Power Quality Solution Options for DC Motor Drives

Technical Report

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REPORT SUMMARY

Background

With the expanding use of both AC and DC adjustable speed drives, very minor electric source disturbances can generate costly equipment and process downtime. Without up-front planning to handle common electric service variations, these complex revenue-producing systems are likely to experience compatibility problems. Solutions for AC drives have been successfully implemented for a number of years with good success through a wide number of available options. For DC drives, the solutions are less common and less well known. This report details the range of opportunities to improve the power quality performance of DC drives and their controls and peripherals.

Objectives

The objectives of this report are to identify the range of power quality solutions for DC drives, focusing on those solutions that can be practicably implemented today, and to discuss the technical challenges the power quality system integrator faces from a DC drive design topology standpoint. This report also provides supporting application case studies related to the solutions presented.

Approach

To accomplish the objectives, the project team reviewed a selection of materials related to DC adjustable speed drives. The team then interviewed a group of experts in the field of solving DC drive power quality problems. This allowed the team to gather state-of-the-art information on application of solutions, as well as a good understanding of the barriers and challenges encountered. This information is presented with a focus on cost-effective implementation strategies, and reference data are provided to enable the reader to perform comparative analyses.

Results

A number of ride-through solutions are presented that can and do resolve power quality related problems for DC adjustable speed drives. The specific options include retrofits, control power and field winding protection, programming fixes, embedded solutions, and replacements with compatible AC drive technologies. Each of the solutions is described in detail with supporting application information. The conclusion is that while DC drives are one of the most challenging technologies to improve upon from a power quality standpoint, it can be done if the solution cost-payback proves reasonable. One of the primary recommendations for the ride-through solutions described is that the facility engineer use a procurement specification to define the needs of the DC drive and the drive controls as follows:

- The output of the power conditioning unit shall provide at least ninety percent of the drive nominal nameplate voltage rating for the duration specified by the process engineer. (This duration may be one-half second if sag and momentary interruption support are all that is required. It may be as much as ten to twenty seconds if it is desirable to bring emergency backup generation on line without dropping the process.)
- The output of the power conditioning unit shall provide sinusoidal voltage to the supported load with not greater than one percent voltage unbalance for the duration specified by the process engineer.
- The power conditioning unit shall be rated to operate without failure or degradation within an operating temperature environment as specified by the process engineer. (Depending on the environment, it may be advantageous to use one of the battery-free UPS technologies if temperature extremes are anticipated and battery lifecycle reduction is a concern.)

EPRI Perspective

DC and AC motor drives are among the most common power electronic-based industrial equipment. When working as intended, these technologies make electricity more valuable by using energy more efficiently and providing much better process controllability than their electro-mechanical counterparts. However, compatibility problems with electrical environments often become a source of complaints from end-users. One of the main causes of the incompatibility is the inability of these power electronic-based loads to maintain process continuity during a momentary voltage disturbance that is most often manifested as a brief decrease in voltage. These events, known as voltage sags or dips, cause a momentary decrease in RMS (root mean square) voltage magnitude, usually caused by a fault in the utility transmission or distribution system. Voltage sags are the most frequent cause of disrupted operations for many industrial processes, particularly those using modern electronic equipment. It is important that electric utilities stay ahead of the learning curve in terms of maintaining state-of-the-art knowledge on the problems and the solutions associated with power electronic-controlled equipment such as the adjustable speed drive. As a result, those customers needing assistance in resolving power-related problems can get the help they need from their power supplier.

Keywords

DC Drive
Adjustable Speed Drive
Power Quality
Power Disturbance

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1
INTRODUCTION

DC motor drives are used in a variety of commercial and industrial applications ranging from rolling mills to printing presses to elevators. The primary considerations for using DC drives center around those applications where there is a need for either high torque or precision speed control. In addition, with many "mature" processes, the designers and system integrators are much more comfortable and familiar with the use of DC motors and their attractive "first costs of implementation." Therefore, they continue to specify the technology over some of the new AC drive alternatives.

In terms of power quality performance, the DC drive presents a unique set of challenges that makes the technology one of the most difficult to protect against electrical variations. In addition, it is one of the most costly technologies on a dollars per kVA basis. Despite these challenges, many customer processes containing DC drives have been successfully bulletproofed against electrical variations by utility power quality personnel and by consultants with acceptable final results. The most expensive DC drive power quality solutions such as flywheels and ultracapacitor energy storage will certainly solve the majority of tripping concerns. Inexpensive fixes such as programming changes and increasing nominal input voltage to the drive will also work in some cases. However, these solutions require extensive understanding of the process in order to ensure success. This report documents a number of those success stories and describes the range of available DC drive ride-through solution options, with emphasis on specific opportunities where successful fixes have been incorporated. In addition, the report documents some of the actual application challenges faced by the customer and the installers.

2
DC DRIVES AND THEIR APPLICATIONS

Before addressing power quality related problems associated with DC variable speed motor and drive systems, it is useful to have a basic understanding of the drive design topologies. This working level knowledge will aid the reader in understanding the technical challenges associated with resolving power quality problems for the various designs. An important objective of this section will be to give a good understanding of the common terminology.

DC Drive Design Topologies

In order to specify power conditioning solutions, the reader will need to understand the difference between an SCR current source drive, a DC chopper type drive, and a single-phase DC drive. The reader will also need to understand the power quality issues associated with regenerative braking. These items are detailed in the following paragraphs.

Basic Three-Phase SCR Converter Topology

The most common DC drive technology is the silicon controlled rectifier (SCR) converter type, where the primary components of the drive are the front-end converter and a DC field winding source. Both of these sources must be able to ride-through electrical disturbances during normal operation as well as during regenerative operation. Controlled rectifiers employing thyristors (i.e., SCRs) are generally used for speed control in industrial DC motor drive systems as shown in Figure 2-1.

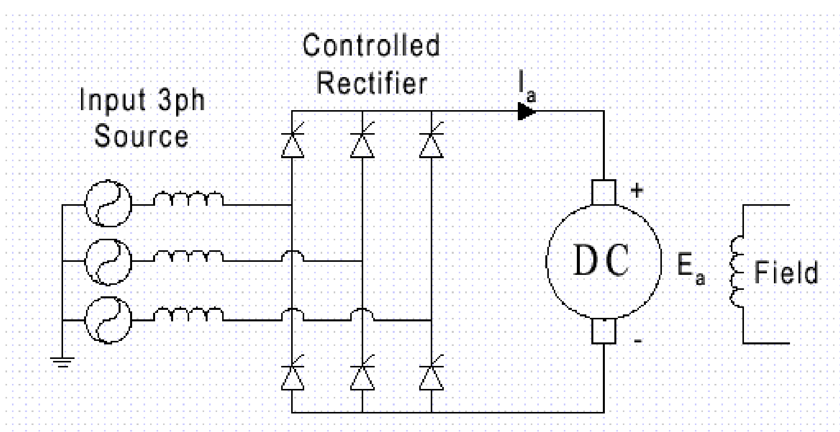

Figure 2-1
Three-Phase SCR DC Drive Converter Topology

Controlled rectifiers provide a variable DC output voltage to the armature circuit by varying the phase angle at which the thyristors are fired relative to the applied AC line voltage. Adjusting the phase angle, and subsequently increasing or decreasing the duty cycle of the rectifier changes the DC motor speed. The commutation of the rotor current is undertaken by the mechanical arrangement of the commutator and brushes. For increased flexibility in controlling the DC motor, the field winding is excited by a separately controlled DC source. This may be generated by another SCR bridge (for speed control above the base speed through field weakening), where the control can be completely variable, or fixed but chosen by the user. Alternately, the field can be completely fixed and supplied by a diode bridge. In all cases, for complete ride-through, this field excitation must be made robust enough to ride-through a power disturbance.

During normal operation of the drive, an SCR is fired every 1/6 of a cycle in a sequence determined by the phase rotation of the AC supply, with each SCR conducting for 2/6 of a cycle. The gate timing of the SCRs is precisely controlled relative to the supply voltage waveform to yield an output with the desired average voltage. Usually a feedback loop (voltage or speed) controls this firing angle. Modern DC drives incorporate timing circuitry that normally synchronizes to the zero crossing of one of the line voltages. A phase-locked loop (PLL) stabilizes the timing circuitry. Phase rotation is determined automatically. Consequently, the firing sequence is determined by the drive’s internal sensing circuitry. Most drives monitor the RMS value of the incoming waveform (usually through a peak detecting circuit) and will trip for undervoltage, overvoltage, phase loss, and excessive current (either line current and/or armature current).

