

Equipment Failures Caused by Power Quality Disturbances

Ashish Bendre, PhD* Deepak Divan, PhD** William Kranz** William Brumsickle, PhD**

**SoftSwitching Technologies
Middleton WI, USA
bbrumsickle@softswitch.com

*DRS Power and Control Technologies
Milwaukee WI, USA
ashishrbendre@drs-pct.com

Abstract— This paper provides insight into a failure mechanism that impacts a broad range of industrial equipment. Voltage surges have often been blamed for unexplained equipment failure in the field. Extensive voltage monitoring data suggests that voltage sags occur much more frequently than voltage surges, and that current surges that accompany voltage sag recovery may be the actual culprit causing equipment damage. A serious limitation in equipment specification is highlighted, pointing to what is possibly the root-cause for a large percentage of unexplained equipment field failures. This paper also outlines the need for a standard governing the behavior of equipment under voltage sags, and suggests solutions to protect existing equipment in the field.

Keywords- Voltage sags; Current surges; Equipment failure; Process control; Converter control; Utility interface

I. INTRODUCTION

For the past 100 years, the utility's job has been to keep the 'lights on.' For today's highly automated factories and processes, that is no longer sufficient. Even a ¼ second voltage sag is sufficient to bring our modern machines to a screeching halt, resulting in hours of interrupted production and irrecoverable scrap. Yet it is interesting to note that most utilities are only required to record outages that last more than 1-5 minutes. So if a factory is experiencing 10-12 momentary interruptions every year, costing millions of dollars in lost productivity, it is likely that the utility would represent that it was providing perfect power. This demonstrates a significant disconnect between the two positions, one that is unfortunately very commonly found.

Thousands of facility-years of power monitoring at large industrial plants clearly demonstrates that, almost without exception, these plants experience anywhere from 8 to 24 power quality disturbances every year that are significant enough to impact plant operations. The vast majority (92-98%) of these disturbances are voltage sags that occur due to lightning strikes, accidents, squirrels or equipment failure on the transmission and distribution grid feeding the plant. Most of the events are of short duration (1-6 cycles), corresponding to the clearing time of upstream utility protective equipment such as fuses, sectionalizers, breakers and reclosers [2,3,14].

It is important to understand the impact of such power disturbances on a plant's equipment and processes. The more obvious impact is on equipment uptime. A process interruption

caused by a voltage sag may require a complete restart of the process, with hours of interrupted production. This can clearly cause substantial economic loss to the plant. However, most plants operate with contingencies built in for unscheduled downtime, and these inefficiencies are typically absorbed within this allowance. For plants with a substantial cost of downtime, voltage sag ride-through solutions can protect against process interruption.

Anecdotal evidence from the field indicates that in some cases, equipment failure has also been observed in conjunction with power disturbances. The market has been conditioned to correlate equipment failure, especially catastrophic failure, with voltage surges [17]. The use of multiple layers of surge suppressors provides clear evidence that the fear of equipment damage drives users to this 'apply and pray' strategy. Yet, voltage sags occur thousands of times more frequently than damaging voltage surges. In fact, even lightning strikes on the power grid, thought to be a main culprit for voltage surges, have rarely been correlated with actually measured voltage surges, but have frequently been correlated with voltage sags [16]. The impact of voltage sags on equipment has not been studied in detail, and the interactions are poorly understood.

This paper demonstrates that the very equipment at the heart of industrial automation—industrial drives, PLC's, robots, and motors—are also possibly most susceptible to damage from short duration voltage sags. This is a very counter-intuitive result as one expects equipment to be robust under lower voltage conditions. Further, it will be shown that equipment specifications that guide equipment designers do not typically provide sufficient margins to ensure that the components remain within their safe operating areas under operating conditions that are frequently encountered in the field. In fact, some of the practices being followed to allow equipment controllers to ride-through voltage sags, may exacerbate the potential for damage to equipment. Finally, the paper presents some techniques for minimizing the potential for damage to typical industrial automation equipment. The paper also points to a need for a standard that specifies equipment behavior under short duration voltage sags, a frequently encountered condition.

II. POWER DISTURBANCES AT INDUSTRIAL PLANTS

Among several detailed studies of power quality on the US power grid. EPRI's Distribution Power Quality Study [1] of-

ferred the first authoritative validation that voltage sags are the most common electrical disturbance experienced by end-users. The Canadian National Power Quality Survey, [2], and the Department of Energy’s Silicon Valley report [3] found similar results.

Ongoing monitoring provides further evidence: A nationwide web-based monitoring system provides access to power reliability and quality data from across the US [4]. With over 1,000 monitors deployed across the US, approximately 700 of which are in large industrial manufacturing facilities, and an event data base of over 300,000 events, the web-based system provides further quantitative understanding of the power disturbances that these facilities actually experience [5]. Some of the relevant data is summarized below.

