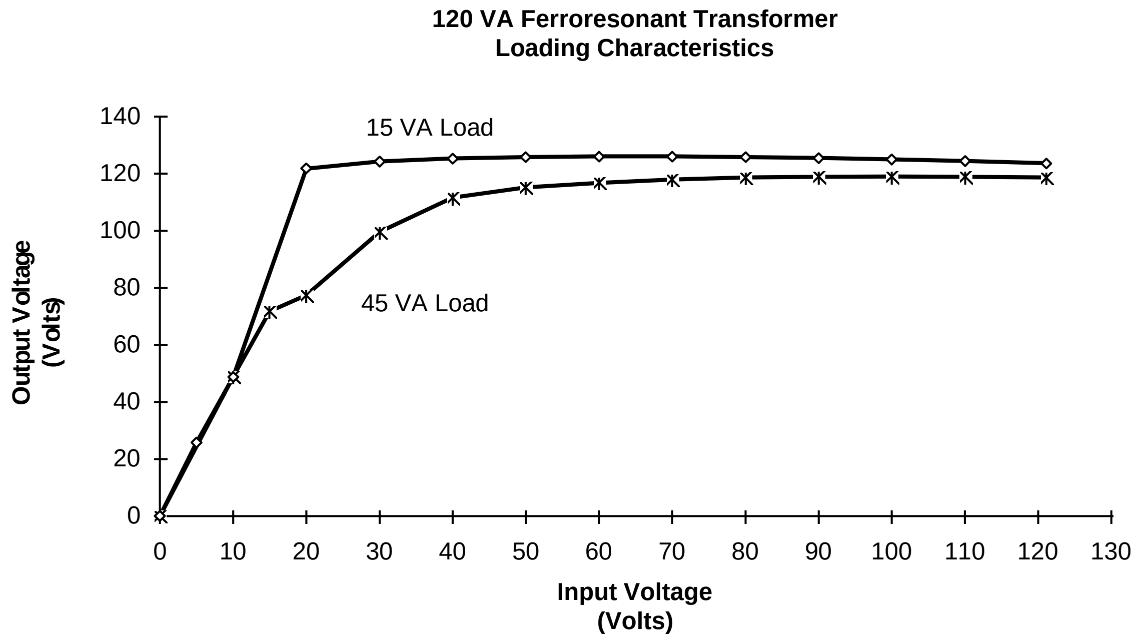

Figure 25: Steady-State Output Voltage Comparison

Equipment Procurement Specification Considerations
Another way companies can combat the voltage sag problem is through their equipment procurement specifications. This essentially means keeping problem equipment out of their plant, or at least identifying, ahead of time, if the equipment needs power conditioning. Several ideas which are outlined below could easily be incorporated into any company's equipment procurement specifications to help alleviate problems associated with voltage sags.

1. First of all, equipment manufacturers should have voltage sag ride through capability curves, similar to the ones generated for this paper, available to their customers so an initial evaluation of the equipment can be performed.

2. The company buying the equipment should establish a mechanism that rates the importance of this new equipment. If the equipment is critical in nature, it will be necessary to make sure adequate ride through capability is included when the equipment is purchased. If the equipment is not important or does not cause major disruptions in manufacturing or jeopardize plant and personnel safety, voltage sag protection may not be justified.

3. Figure 26 was taken from an IEEE paper titled, "Predicting and Preventing Problems Associated with Remote Fault-Clearing Voltage Dips." It plots the relative probability of experiencing a voltage sag of a certain value. For example, the relative probability of experiencing a voltage sag to 80% of nominal voltage is 1.0. This chart is indicative of most power systems. It shows a dramatic drop-off in the relative probability of experiencing a sag of 70% or less. It makes sense that if an upper limit was chosen for a ride through capability specification, it should be somewhere in the 70-75% range. A more ideal value would be around 50% because this is where most contactors drop out.

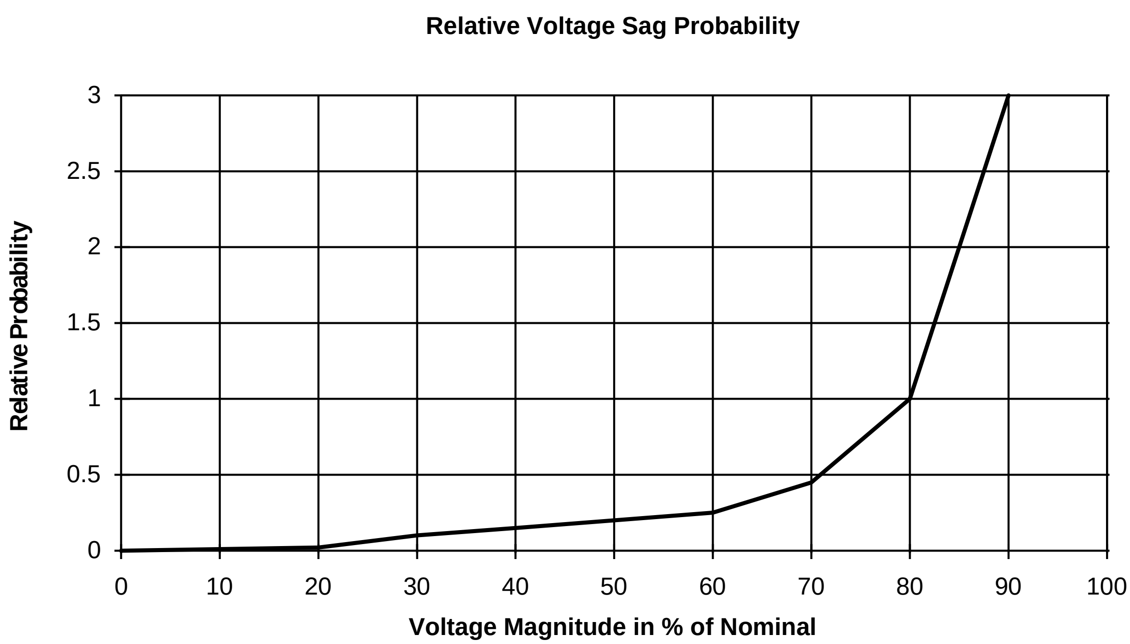

Figure 26: Relative Voltage Sag Probability

Conclusions

1. Voltage sags are becoming an important concern to industrial plants due to the increasing complexity and sensitivity of today's electronic loads. Down time results in manufacturing delays and hence, lost revenue.

2. Single-line-to-ground faults on the utility power system are the most frequent cause of voltage sags. A single-line-to-ground fault on the primary side of a distribution transformer will result in a voltage sag with the worst phase-to-phase voltage on the secondary becoming no less than 33% of normal.

3. The sensitivity of industrial plant electronic control equipment varies greatly. Actual voltage sag testing revealed that some equipment drops out quite easily, while other equipment can maintain operation even with zero voltage lasting for several cycles.

4. Ferroresonant transformers can be applied economically to enhance voltage sag ride through capability. For best results, CVTs should be sized four times greater than the load they are to protect. If more protection is needed, uninterruptible power supplies may be needed.

5. Equipment procurement specifications can be used to keep problem equipment out of the industrial environment. A specification requiring a ride through capability down to 50% of normal voltage would be sufficient to ride through most voltage sags.

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