Voltage sags can create havoc with the timing circuitry for the SCR-based DC drive. The firing circuit timing requires a solid zero crossing, and looks for this zero crossing to occur at a regular interval. The phase angle jump that occurs during a voltage sag will impact the regular interval of the zero crossing and may cause the drive to lose synchronization with the source. The PLL circuit can usually hold the synchronization for a short time. Too often, however, the drive will experience confusion in the timing circuit. Some drives will initially disable firing of the SCRs during the anomaly and allow the motor to coast. Other times, the phase jump will cause a phase-loss detector to trip the drive. In an extreme case, the phase sequence detector will sense a reversal of the phase rotation of the source, and will begin firing the SCRs in the incorrect sequence. In this case, the drive will either trip due to overcurrent, or blow one of the input fuses or SCR protection fuses.

Three-Phase DC Drive with Chopper

The DC drive and chopper topology utilizes a diode rectifier (similar to that used in an AC drive front-end) followed by a DC-DC converter (chopper) as shown in Figure 2-2. This topology is widely used in lower power servo and high power traction applications (single-phase). Since DC drives with chopper topologies have the same rectifier front end as AC drives, ride-through is achieved in a similar way to that for AC drives. Choppers provide a variable DC voltage from a fixed DC supply voltage by controlling the on-to-off time ratio for which the DC supply voltage is applied to the motor. Similar to the SCR-type drive, the commutation of the rotor current is undertaken by the mechanical arrangement of the commutator and brushes. The field winding is excited by a separately controlled DC source, or the field can be completely fixed and supplied by a diode bridge.

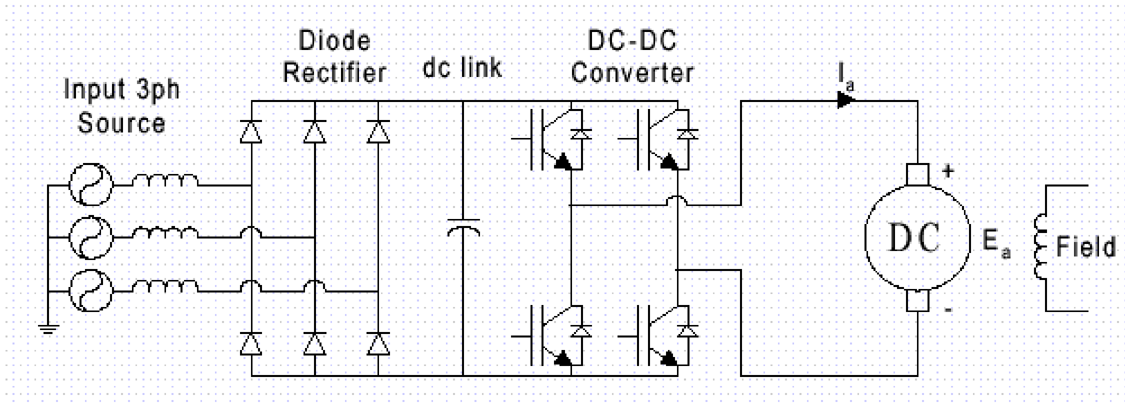

Figure 2-2
Three-phase DC Drive with Chopper

Single-Phase DC Drives

Single-phase DC drives are commonly used for lower power levels (1/4 - 2hp) for applications such as small conveyors, printing presses, mixers, robotics, exercise equipment, etc. At higher power levels, three-phase systems are used due to their improved input (lower harmonics) and output quality (lower armature ripple current, and better motor performance). The single-phase DC drive may be full wave rectified (Figure 2-3) or may be half wave rectified.

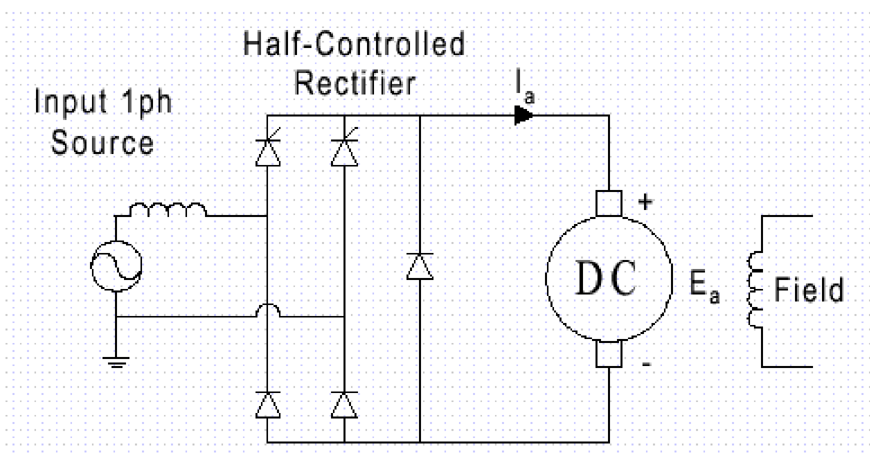

Figure 2-3
Single-Phase Full Wave Half Controlled DC Drive Topology

Regenerative Braking

In some applications, such as in the steel and paper industries, regenerative braking and speed reversal are required frequently. Applications requiring DC motor braking for speed reduction and reversal dictate the need for four-quadrant control of the drive. Power can either be drawn from the utility source or injected back to brake or slow down the DC motor. For full control of the DC motor, two back-to-back connected thyristor converters can be used as shown in Figure

2-4, which allows four-quadrant operation. Torque can be reversed by first zeroing the current in the bridge, providing motoring current, and then increasing the current in the inverse parallel bridge. Speed reversal is accomplished by reversing the roles of the forward and reverse converters. Care must be taken upon reversing the DC current since a short circuit path exists if both the forward and reverse bridges are triggered simultaneously. Therefore, the currents in both bridges must remain at zero for a time before turning on the reverse conducting bridge. This allows the forward conducting bridge to recover its blocking ability.

During regenerative braking, the active converter operates as an inverter and the DC motor acts as a generator, supplying power to the electrical system (see Figure 2-4). If a voltage sag occurs during this inversion operation, insufficient line voltage and commutation failure could occur, resulting in blown fuses and interruption of the process.

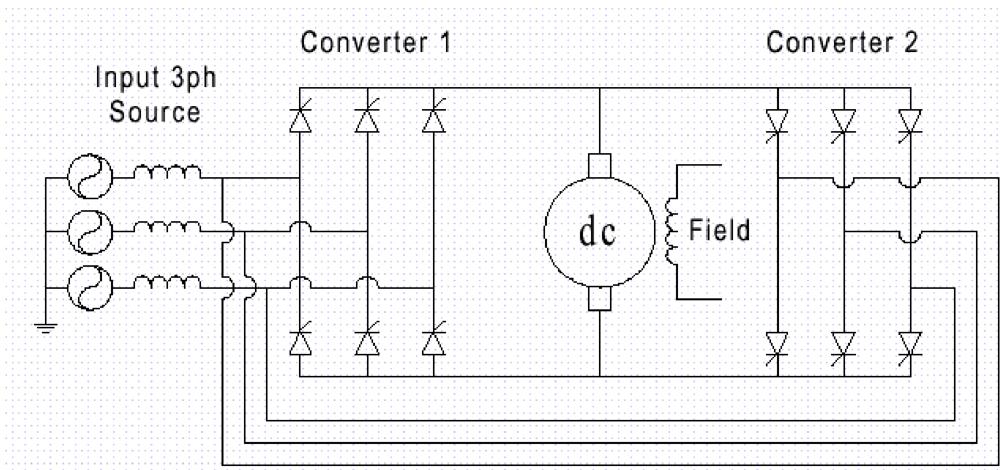

Figure 2-4
Three-phase DC Drive with Regenerative Braking Circuit

Commutation Failure During Regeneration

During regenerative braking, the DC motor becomes a current source and the regeneration bridge rectifier back feeds the AC power source. Thyristor turn on is controlled by the gate driver, and turn off begins to occur when the voltage across the thyristor goes negative. During a sag condition, commutation failure (i.e., the failure of current to commutate from one thyristor pair to another) will occur and cause a short circuit condition of the regenerative DC motor load. This results in large destructive currents. Therefore, DC drives are more susceptible to voltage sags during regenerative braking than they are during normal operation.