Figure 1 shows the waveforms associated with a voltage sag captured at a large industrial manufacturing plant in the Midwestern United States. The waveform shows a dramatic phase shift, with resulting voltages down to 50% of nominal for several cycles. Figure 2 shows a magnitude-duration (mag-dur) scatter plot of events recorded at one industrial facility over a period of one year. Each event is recorded as a point, corresponding to the duration and worst case magnitude recorded for the voltage deviation event. For this particular plant, there were a total of 77 recorded events, all of which were short duration (<1 second) voltage sags. Of these approximately 16 events were outside the Information Technology Industry’s (ITI) curve that provides guidance to equipment manufacturers on voltage susceptibility that they should design into equipment [6]. Clearly, this indicates that even if all the equipment at the plant was designed to comply with the ITI curve, they may have experienced 16 power related process interruptions over a year.

Figure 3 depicts an aggregation of over 3,200 events recorded at approximately 100 large manufacturing plants in various parts of the continental US over a period of one year. The overwhelming majority of the recorded events are voltage sags, with few voltage swells and outages, apart from the Northeast blackout of August 14, 2003. These sags are recorded in all parts of the country, and on all types of utility connection, from 4 kV to 138 kV.

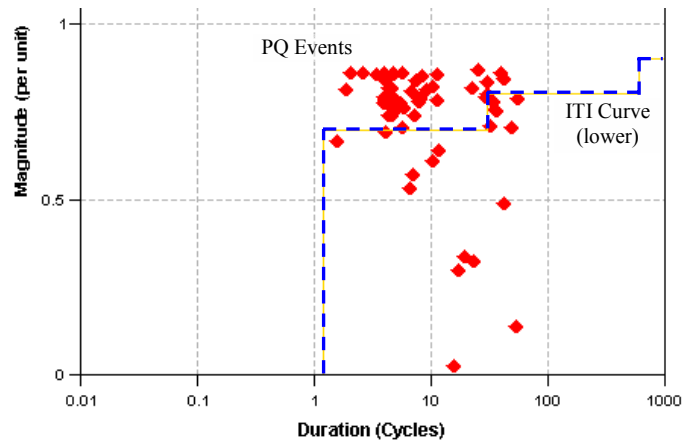


Figure 2 Voltage disturbances experienced at a major US industrial facility over a 12 month period ending in 2003 (1 cycle is 16.7 ms).

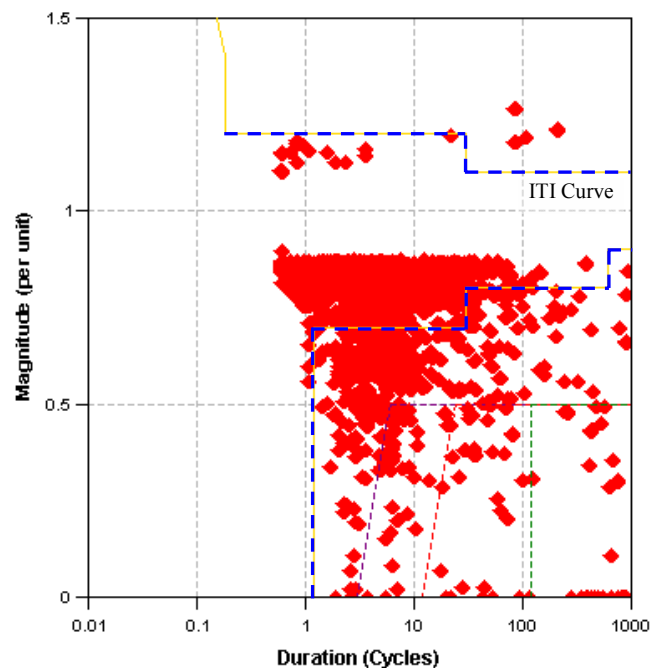


Figure 3 Aggregation of over 3,000 voltage events recorded at 100 large manufacturing plants in the US over a period of one year (1 cycle is 16.7 ms)

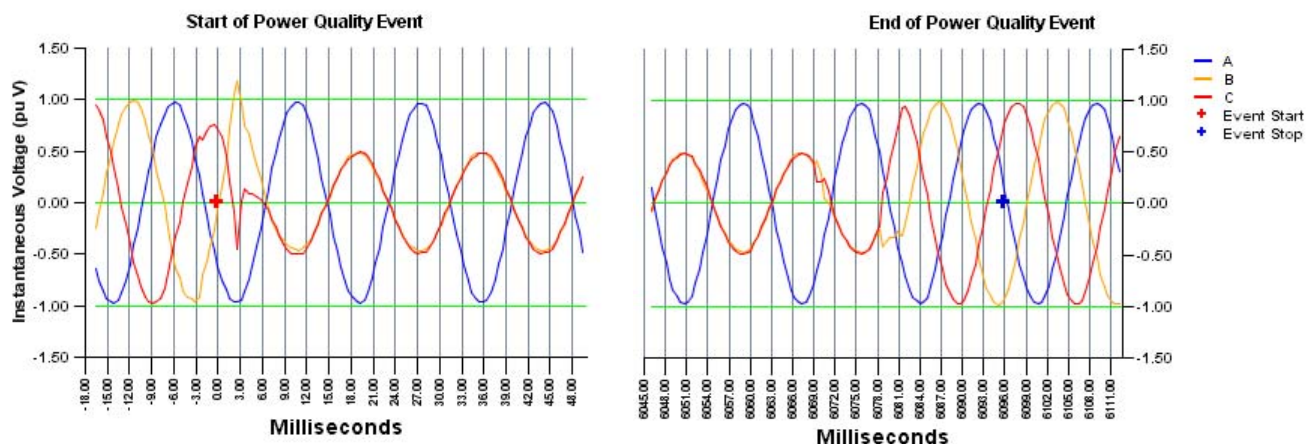


Figure 1. Instantaneous voltage captured during a voltage sag at a large industrial facility

There is now an overwhelming amount of data to validate that industrial plants everywhere typically experience from 10 to 40 power disturbances per year—mainly voltage sags. Over half of these events are likely to impact equipment and processes. What is still not clear is: How do these voltage sags interact with equipment on the factory floor?

III. EQUIPMENT VOLTAGE SUSCEPTIBILITY

A modern automated factory is replete with voltage-sensitive devices and processes, among them computers, programmable logic controllers, sensors, servo drives, robots, CNC machines, extruders, and aseptic processes. A common characteristic of all these devices is a dc supply that converts incoming single or three phase ac line voltage into a dc voltage that feeds the electronics and power electronics components [7], [8]. A schematic of a typical rectifier is shown in Figure 4. A diode bridge is used to rectify the incoming voltage, while a capacitor (C_{dc}) is used to create a constant dc voltage. The impedance of the ac line, input transformers and input line filters (ac or dc) provide some level of isolation from the ac line.

Under normal operation, the capacitor provides a filtered dc bus voltage for the load. The allowable ripple voltage and load current provide the equipment designer with guidance for choosing a specific capacitance value. Typical ripple voltage and input line current are shown in Figure 5. One can see that such power supplies feature unity displacement factor, but poor harmonic factor, resulting in a poor overall power factor. This type of power supply is ubiquitous and is used in virtually all equipment found on the factory floor.

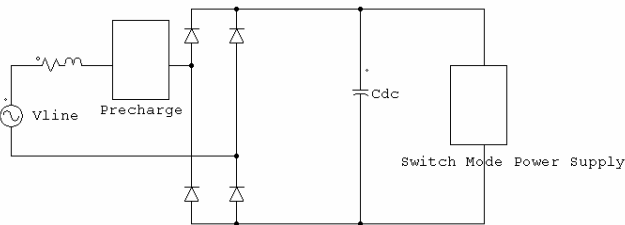


Figure 4 Schematic of a typical single phase rectifier

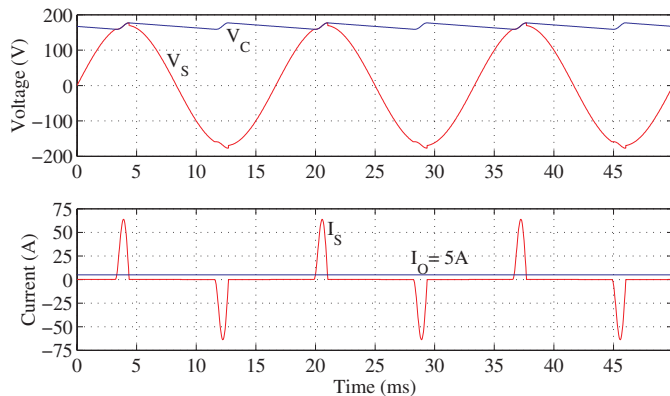


Figure 5 Example ripple voltage and ac line current for a single-phase rectifier with constant dc load current.

Equipment start-up occurs with a discharged capacitor, and can result in extremely high inrush currents. This is a well recognized problem, and is tackled typically with a ‘soft-start’ or ‘inrush current limiter’ circuit [9]. In small rated power supplies (<200 watts), the soft-start function is achieved with a negative thermal coefficient (NTC) resistor, which has a high resistance value when cold, but decreases dramatically in resistance as it heats up. Thus, upon startup, the current is limited by the NTC. As the NTC heats up, its resistance drops to the point that it does not sustain a large voltage drop in steady state. For larger rating systems, the soft start function is achieved with a pre-charge resistor and bypass contactor. The pre-charge resistor limits the current drawn from the ac line until the capacitor C_{dc} is charged, at which point the bypass contactor is turned on.