3

DC DRIVES AND POWER QUALITY VARIATIONS

While DC drives are certainly sensitive to power quality variations, they also have the potential to reduce the level of power quality for a facility if not specified and installed properly. For example, along with facility level increases in harmonic voltage and current distortion, the SCR-type rectifier used in many drives can create commutation notching. This notching and their associated voltage transients can potentially create problems for other facility equipment and in some cases, even cause problems with the process where the offending drive is used. This section details the ranges of electrical disturbances that may cause upset of DC drives, and describes the range of disturbances that the drive itself may contribute to a facility.

Power Quality Variations That Upset DC Drives

Most state regulating bodies adopt ANSI C84.1, “Electric Power Systems and Equipment - Voltage Ratings (60 Hertz),” as their standard for service voltage. For low-voltage delivery (120 volts to 600 volts), ANSI C84.1 requires a voltage between ±5 percent of the specified system nominal voltage. Therefore, for the purposes of this document, any voltage deviation outside of this range for any period of time will be considered a power quality variation. All descriptions of power variations derive from the IEEE Standard 1159 “Recommended Practice on Monitoring Power Quality.” Some example graphical representations of the electrical disturbances discussed in this report are shown in Figure 3-1.

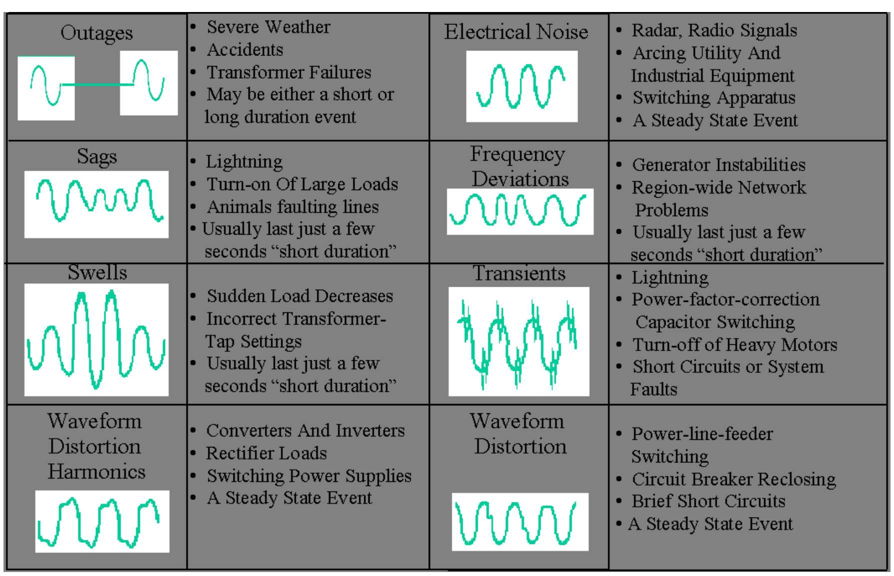

Figure 3-1
Graphical Representations of Applicable Electrical Disturbances

IEEE Standard 1159 categorizes the disturbances by type as well as duration and frequency (or spectral content). In general, the disturbances can be categorized using their duration and may be thought of as transient, short duration, long duration, or steady state. A transient event would be over within a split second (e.g., a lightning strike). A short duration event would last just a few seconds. A long duration event would last minutes or hours, and a steady state event would be continuously observable (e.g., flicker in lighting systems). For the purposes of this report, some basic definitions are provided for each event with a brief description of how DC drives and the peripheral controls and equipment in an industrial process may be affected by the variations. This will allow for later discussion of potential solutions.

Oscillatory Transient (Duration – Split Second)

Oscillatory transients are distortions of electricity caused by the starting/stopping of large motors, capacitor switching, and other electronic loads. As opposed to an impulsive transient, an oscillatory transient has two directions (both positive and negative). These electrical disturbances can damage the electronic equipment, cause process controls and adjustable-speed drives to trip, and corrupt data. The general mode of disruption from these transients is upset as opposed to damage and in most cases, the DC drive is the transient generator. Primarily, the SCR-style drive creates these oscillatory transients during SCR commutation.

Impulsive Transient (Duration – Split Second)

Impulsive transients are distortions of electricity caused by nearby lightning strikes and the opening of an inductive circuit. As opposed to an oscillatory transient, an impulsive transient has only one direction (positive or negative). These electrical disturbances can damage the components of electronic equipment, cause process controls and adjustable-speed drives to trip, and upset logic controlled processes. Impulsive transients, while uncommon, will generally result in equipment damage, such as failures of front-end rectifiers and blown fuses.

Interruption (Typical Duration Less Than a Second to a Few Hours)

Interruption to the industrial facility generally means a process stoppage. Electrically speaking, an interruption means the voltage has gone away completely for some period of time. This is usually the result of a circuit breaker or other protective device opening up momentarily, or in more severe cases, electric service system hardware failure. Generally speaking, if the power is interrupted for any duration at all, the equipment is going to trip off line or will reset. This report will investigate opportunities to help DC drives withstand some of the shorter interruptions lasting less than a few seconds, as well as opportunities to hold the process up with backup power systems while generators or other emergency systems come on line.

Voltage Sag (Typical Duration Less Than a Few Seconds)

A voltage sag is a brief decrease in the normal steady state voltage level. Motors starting and remote faults can cause voltage sags in the electric service system. In an industrial environment, voltage sags are notorious for causing DC drive trips as well as peripheral process equipment to shut down. According to power quality studies throughout the world, the sag is the most prevalent RMS power quality variation, occurring eight to ten times more often than interruptions. Particularly with SCR-type DC drives, the detection circuits will cause the drive to shut down if the half-cycle RMS voltage drops below about 87 percent of the nameplate rating. This ensures that the SCRs can commutate properly. For chopper type drives, the voltage typically drops to about 80 percent for three-phase sags before the drive shuts down, and drops even lower for single-phase sags. If a sag occurs during regenerative operation, the drive will trip at the 87 percent level regardless of the number of phases sagged.

Undervoltage (Typical Duration a Few Minutes to a Few Hours)

An undervoltage is simply a version of a voltage sag that lasts quite a bit longer and is normally not as severe in terms of how much the voltage drops down from the normal steady state voltage level. Undervoltage conditions can cause equipment to react much more sensitively to sags and interruptions than might otherwise occur because the equipment does not have the energy storage that it would have at normal operating voltage. Generally, the results of an undervoltage are identical to those experienced during the voltage sag previously described.

Voltage Swell (Typical Duration Less Than a Few Seconds)

A voltage swell is a brief increase in the normal steady state voltage level. Switching off large loads, remote faults in the power system, and capacitor switching can generate voltage swells. Swells can cause DC drives and peripheral controls and equipment to shut down, components to overheat, and fuses to blow. DC drive regeneration can also cause a voltage swell, which then must be absorbed by the electric power system. This requires some coordination and process optimization, usually through the system integrator or the manufacturer of the drive to ensure successful process operation.

Overvoltage (Typical Duration a Few Minutes to a Few Hours)

An overvoltage is a version of a voltage swell that lasts quite a bit longer and is normally not as severe in terms of how much the voltage increases from the normal steady state voltage level. If the overvoltage condition exceeds approximately 15 percent of the equipment nameplate maximum rating, this can cause equipment to be much more prone to overheating and insulation failure than normal. For DC drives, an overvoltage will typically cause a trip, as the unit will self-protect itself when the overvoltage trip threshold is exceeded.

Voltage Notches and Noise

Voltage notching is a periodic voltage disturbance caused by the normal operation of selected electronic equipment's internal semiconductor switching devices commutating current from one phase to another. DC drives are definitely generators of this type of disturbance. During commutation, two phases of a three-phase voltage source are nearly short circuited, causing notches in the respective phase-to-phase voltage. Voltage notches, while not a threat to equipment components, can cause microprocessor-based control systems and computer equipment to shut down or lock up. If the corresponding transients created along with the voltage notching are near the zero crossing of the sinewave (see Figure 3-2), digital clocks and timing control circuits can run or count too fast, resulting in time errors and process malfunctions.