When the power supply is subject to a short duration voltage sag, the incoming voltage reduces to a level below that needed to recharge the capacitor, causing the line current to reduce temporarily to zero. During the sag event, the capacitor C_{dc} continues to discharge into the load, reaching a value that can be significantly lower than its normal steady state voltage. Until this point, the rectifier has not experienced any extraordinary stresses. If this were a normal ‘turn-off’ operation or complete power loss, the soft start circuit would reset and recover its current limiting properties, and the equipment would be ready for a normal startup event. However, in the case of short duration sags, there is not sufficient time for the NTC circuit to cool down or for the contactor circuit to reset. Now, when voltage returns to normal, there is no active soft-start function and the resulting current surge is the root cause of much of the industrial equipment damage that is observed.

Figure 6 shows the measured inrush current that flows into a 120Vac off line power supply at normal power up, while Figure 7 shows the inrush observed at the end of a 50% voltage sag. Such power supplies are routinely used in PLCs and other electronics equipment. The current pulses seen are drastically different, as normal power up inrush current is limited by the proper operation of the precharge circuit while the return from sag inrush current is not. Figure 7 shows a peak current of 70 Amperes, compared with rms currents of 1 Ampere and peak currents of <15 Amperes that flow under normal conditions. The amplitude of the abnormal currents will depend upon the impedance characteristics of the source, and the low source impedance inherent in large industrial installations can be catastrophic for small power supply front ends.

The preceding discussion clearly shows that abnormal current pulses are likely to flow following a voltage sag but does not give any indication as to the potential to cause damage. Similar inrush currents can be observed at end of sag for three phase power supplies, especially with symmetrical voltage sags. The next section presents a simplified analysis of end of sag inrush currents, allowing a preliminary assessment of the safety margins for the components and devices used.

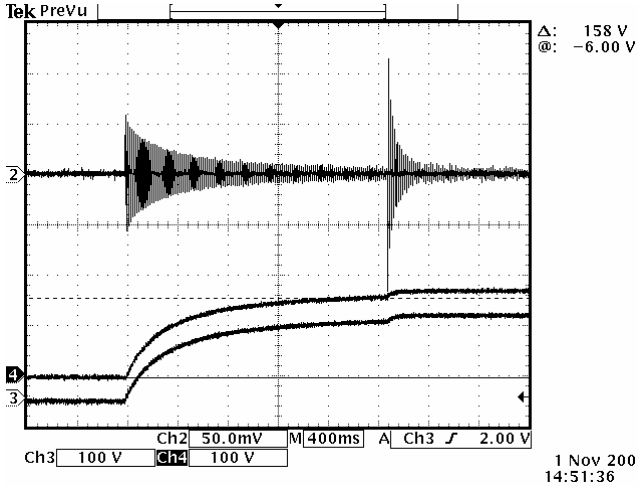


Figure 6 Proper operation of precharge circuit during power up: Top: input line current (5A/div) Bottom: DC Bus voltage (100V/div).

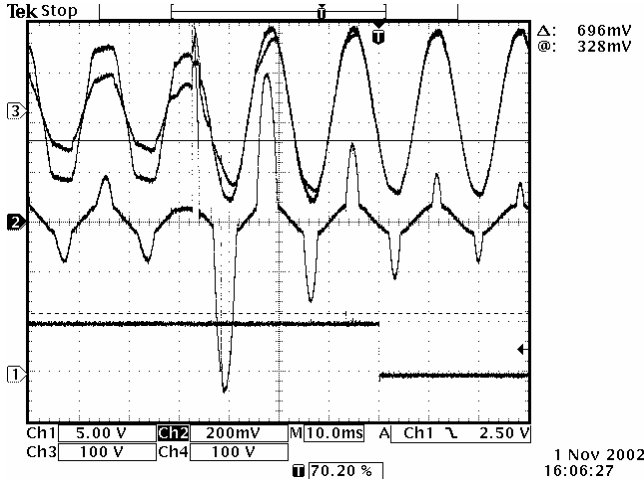


Figure 7 Improper operation of precharge circuit during return from sag: Top: Input voltage (100V/div), Middle: Input current (20A/div)

IV. SIMPLIFIED ANALYSIS OF CURRENT INRUSH

Figure 8 shows a simplified representation of a single-phase rectifier system just before, during and after the voltage sag. The load is assumed to be a dc current source (I_o), and the input filter and source impedances are lumped into one inductor, L_s . A single phase sinusoidal source V_s is assumed. The normal line current drawn by this circuit is shown in Figure 5. For the purposes of this analysis, the voltage sag is assumed to begin and to end at a peak of the line voltage. This corresponds to worst case stress calculations, and limits the consideration of sag durations to half-cycle multiples. The short circuit ratio,

$$SCR = \left(\frac{V_s}{\omega_s L_s / I_o} \right),$$

is assumed to be very large and the resonant frequency,

$$f_{LC} = \frac{1}{T_{LC}} = \frac{1}{2\pi\omega_{LC}} = \frac{1}{2\pi\sqrt{L_s C_{dc}}},$$

is assumed to be much larger than the line frequency. Both these assumptions are generally true for practical rectifier circuits.

Over the half cycle, the capacitor voltage decays by approximately

$$\Delta V = \frac{I_o T_{60}}{2C_{dc}}, \quad (1)$$

where T_{60} is the 60 cycle period. Under normal operating conditions, the capacitor is essentially charged to close to the peak of the ac line voltage (V_p) plus $\Delta V/2$. This of course presumes that the depth of the voltage sag is greater than ΔV . Under voltage sag conditions, the capacitor voltage would continue to decay further, beyond the half cycle. For a sag of N cycles ($N = 1/2, 1, 1\frac{1}{2}, 2, \dots$), the voltage droop is $(2N\Delta V)$, giving an end voltage of $(V_p - (2N-1/2)\Delta V)$. During the sag, the diode bridge is reverse biased, and the line current decreases to zero. At the voltage sag end, the voltage reverts instantly back to nominal (this is assumed to occur at the peak). Under these conditions, a large initial current pulse flows from the line into the capacitor of

$$i(t) = I_p \sin(\omega_{LC}t), \quad (2)$$

where

$$I_p = \frac{(2N - 1/2)\Delta V}{\sqrt{L_s / C_{dc}}} = \frac{(2N - 1/2)\Delta V}{Z_o}. \quad (3)$$

This current pulse flows for a half cycle and ceases, in turn causing the capacitor voltage to jump up to $(V_p + (2N-1/2)\Delta V)$. Figure 9 shows simulation waveforms that illustrate this circuit behavior.

Examining the input circuit, the peak voltage and the peak current are possible causes of damage or equipment malfunction. The peak voltages observed can generally be handled by the surge rating of typical electrolytic capacitors. The current pulse is seen to flow through diodes, input reactors and input line fuses, components that are typically not very sensitive to high transient peak currents, provided average current ratings are not exceeded.

However, diodes, fuses, printed circuit board tracks and wires have short-time thermal stress limits, expressed as maximum I^2T , ratings, that can cause device destruction when exceeded. It is interesting to see whether I^2T ratings are exceeded at end of sag. The I^2T for the current pulse in (3) is calculated as:

$$I^2T = \left(\pi I_o (N - 1/4) \frac{T_{60}}{T_{LC}} \right)^2 T_{LC} . \quad (4)$$

The I^2T value can be normalized to $\frac{I_o^2 T_{60}}{2}$, to yield

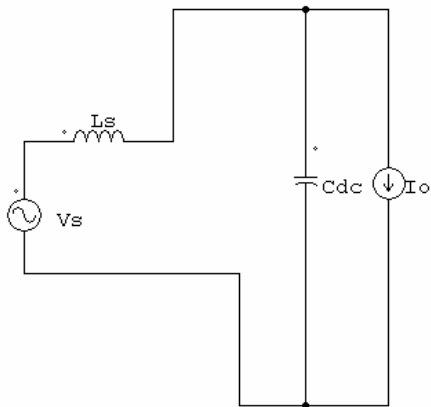
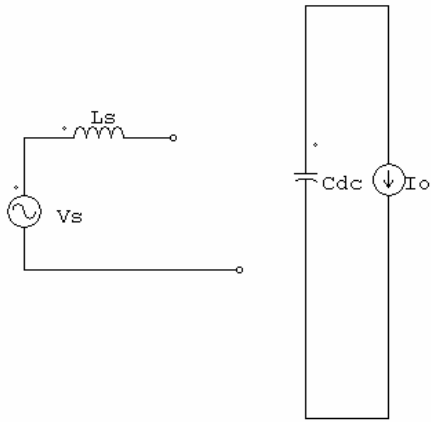
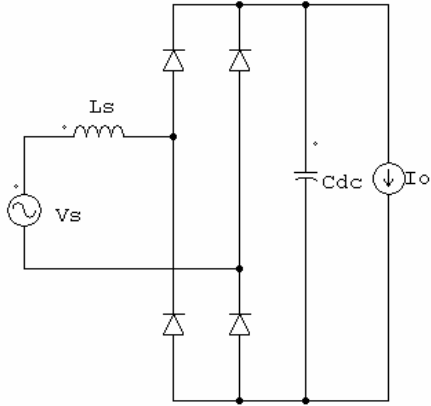


Figure 8 Simplified representation of the system just before (top), during (middle) and after (bottom) the voltage sag.