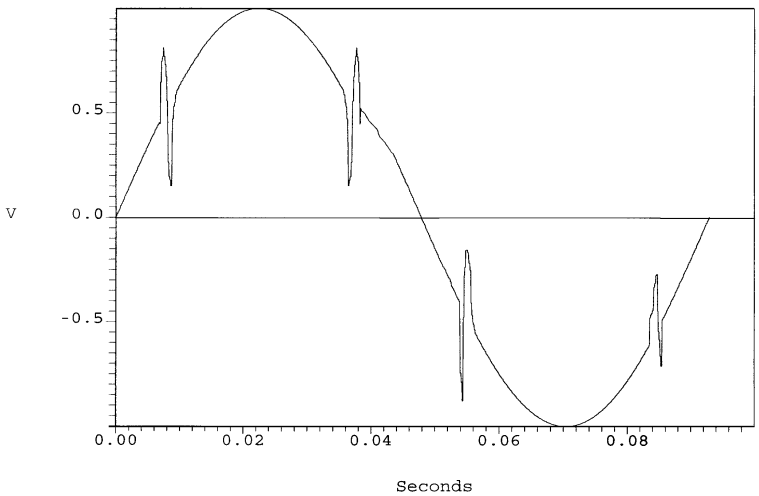

Figure 3-2
Example Voltage Waveshape with Commutation Notching

Harmonic Distortion

Harmonic distortion is the presence of frequencies in the voltage or current that are multiples of the fundamental power frequency. DC drives always create harmonic current distortion. Generally, as long as the power system is sized to handle the harmonic currents generated by the drive, there will be no problems. If the system is undersized, the harmonic currents flowing through the impedance of the power system will create voltage drops at those harmonic frequencies, resulting in voltage distortion. Harmonic distortion can cause overheating of electrical equipment and wiring. If this distortion reaches levels that cause other equipment to malfunction, the problem will need to be fixed through methods such as the installation of isolation transformers, line reactors, or harmonic filters.

How Often Do These Disturbances Occur?

Efforts to define electrical environments are documented through an assortment of power quality surveys both in the United States and around the world. This document includes a summary of the North American surveys with the likelihood of occurrence of the various types of disturbances. The most prominent and comprehensive North American studies of electric service system power quality are those studies conducted by EPRI, the Canadian Electrical Association, and National Power Labs. Each of these studies was conducted at a different power system connection point. Therefore, the combined results yield an extremely credible assessment of overall power quality regardless of connection location or voltage level. Between the three surveys, there is information on utility distribution system voltage performance, building service entrance performance, and also single-phase 120 volt "point of equipment connection" performance.

For the purpose of evaluating load equipment sensitivity, the results of these power quality surveys were combined into a power quality performance profile that is shown in Figure 3-3.

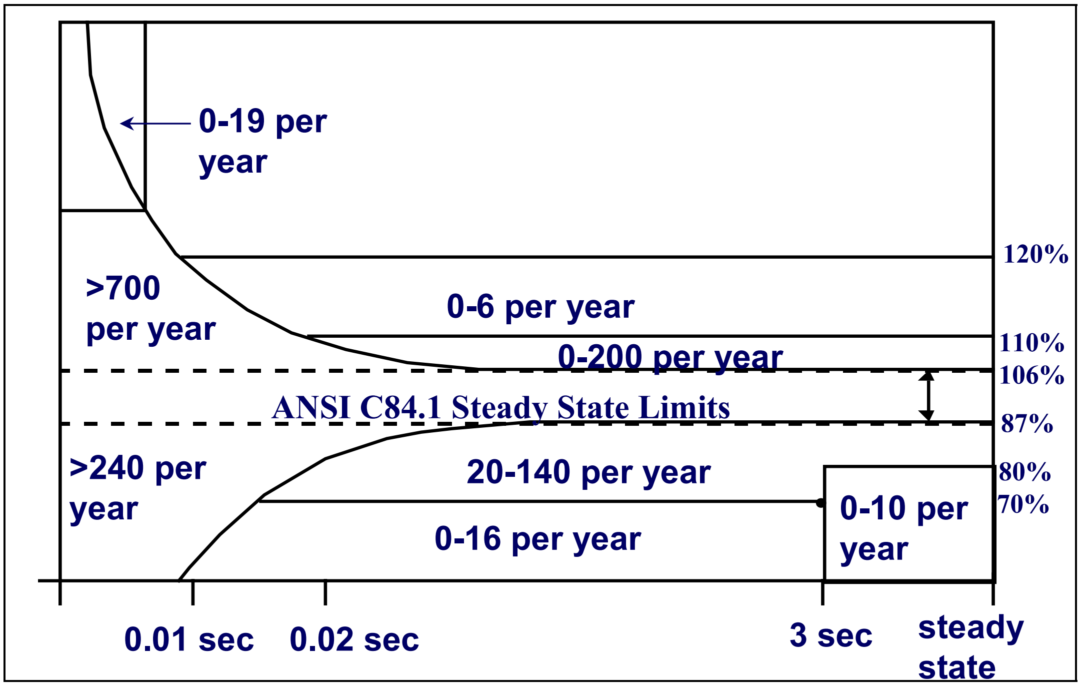

Figure 3-3
Disturbances Per Year Probability Profile From PQ Survey Data

Figure 3-3 shows a yearly average for all locations monitored in terms of how long the disturbances last and how severe they can be in terms of either voltage that is lower or higher than the steady state system nominal voltage level. For example, the range that indicates zero to six disturbances per year can be interpreted as follows: Ninety-five percent of all sites in North America will experience some number of disturbances between zero and six per year with severity greater than 110 percent of the normal steady state voltage level, but not more severe than 120 percent of the normal steady state voltage level.

Each of the ranges in Figure 3-3 can be interpreted with a similar type of logic looking at both of the axis parameters of how long and how severe. This particular figure is extremely useful when we also know how well the equipment is able to tolerate either low or high voltage, and when we want to predict how often that equipment will have upsets in a given year. It can also be beneficial for industry organizations and manufacturers who want to design their equipment to withstand the greatest number of electric service variations for the lowest possible cost. An example of this is shown in Figure 3-4. Sag and undervoltage information from Figure 3-3 has been overlaid with information on how often some industrial control equipment test results (developed by EPRI PEAC Corporation) are impacted by power quality variations.

This figure shows that the programmable logic controller profiled would be upset less than five times per year. The 120 Vac relay profiled would be upset more than twenty times per year because it is more sensitive to voltage variations than the other devices.

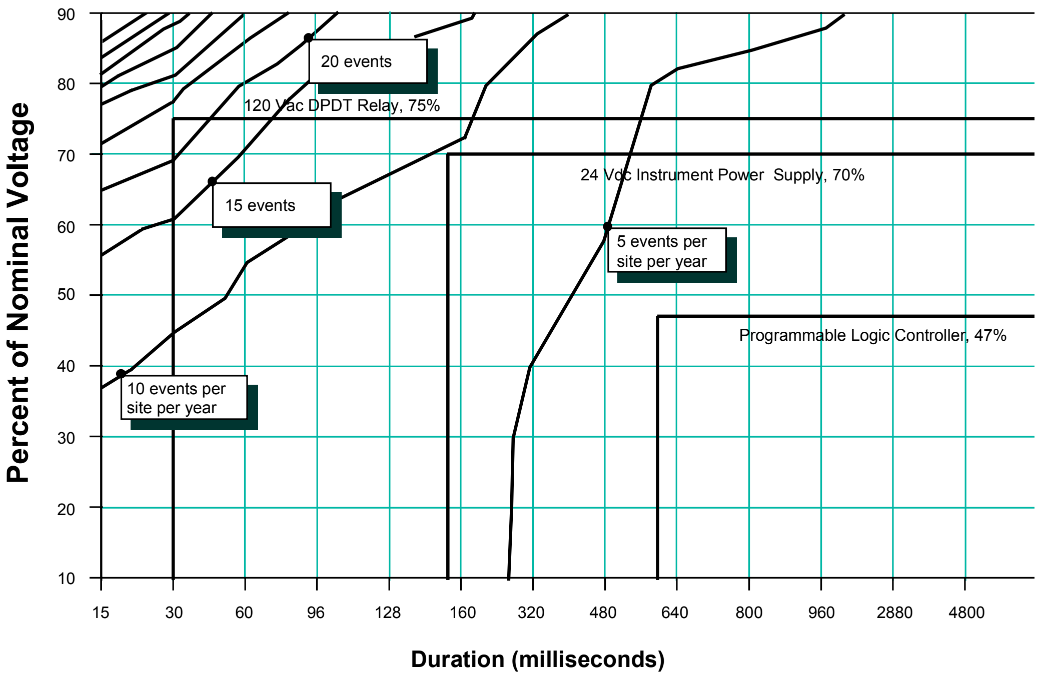

Figure 3-4
Sag and Undervoltage Impacts on Industrial Control Equipment (Events Falling below the Horizontal Line and to the Right of the Vertical Line will Upset Each Piece of Equipment Shown in the Figure)

Overall, there are two conclusions that can be drawn from the power quality survey data that has been collected. One conclusion is that the majority of electrical disturbances do not last very long. In fact, nine out of ten disturbances last less than a few seconds. This means that if the connected equipment has the ability to withstand a few seconds of variation in voltage, it may not be affected by many of these short disturbances. Another conclusion is that voltage sags are the most common of all electrical disturbances. Long interruptions can and will occur, but generally they are limited to just a few per year. Overvoltage disturbances can occur as well, although they are not very common. Based on this information, we find that the best ways to improve the performance of DC drives, their corresponding controls, and the processes into which they are integrated is to target the most common power quality variations and evaluate ways to provide drive ride-through for those events.