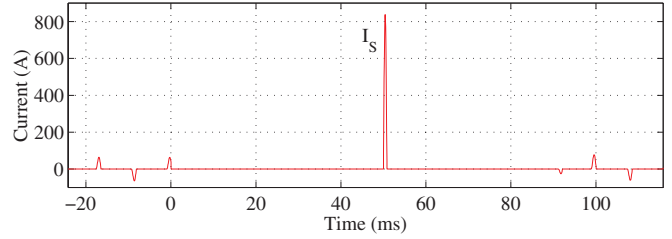
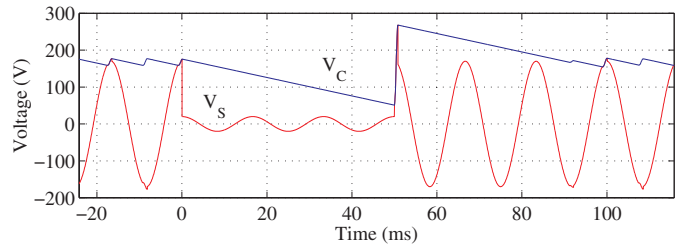


Figure 9 Simulation waveforms for the case $I_o=5A$, $N=3$ cycles, $V_s=120VAC$, $L_s=35\mu H$, $C_{dc}=2,000\mu F$

$$(I^2T)_{Normalized} = 2\pi^2 (N - 1/4)^2 \frac{T_{60}}{T_{LC}} \quad (5)$$

It is interesting to note that the normalized values for I^2T are independent of actual I_o and capacitance value. Further, the only requirement on depth of sag is that the voltage during the sag be lower than the dc voltage on capacitor C_{dc} . Thus larger values of C_{dc} that provide lower dc ripple, will tend to suffer from higher values of I^2T stress. For $N = 1/2$ we have the normal case with no voltage sag. For $T_{60}/T_{LC} = 10$, this yields

$$(I^2T)_{Norm} = 1.25\pi^2 .$$

This is typically well within the design specification for most diodes, and would be considered to be a safe design. If the sag duration increases to 3 cycles ($N=3$), the stress on the diode increases by a factor of 121, and by 529 for a 6 cycle sag. These are clearly alarming numbers, and need to be fully reconciled with actual diode ratings and circuit parameters.

Table 1 shows typical diode ratings for actual devices rated at 1 Ampere to 100 Amperes. Also shown is I^2T as calculated from (4). Again assuming $T_{60}/T_{LC} = 10$, the worst case I^2T values are calculated for various N . The diode rating is assumed to be the same as the value of I_o . The simulation results, shown in Figure 9, are for the case $I_o = 5A$ and $N = 3$. The I_p value calculated by (3) was within 3.5% of the simulation value and the I^2T value calculated by (4) was within 5% of the simulation value and showed the right trending; this demonstrates that this simplified analysis provides a conservative design guideline.

TABLE I. I^2T CALCULATIONS VERSUS RATINGS

I_D Average (A)	I^2T Rated (A^2s)	I^2T N=0.5 (A^2s)	I^2T N=3 (A^2s)	I^2T N=6 (A^2s)	I^2T N=9 (A^2s)
1 A	18	0.10	12.4	54.4	126
5A	180	2.6	311	1,360	3,149
20A	700	41	4,976	21,754	50,376
100A	15,000	1,028	124,398	543,856	$1.26 \cdot 10^6$

Table I clearly shows that all the diodes would have been very safe under normal operating conditions ($N = 0.5$), and for use with inrush current limiting circuits. However, serious questions are raised about the survivability of these diodes or appropriately coordinated fuses under even fairly short duration (3-9 cycle or <0.15 seconds) voltage sags. Data from Figure 3 clearly indicates that such voltage sags are very common. Anecdotal evidence from major manufacturers of PLCs, robots, motor drives, and medical equipment validate that damage to input power supply components is the most commonly reported field failure mechanism.

The impact on single and three phase input stages can be significantly different. Going back to the root cause of most power disturbances, utility system faults, it is seen that most faults tend to be asymmetrical faults—tree contact, squirrels, line-line short, line-ground short, etc. Few faults are fully symmetrical in nature. Every asymmetrical fault shows up as a sag on a single phase line and causes substantial inrush current to flow at end of sag. For a three phase input stage, e.g., Figure 10, the maximum value of any line-line voltage will determine the extent to which the capacitor voltage will decay, and will in turn govern the amplitude of the inrush current at end of sag. For asymmetrical sags, the rectifier will essentially behave as a rectifier with single phase excitation with higher peak line currents than for the balanced three phase case. Further, for a symmetrical three phase sag, the behavior at end of sag would be similar to that discussed for the single phase case above.

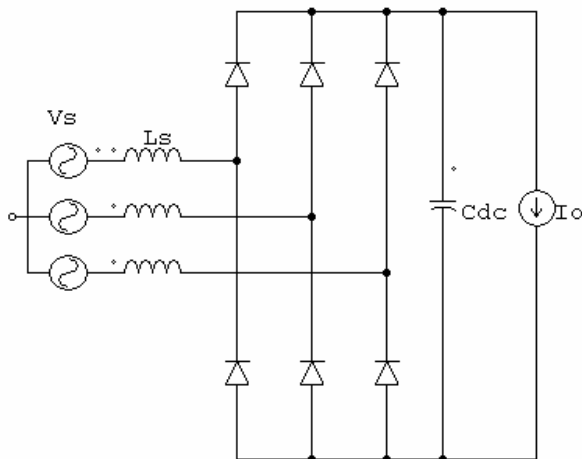


Figure 10 Schematic of a typical three phase rectifier

It is also interesting to analyze frequency of occurrence for such events. Data suggests 40 power quality events per year at a typical manufacturing plant, of which 20% or 8 events are

assumed to be symmetrical three phase events. Half of the remaining 32 events are assumed to be single phase to ground events, while the balance are assumed to be line to line events. For this type of event distribution, single phase loads are likely to see approximately 24 surge current events per year, while three phase loads will experience 8 surge current events per year. It should be remembered that the analysis presented here represents a simplified worst-case analysis, with an emphasis on understanding the underlying fundamental issues. The actual stress will depend on the shape of the voltage during the sag, and the actual point on wave at which the voltage returns to nominal. A more detailed analysis will be presented in a later paper.

V. INDUCTION MOTOR SUSCEPTIBILITY

The second major category of equipment found in industrial manufacturing is line connected induction motors. Smaller motors tend to be direct line-start, while larger machines use reduced voltage starting with Y- Δ starters or solid state soft starters. Clearly, the direct line start motors and their loads have been designed for the current and torque transients that accompany a line start. On the other hand, the reduced voltage start motors are particularly vulnerable to power line sags. In any case it is important to understand the interaction of induction motor loads with the power system, particularly under system fault conditions [10], [11], [12].

A common misconception is that the motor is disconnected from the line under voltage sag conditions, probably because many system faults result in an upstream breaker operation. However, as most motor starters and contactors will not drop out for short sags of up to 3-6 cycles, it is clear that the more applicable situation is one where the motor remains connected to the line. If we consider a typical voltage sag waveform of the type shown in Figure 1, it is clear that significant levels of positive and negative sequence currents will be generated, resulting in substantial positive and negative torque transients both at the beginning and end of sag.

Figure 11 and Figure 12 show simulation results of the typical terminal voltage, current and torque for an induction motor operating with a closed and an open contactor during the sag interval. With a closed contactor, we see a large torque transient at the beginning and end of sag, while there is no torque transient at the beginning of sag with an open contactor. For sags with sufficient residual voltage to provide magnetization, the motor continues to draw high current and tends to support the line voltage. At the end of the sag, another large current and torque transient are seen to occur. The measured data for an induction motor responding to an open contactor interruption [13] is shown in Figure 13. This measurement shows a 20 p.u. level torque and 12 p.u. peak current at end of sag correlates well with the simulation results obtained in Figure 11 and Figure 12. An even higher level of torque transient can occur with a closed contactor at beginning of sag. Such an impulse torque transient can damage shafts and certain types of loads. If the sag lasts for sufficient time, the motor starter/contactor will trip, interrupting the process. However, it should be noted that the beginning of sag torque cannot be avoided as the contactor cannot respond fast enough to eliminate the transient.

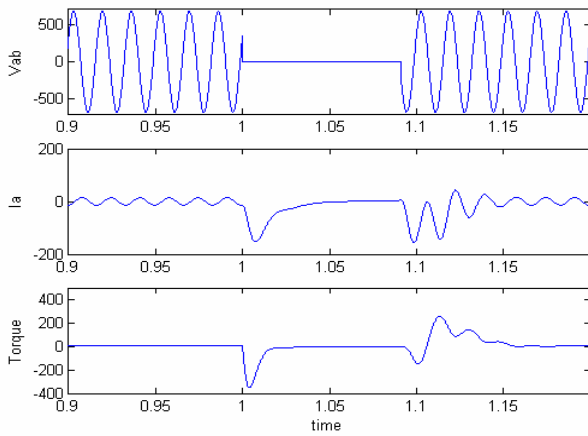


Figure 11 Terminal voltage, current and torque for an induction motor operating with a closed contactor

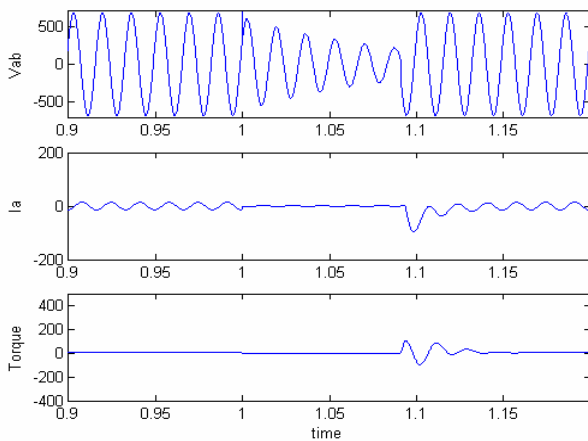


Figure 12 Terminal voltage, current and torque for an induction motor operating with an open contactor