4
DC DRIVE SOLUTION OPPORTUNITIES

DC drive solutions for power quality ride-through are some of the most challenging in terms of both cost and feasibility. However, successes in the field have been documented, and with a good understanding of the drive topology and the process requirements, any process utilizing DC drives can be assessed for potential ride-through opportunities. The primary opportunities presented in this section are for sag and momentary interruption-related upset because these are the most common power quality problems associated with DC drives. By using a systematic approach, DC drive ride-through solutions can be evaluated within five categories.
These include:

- Retrofit solutions
- Control power solutions
- Programming solutions
- Embedded solutions
- DC drive replacement with AC technology

Each of these opportunities is detailed in the following sections. Where there is a distinction, the opportunities are segregated by the DC drive topology (e.g., SCR type, chopper type, or single-phase) and by whether special considerations exist for regenerative applications.
A summary table has also been included to aid in cross-referencing the entire range of solution opportunities.

While this section focuses primarily on momentary sag and interruption ride-through of the drive and the drive controls, it is widely recognized that DC drives can also create voltage distortion problems and transient generation problems. These problems are beyond the scope of this document, but there are a number of references that focus on the application of isolation transformers and/or harmonic filters to minimize the impact of the drive on the rest of the facility and on the utility power system. For a primer on drive-induced harmonics and voltage notching, see IEEE Standard 519, “Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.”

Retrofit Solutions for Sag and Momentary Interruption Mitigation

Retrofit solutions described here include modifications intended to improve the voltage quality supplied at the DC drive input terminals. Examples include installation of power conditioning devices, improvements to either nominal steady state voltage or the existing voltage balance, and installation of add-on circuitry or controls intended to keep the drive from shutting down.

With retrofit solutions, it is very important to ensure that the DC source controlling the motor field winding is conditioned along with the primary drive input.

Improvements to Nominal Steady State Voltage Levels

The first line of defense against low RMS voltage variations (primarily voltage sags) is to ensure that the DC drive has a nominal operating voltage that is "at or slightly above" the steady state nameplate rating of the drive. This step is essential to help minimize the number of nuisance trips experienced by the DC drive system. Actual field problems with DC drive nuisance tripping have been partially resolved by bringing the nominal voltage at the drive terminals to a level that is slightly above the equipment nameplate rating. Many DC drives will typically be set with a sensitivity threshold at 87 percent of the nameplate voltage and will trip if the voltage drops below this value for more than a few cycles. The drive will use either peak detection or RMS detection circuitry to monitor the input voltage and determine when to shut down or trip. Because the trip threshold is a fixed value (e.g., 400 volts for a 460 volt rated drive), the higher the nominal voltage, the better the chances of the drive not tripping during moderate voltage sags). The primary means of accomplishing steady state voltage improvement is to either adjust transformer tap settings upstream of the drive (where possible), or to use buck-boost transformers when it is not feasible to tap-up the voltage at the upstream transformer.

The tap-up options are either at the facility/area service transformer or at any downstream isolation transformer supplying the drive. The challenge with tapping up the facility/area transformer is that all loads on that feed will see the increase. For larger facilities, this can be a problem during light load conditions and on weekends when the voltage may become unacceptably high. *The recommended practice before performing any tap changes is to monitor the steady state voltage for a few weeks. This establishes a high and low steady state baseline and ensures that tapping up the transformer will keep the steady state operational voltage from exceeding plus ten percent of the desired system nominal during light load conditions*.

Buck-boost transformer options are generally performed at the drive or at the panel supplying the drive. Buck-boost transformers come in a variety of voltage ratings and are versatile because their terminals may be field-connected in many ways to meet the voltage requirements of industrial equipment, including connection as a standard fully isolated transformer. A buck-boost transformer can be field-connected as an autotransformer, which can either decrease (buck) or increase (boost) the supply voltage from five to twenty percent, depending on the way the primary and secondary windings are connected. Because only the secondary windings carry load current in an autotransformer configuration, a buck-boost transformer can supply a load rated as much as ten times higher than the kVA rating on the transformer nameplate. And although buck-boost transformers are single-phase, they can be applied to most three-phase equipment by matching three single-phase transformers. As an autotransformer, the buck-boost transformer has two principal applications in an industrial environment. First, it can be used to match an existing utilization voltage to equipment voltage. Because a buck-boost transformer can be configured as an autotransformer, it can match this load to an existing power supply. Such a transformer would be smaller and therefore considerably less expensive than a step-up or step-down isolation transformer. A circuit diagram for a typical buck-boost transformer is shown in Figure 4-1.

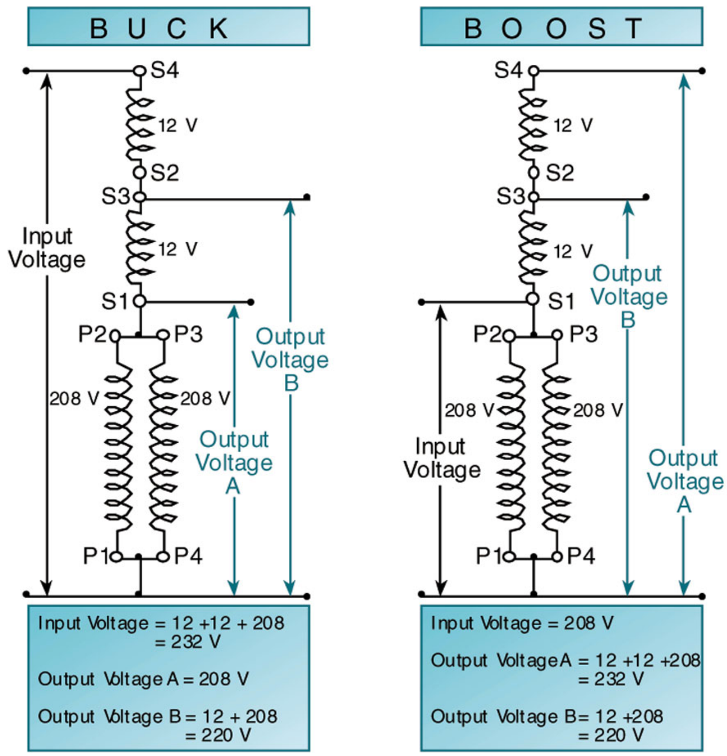

Figure 4-1
Buck-boost Transformer Circuit Diagram and Connection Configurations

Improvements to Steady State Voltage Balance

The second line of defense against low RMS voltage variations is to ensure adequate voltage balance between the phases at the drive terminals. While this balanced voltage recommendation may not seem to be low voltage trip related, it actually is. During unbalanced voltage sags, the DC drive can trip (either due to low RMS detection or to armature current unbalances). In addition, with the SCR drive topology, the better the voltage balance, the easier it is for the SCR pairs to commutate. In theory, a drive that is only running at half load could ride-through a sag down to 50 percent of nominal voltage without problems as long as the SCR pairs commutate properly. Unfortunately, the majority of voltage sags are single-line to ground, usually resulting in a two-phase sag at the drive terminals. The deeper the sag, the less likely the drive will be able to properly commutate the SCRs.

If voltage unbalance is already present, the situation is exacerbated, so it is important to ensure optimum voltage balance for DC drive feeder circuits. It is not a focus of this document to detail the methodology for improving voltage balance for facilities and power systems. An excellent reference for this procedure is EPRI PEAC PQTN Application #12, “Matching Utilization Voltages to Motor Nameplates.” Along with procedures for evaluating motor compatibility, the document contains sections on the use of buck-boost transformers and a procedure for improving power system voltage balance.

With optimum voltage balance and voltages at or above the nominal equipment nameplate, drive tripping problems can be minimized. While a proper steady state nominal voltage is not going to solve all drive tripping problems, in many cases it can reduce the number of nuisance trips by one-third to one-half. *This is recommended as the first step in DC drive sensitivity reduction.*

Utilization of Power Conditioning Devices

A number of power conditioning devices have been proposed for use with DC drives. Most are expensive with respect to the initial drive installation, as they involve sizing the power conditioning for the entire load rating of the drive. Some devices are not economically feasible or are still in the research and development stage. The primary concept behind DC drive power conditioning device solutions is to keep the voltage at the input terminals to the drive at a level greater than ninety percent of the nameplate rating with minimal voltage unbalance. For fractional and small horsepower DC drives, the costs for these solutions may be easy to justify. Larger systems will require a comprehensive understanding of the costs of equipment upsets and a corresponding cost-payback analysis involving the estimated annual losses and the power conditioning equipment installed costs. The list of potential solutions that are available today that can accomplish this objective include:

- Motor Generator Sets
- Uninterruptible Power Supplies with Battery Storage
- Uninterruptible Power Supplies with Flywheel Storage
- Uninterruptible Power Supplies with Ultracapacitor Storage
- Dynamic Voltage Injection Power Conditioners

A number of EPRI reports listed in the bibliography provide detail on these power conditioning technologies. These technologies are now commercially available from one or more vendors, and prices on some are coming down considerably as these devices gain popularity. Some of the non-commercially available technologies that may be available in the future have been omitted from this list, such as the super conducting magnetic energy storage device and fuel cells.

Without going into detail on the specifics of each technology, it is sufficient to say that each listed device can perform full load support for the DC drive (provided the output specifications meet the greater than ninety percent voltage requirement). It is a matter of feature preference, as well as whether or not the cost-payback analysis is acceptable. Selection of the most appropriate power conditioning device from the bulleted list can be accomplished using the following procurement specification.

1. The output of the power conditioning unit shall provide at least ninety percent of the drive nominal nameplate voltage rating for the duration specified by the process engineer. (This duration may be one-half second, if sag and momentary interruption support are all that is required, or may be as much as ten to twenty seconds, if it is desirable to bring emergency backup generation on line without dropping the process.)

2. The output of the power conditioning unit shall provide sinusoidal voltage to the supported load with not greater than one percent voltage unbalance for the duration specified by the process engineer.
3. The power conditioning unit shall be rated to operate without failure or degradation within an operating temperature environment as specified by the process engineer. (Depending on the environment, it may be advantageous to use one of the battery-free uninterruptible power supply (UPS) technologies if temperature extremes are anticipated and battery lifecycle reduction is a concern.)

Control Power Solutions and Field Winding Solutions

Control power solutions include the logic and control circuit of the DC drive as well as any external controls. When considering conditioning of drive controls, any external starters, contactors, emergency stop circuitry, and logic controller devices also need to be conditioned. There are a number of low cost power conditioners that can accomplish this conditioning task, ranging from constant voltage transformers, to UPS products, to coil and contactor hold-in devices. It is important to recognize that conditioning just the drive itself will not always work, if the control power elements are not also conditioned. *It is a recommended practice to always apply power conditioning solutions to the drive controls, control power circuit, and to the field winding for the DC drive any time power conditioning is applied to the primary drive input.* The primary specification for these control power solutions is that the conditioning device should have a sinusoidal no break output at all times. Even a one millisecond break in the output waveshape is enough to cause sensitive relays and contactors to trip off line, so care must be taken to ensure that the no break specification is met and has been tested out in actual field situations.

A unique opportunity does exist with respect to the DC drive chopper topology to condition just the controls and the field winding without necessarily having to condition the primary drive input. If the drive is not regenerative and utilizes the chopper topology, success can be achieved for the majority of short duration voltage sags (less than one-half second) by conditioning the controls and the field winding.

For the chopper drive, there is also an opportunity to provide DC bus support by utilizing one of the DC bus ride-through devices available, such as the one described in the EPRI PEAC Test Brief #34, "Performance of an ASD Ride-through Device During Voltage Sags." These devices provide energy to the DC bus of AC adjustable speed drives and to chopper type DC drives to keep the DC bus at a level greater than the undervoltage trip setting. This enables the drive to stay on line during voltage sags down to approximately forty percent of nominal voltage. They will not help SCR-type DC drives, but work well for any voltage source drive such as the DC chopper and most AC drives.

Programming Solution Opportunities

Programmed ride-through involves a number of opportunities requiring dialogue between the process engineer and the drive manufacturers' application engineers. A few examples include:

- Changing the drive control algorithm to stop firing the rectifier during sag and interruption conditions
- Turning of the SCR firing control to stop regenerating during sags
- Delaying armature overcurrent and unbalance signals for a period of time long enough to ride-through a ten or twenty cycle voltage sag

Many drive manufacturers do have successful application case studies utilizing these techniques. Programming solution opportunities either by way of changes to the drive control algorithm or the occasionally available power quality firmware upgrades must involve the drive manufacturer as well as the process engineer. Once the torque and speed requirements of the process are clearly understood, and the manufacturer clearly understands the momentary nature of the disturbances (such as sags) that are being targeted for ride-through opportunity, then a decision can be made in terms of whether or not the application in question is a good candidate for programmed ride-through.

If the process requires constant speed and constant torque at rated load, then the process is not a very good candidate for programmed ride-through. For any other processes, programmed ride-through should be considered and is a viable solution to minimize the number of trips experienced by the DC drive. Even processes, where regenerative braking is extremely common (such as an elevator drive), may prove to be good candidates for programmed ride-through. Any time programmed ride-through is considered, the involvement of the manufacturer and the process engineer is essential. Regardless of whether this programming involves disabling the firing of SCRs or reprogramming the logic controller to wait a few seconds before reacting to relay contact fault signals, the same thought process must be used. This thought process (in order of priority) involves answering the following questions:

1. Safety – If I change the reaction of this piece of equipment so that it does not trip during voltage variations lasting less than a second or so, will the change compromise (or possibly enhance) any aspect of personnel or plant safety?
2. Performance – If I make the changes, will the process now have the ability to ride-through these momentary voltage variations that otherwise would result in lost production and scrapped or reduced quality product?
3. Cost/Benefit – Will the changes be justified in terms of reasonable payback if the number of process interruptions is reduced?

Embedded Solutions

Some manufacturers have begun to offer products that will withstand short electrical disturbances fairly well, or provide harmonic current minimization or noise isolation. These manufacturer-supplied options are referred to as “embedded solutions,” and are typically offered as an added cost item. It should not be expected that embedded power quality solutions would be built into the drive if the manufacturer was in a competitive bidding process and the required power quality performance capability was not requested in the original equipment procurement specification. Most embedded solutions are similar to those described in the previous section on programmed solutions with the addition of built-in ride-through for the controls and the field winding.

The primary means of attaining embedded solutions in new or upgraded DC drive applications is to utilize an equipment procurement specification. A good, generic equipment procurement specification will consider not only the drive, but also the controls and any ancillary support processes, such as steam, instrument air, lighting, etc. Following is a sample procurement specification that can help in obtaining "power quality friendly" DC drives and support processes.

- Specify the equipment's response to switching voltage transients as follows: "The equipment shall not trip as the result of transient overvoltages (impulsive and oscillatory) that can be as high as 2.0 per unit (of normal input voltage) at a damped frequency in the range of 300 to 800 Hz for one cycle. These transients may have significant energy associated with them but should not cause failure of the equipment's protective devices and other components that make up the equipment."
- Specify the equipment's response to voltage sags as follows: "At rated load, the electronic equipment shall be able to ride-through voltage sags down to fifty percent input voltage for thirty cycles without causing any disruption to the equipment and its associated loads."
- Specify the requirements for the equipment's input line-current total harmonic distortion as follows: "The equipment shall have appropriately sized AC line reactors, chokes, or equivalent impedance input isolation devices to limit the equipment's input-current total harmonic distortion to under forty-five percent at full load."
- Specify the need to evaluate the equipment's potential to be interfered with by RFI/EMI generated by other facility electronic and switching loads. Ask the equipment manufacturer about any special electronic equipment, separation and shielding of the input power line, cable separation and shielding, and grounding requirements. Also, request if there are any special cabling recommendations for all the equipment's control and process signal wires.
- Specify that the lighting and other support processes, such as steam and instrument air, have the ability to either "hold in" or restart if power returns to normal within two seconds of an electrical disturbance.