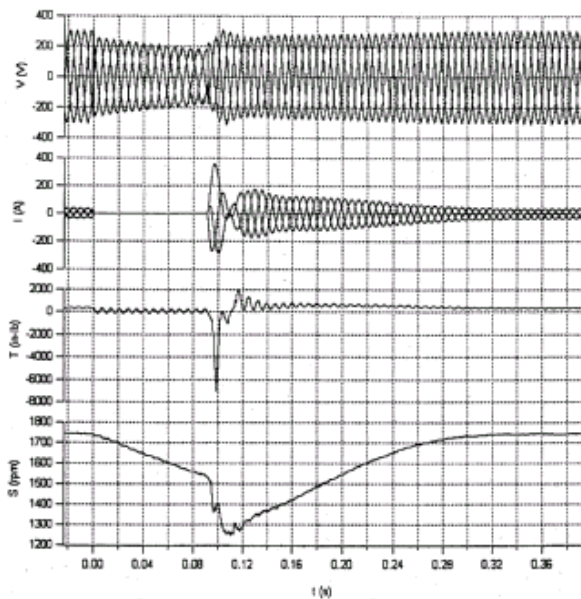


Figure 13 Measured torque and current for an induction motor subjected to a 5.5 cycle interruption [13].

VI. SYSTEM INTERACTIONS AND SOLUTIONS

In a typical manufacturing plant, the incoming power is distributed such that while there are several types of equipment and tools that are directly connected to the incoming three phase power, there is an even larger number of different controllers, sensors and power supplies that are connected to a single phase source derived from the incoming line-line or line-neutral three phase voltage. As such, a normal manufacturing plant will have a mix of single and three phase dc power supplies as front-ends for the equipment in the plant. In addition, there will be a fairly large number of direct connected induction motors.

Based on the sensitivity of typical equipment, many of the 40-50 power quality events that occur will cause process interruptions [14]. Failure of specific equipment will depend on the input stage designs, distribution of symmetrical and asymmetrical sags, and the random nature of the point on wave at end of sag. This makes it very difficult for any single manufacturer to systematically track equipment failure within the facility, and to correlate it with a specific power disturbance. Positive correlation can be obtained by tracking equipment failures as recorded by the equipment manufacturer. For some specific products that have been investigated (including PLCs, robots, drives and medical equipment), it seems to be clear that input stage failures, in particular diode failures and burnt out traces/fuses/wires, seem to represent the most significant reliability problem. This paper provides a means of understanding such failures.

Two approaches are possible to fix the problem. The first is based on designing the equipment to survive voltage sags. This may be distinct from the issue of having the equipment ride-through a voltage sag. As equipment specifications today do not include voltage sag recovery characteristics, it is no surprise that equipment remains unprotected. Developing a standard to address equipment behavior upon sag recovery is clearly the long-term solution to fix the problem.

In the near-term, a retrofit solution is required that eliminates the voltage sag, or eliminates the current surge that occurs on voltage sag recovery. Voltage sag correctors are available commercially [15] that allow equipment rated at 250 VA to 2,000 kVA to ride through voltage sags. While these devices mainly target process ride-through, they clearly protect the equipment from the voltage sag recovery transient, and eliminate the dangerous current surge.

VII. CONCLUSIONS

This paper provides insight into a failure mechanism that seems to have broad impact across a wide range of industrial equipment. Typical users and equipment vendors have focused on voltage surges as being the dominant mechanism for unexplained failures occurring in the field. Based on voltage disturbance data from industrial plants, it is seen that voltage sags occur much more frequently than surges, and that a current surge that accompanies voltage sag recovery is the actual culprit causing equipment damage.

Analysis of the current surge reveals a serious limitation in basic specification that most equipment is designed to. It is seen that for voltage sags that last 3-9 cycles, a very common

occurrence at industrial plants, the I²T rating of the diodes and/or fuses can be exceeded, resulting in failure of the input rectifier stage. Based on discussions with equipment vendors, this may possibly be the single most significant root-cause of equipment failure in the field.

Voltage sags and sag recovery can also severely stress electro-mechanical equipment, such as motors and actuators, although it is felt that the issue may be better contained in terms of overall impact at an industrial plant.

Given the widespread nature of the problem, a two part solution is required. In the long-term, equipment behavior with short duration voltage sags needs to be characterized and made part of an overall design specification. In the near-term, retrofit solutions such as voltage sag correctors can provide equipment ride-through as well as protection against the deleterious effects of voltage sags.

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