DC Drive Replacement with AC Technology

Traditionally, DC motor drives have been used in applications requiring high starting torque, high torque at low speed, and applications requiring precise speed and torque regulation. This is due to their low initial cost, excellent process control performance, and relatively simple control characteristics. However, in recent years, new high performance AC drive technologies have made these drives practical solutions to many applications where formerly only DC drives were used. The new generation AC drives, or vector control drives, allow drive users all the process control benefits once held only by DC drives. The "sensorless" vector control drive allows all the desirable DC motor control characteristics without the need for encoder feedback. This drive uses measurements of two motor currents and motor model parameters to control the speed and torque of the motor independently.

Test results conducted by the EPRI PEAC Power Quality Test Facility clearly show that AC drives are substantially less sensitive to power quality variations than their DC counterparts. In addition, the number of cost-effective power quality solution options for AC drives are easier to accomplish. Therefore it is a *recommended practice that for any new drive installation or replacement application, AC drives should be seriously evaluated as the technology of choice.* While the first costs may be a bit higher for the AC drive, the overall costs savings in reduced maintenance and power quality related downtime reduction could far outweigh this first cost difference.

Table 4-1 lists general drive performance parameters for the three most common adjustable-speed drives. Based on each application's requirements (e.g., tight tolerances for torque control, orienting the work product, or maintaining full torque at zero speed), Table 4-1 can be used to narrow down the particular drive technology that best suits the application. In the final analysis, the prospective process equipment vendors application engineer should be consulted for suggested enhancements that extend the utility of the best drives from among the varied offerings of drive manufacturers. For further reading, a comprehensive assessment of AC versus DC drive comparisons was performed by EPRI in 1998. That information is available in an EPRI technical report titled: *An Assessment of High Performance AC Motor Drives Versus DC Motor Drives,* EPRICSG, Palo Alto, CA: 1998. TR-112111.

Table 4-1
General Drive Performance/Cost Comparisons

Application Requirements	DC Drive – SCR	AC Drive – Volts/Hz Control	AC Drive – Sensorless Vector
Relative speed range	Wide (20:1)	Narrow (5:1-10:1)	Widest (6000:1)
Speed control	Yes	Yes	Yes
Torque control	Maybe	No	Yes
Positioning	Maybe	No	Maybe
Orienting (zero index)	Maybe	No	Yes
Open loop speed Regulation	± 2% of base speed	± 3% of base speed [1]	± 0.4% of base speed [1]
Closed loop speed regulation	±1% of set speed	± 1% of set speed	± 0.01% of set speed
Can maintain full torque at zero speed?	No	No	Yes
Motor brushes required?	Yes	No	No
Can operate multiple motors from one control?	Yes, but not recommended	Yes[2]	No
Relative cost	$	$-$$	$$-$$$

Source: EPRI TR-112111
Notes: [1] Governed by motor size and motor percent slip
[2] Individual motor protection must be considered

Summary

A number of ride-through solutions have been presented to resolve power quality related problems for DC adjustable speed drives. The specific options include: retrofits, control power and field winding protection, programming fixes, embedded solutions, and replacements with compatible AC drive technologies. Each of the described solutions has been evaluated, and more information on the advantages and disadvantages of each application is available from the engineering team at the EPRI PEAC Power Quality Test Facility in Knoxville, Tennessee. These efforts have been spearheaded primarily through the leading electric utilities that sponsor EPRI's system compatibility research project. Through this research, drive incompatibilities with electric power have been evaluated. Solutions have been proven either at one of the test labs that participates as part of the power quality test network or in actual field installations with a willing end-user. The conclusion is that while DC drives are one of the most challenging technologies to improve from a power quality standpoint, it can be done if the solution cost-payback proves reasonable. Each of the solutions described has been put into Table 4-2 for quick reference and comparison purposes.

Table 4-2
Comparison of DC Drive Power Quality Improvement Opportunities

Proposed PQ Improvement Solution	Applicable to:			Typical Size Range for This Solution	Cost vs. Motor/ Drive System	Comments
	SCR	Chopper	1 Ø			
Increase steady state nominal voltage at drive terminals	√	√	√	Any	0-10%	May be accomplished via existing transformer taps or by installing buck-boost transformer
Improve steady state voltage balance at drive terminals	√	√		Any	0-10%	See PQTN Application Note #12 referenced in the bibliography for more information
Motor generator sets with UPS transition ability	√	√		>100kVA and custom sizable for load	>100%	Usually most cost-effective in large sizes when a full process or multiple processes need protection
UPS with battery storage	√	√	√	Custom sizable for load	100%	Most cost-effective storage technology to date
UPS with flywheel storage	√	√		100kVA to 500kVA	100%	Cost-effective for ride-through less than thirty seconds
UPS with ultracapacitor storage	√	√		>100kVA to 500kVA	100%	Technology is now cost comparable to battery storage for ride-through less than thirty seconds
Dynamic voltage injection power conditioners	√	√		500kVA to 10 MVA	>100%	Usually most cost-effective in large sizes when full plant or multiple processes need protection
Control power solutions	√	√		1kVA to 10kVA	<20%	Recommended for all DC drive process related upset
Field winding solutions	√	√		1kVA to 10kVA	<20%	Recommended for all DC drive process related upset
Programming modifications	√	√		Any	<10%	Important to ensure safety is not compromised
Control card retrofits	√	√	√	Any	<25%	Requires manufacturer involvement
Embedded solutions	√	√	√	Any	10-20%	Use power quality procurement specification checklist
Replace DC drive with AC	√	√	√	Any	100-200%	Cost-effective when lifecycle analysis is performed

5
IMPLEMENTATION CASE STUDIES

To demonstrate successful DC drive solutions that have been implemented in the field, several papers have been included as references in the bibliography, and a summary of these case studies has been included in this section for convenience. The specific cases described here include one case where a CNC machine utilizing DC drives on the servo was sensitive to voltage sags; one case where a printing press was experiencing paper tearing voltage sags; and a case where a DC motor-controlled capstan on a wire drawing machine was creating wire breaks during voltage sags.

CNC Machine Case Study

This facility manufactures high priced helicopter components, and they had been experiencing substantial losses (greater than ten thousand dollars per event) each time a voltage sag occurred. The CNC machines on site that fabricated the helicopter parts were complex processes, each containing a DC servo drive, a DC gear drive, an AC spindle drive, a programmable controller, a DC power supply, and several sensitive relays and contactors. It was determined that while the DC drives were probably the most sensitive components in the process, a full machine solution would be needed because the other process elements were very sensitive as well. Monitor data indicated that sags at ninety percent of the system nominal voltage were tripping the machines. Because of the tree and animal exposure out of the substation supplying this facility, sag events at or below this level could occur thirty to fifty times per year.

After discussing the problem with the facility engineer, it was understood that only eight of eleven machines would trip during the sag conditions, while the other three operated through all but the most severe events. With this information in mind, a quick audit of the control cabinets for each of the machines was undertaken. The findings were that the nominal voltage feeding the entire group of CNC machines was 225 volts. The eight machines that did trip had nameplate nominal ratings of 240 volts while the three machines that did not trip had 200 volt nominal nameplate ratings. The facility engineer indicated that before the three new machines with the 200 volt nameplates were procured and brought on line, the service transformer had been adjusted one tap setting to bring the nominal voltage down from the old nominal of approximately 245 volts. He also indicated that the tripping problems became much more frequent after the tap change.

The solution to this problem was to tap the voltage back up so that the eight 240 volt rated machines were less prone to nuisance tripping. In addition, buck-boost transformers were used on the three machines that required 200 volts to buck the voltage down on those machines to a level slightly above the 200 volt rating. The end result was a reduction in the number of nuisance trips to less than ten per year, and a customer that was reasonably satisfied with the reduction. The cost was less than $5,000 per machine to procure and install the buck-boost transformers. The customer investment was minimal compared to the price of a UPS or other full power conditioning solution for these 100 kVA rated machines. While the full power conditioning solution would have reduced the number of damaged and scrapped parts to nearly zero, the installed price of approximately $100,000 per machine did not yield a reasonable cost-payback period.

Newspaper Printing Press

The printing presses at a major newspaper publishing facility were tripping off line due to voltage variations on the incoming power line. The facility has four printing presses, each of which is fed from twelve large spools of paper. Each spool is powered by a twelve-horsepower DC motor and DC drive. If one of these drives trips off line due to an undervoltage, the paper is torn from the spool and the process is stopped. While the process is down, the torn paper must be untangled, removed, and re-threaded through a series of tensioning arms and the press itself. Each of these spooling machines, called reel tension pasters (RTPs), requires approximately 15 minutes of preparation before restarting. Additionally, fuses or SCRs in the affected DC drive may fail due to regeneration as the inertia of the heavy spool keeps the motor spinning during the voltage sag. Considering the very tight printing schedules that must be kept to deliver the newspaper on time, downtime is a critical matter.

A retrofit had been recommended by the manufacturer that is designed to initiate an orderly shutdown of the RTP in the event of a voltage sag. The goal was not to prevent the drive from tripping, but rather, to implement a smooth shutdown so that paper is not torn. If the printing press and the RTP are allowed to come to a controlled stop, the process can be restarted easily with the push of a button.

The suggested retrofit was installed on one machine, which then needed to be tested before further investment was made for the rest of the presses. Rather than waiting weeks or months for voltage sags to impact the equipment, the serving utility asked EPRI PEAC to test the installed retrofit with a portable sag generator that can induce voltage sags at the machine and monitor the response of critical components during the sag conditions. The objective was to test the retrofitted RTP by injecting voltage sags of various magnitudes and durations. The investigators were looking for controlled shutdowns rather than a ride-through. From experience, the team's definition of controlled shutdown is described by two criteria: no torn paper and no failed fuses or SCRs.

Each RTP feeds paper to its press using a twelve-horsepower DC drive, which is three-phase, delta-connected, and operates at 480 volts. The DC drive and motor turn a set of belts that are lowered and come to rest on the spool of paper. The moving belts spin the spool, dispensing paper from the ground floor to a printing press located above on the second floor. If the RTP drive trips due to a voltage sag, it may attempt to suddenly change the speed of the belts. The heavy spool of paper cannot change speed instantly, and the belts shred the paper where they make contact with the spool.

Additionally, the regeneration from the spinning DC motor has been known to cause SCRs and/or fuses in the DC drives to fail. This is a common problem in DC drives, which are often used in applications where inertial loads cause energy to flow from the spinning motor back to the AC bus. The DC drive’s line-commutated inverter relies on the AC bus to provide the cut-off (commutation) of the SCRs. During a voltage sag, there may not be sufficient voltage present to commutate the SCRs. When the opposing SCR is then turned on, a direct short circuit results across two phases. Fast-acting semiconductor fuses are often used by drive manufacturers to minimize damage to the SCRs.

The best way to prevent the failed SCRs and fuses is to quickly detect the voltage sag and then break the electrical connection between the drive and the motor. A simple contactor can break the armature connection when signaled to do so. Since these particular drives did not have a built-in fault indicator for low voltage, an external three-phase voltage monitor was installed as part of the retrofit. The voltage monitor’s sensitivity is adjusted so that it is slightly more sensitive than the DC drive. When it detects a voltage sag, it opens a set of contacts, which in turn opens the armature contactor allowing the DC motor to coast freely with the spool. A time-delay relay then keeps the armature contactor open until the motor stops spinning (currently set for approximately twenty seconds). The main printing press is also retrofitted with the same type of voltage monitor so that it can issue a controlled stop signal to its twelve drives.

During the controlled sag tests, the paper continued to tear and the testing team realized that there was a slight coordination problem between the trip points on the two voltage monitors. Some voltage sags tripped the three-phase monitor on the RTP without tripping the monitor on the main press. Adjustments were made to the sensitivity setting of the voltage monitors, but the issue remained that one monitor would respond to the sag while the other did not. Also, upon a system trip, the heavy spool was coasting faster than the drive belts, thus tearing the paper. The press contractors suggested that the electro-mechanical brake (core brake) installed on the spooler should be applied when the drive trips. The brake slows the heavy spool, while the belts and DC motor coast. The appropriate connections were made so that the brake would be engaged when the RTPs three-phase monitor tripped. In the new configuration, sag tests were conducted and the system successfully came to a controlled stop without tearing the paper approximately ninety percent of the time. With this test data yielding a better understanding of the causes of the paper tearing, the manufacturer proposed a new drive control card that they had available which had faster monitoring and shutdown response capabilities. The proposed solution was tested to the satisfaction of the manufacturer and the printing facility operators at the EPRI PEAC Test Facility and was then installed on site with successful results. This case emphasizes the important recommendations made in Section Four regarding the need to have the cooperation of all parties, including the manufacturer and the end-user when evaluating solution options for DC drives.

Single-phase DC Drive on a Wire Drawing Process

In some cases, traditional power conditioning solutions for DC drives are not the most cost-effective means of dealing with the problem. Sometimes the obvious fixes are not the most apparent. The problem described here involved a tungsten wire drawing plant where they make the fine wire filament for incandescent lighting. The plant was having difficulty with their wire drawing processes during utility distribution system voltage sags. Any time the voltage at the plant sagged below eighty-five percent of nominal for more than two cycles, wire drawing machines would reportedly drop off line. While the whole plant was exposed to these disruptive voltage sags, the major (and most costly) process issue was identified as a group of approximately 200 final spooling machines for the fine strand finished wire product. Breakage of this finished wire would result in scrapped product and significant machine downtime costs, with estimated losses of over $100,000 per year. It takes nearly three days for a single machine to produce a full spool of wire, and if the wire breaks before the spool is less than half full, the spool must be scrapped. Figure 5-1 shows a functional diagram of the wire drawing process for one of the 200 fine strand machines.

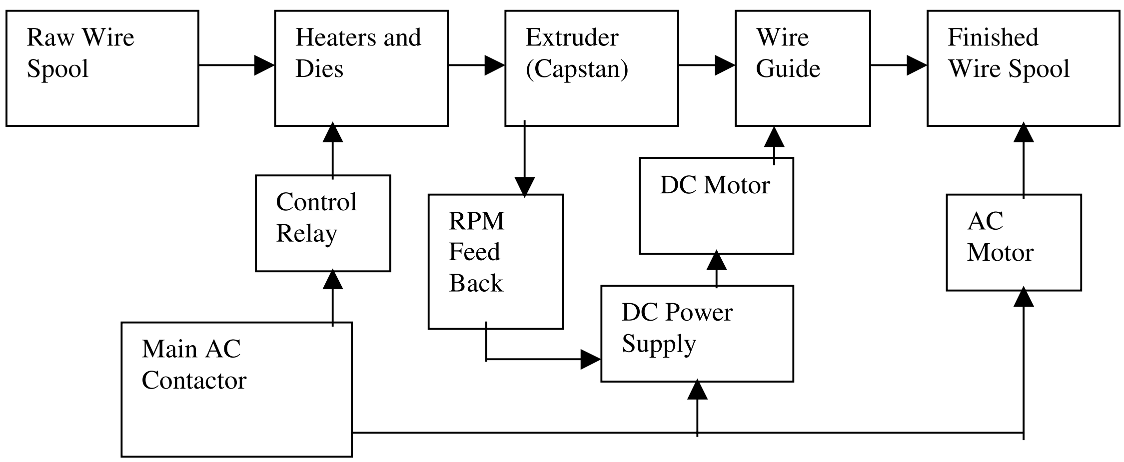

Figure 5-1
Functional Block Diagram of the Wire Drawing Process

The wire is coated with a liquid graphite mixture and then drawn through a series of twenty heated dies that stretch the wire to the proper gauge. The wire is pulled through the dies by a single-phase DC motor controlled capstan. After the wire comes across the capstan, it is automatically wound onto a spool. A separate AC motor controls this spool.

EPRI PEAC conducted testing with a portable sag generator to better understand what was happening to the wire drawing machines during voltage variations, and to locate the point where the wire breaks were occurring. The wire break was located between the capstan and the final spool every time the voltage sagged below the critical level. The curve shown in Figure 5-2 describes the sag tolerance envelope for the process as a whole. This whole process ride-through curve was not identical to that of any of the individual process elements, which indicates that mechanical complexities and component interactions were contributing to the wire breakages experienced with these machines. The fact that the wire broke between the capstan (controlled by the DC motor power supply) and the spooler (controlled by a 0.25-horsepower AC motor) indicated that a serious stress transient was developing between these two components during voltage sag conditions. It was clear from the testing that the DC drive controlled capstan was the weakest link in this part of the extrusion process.

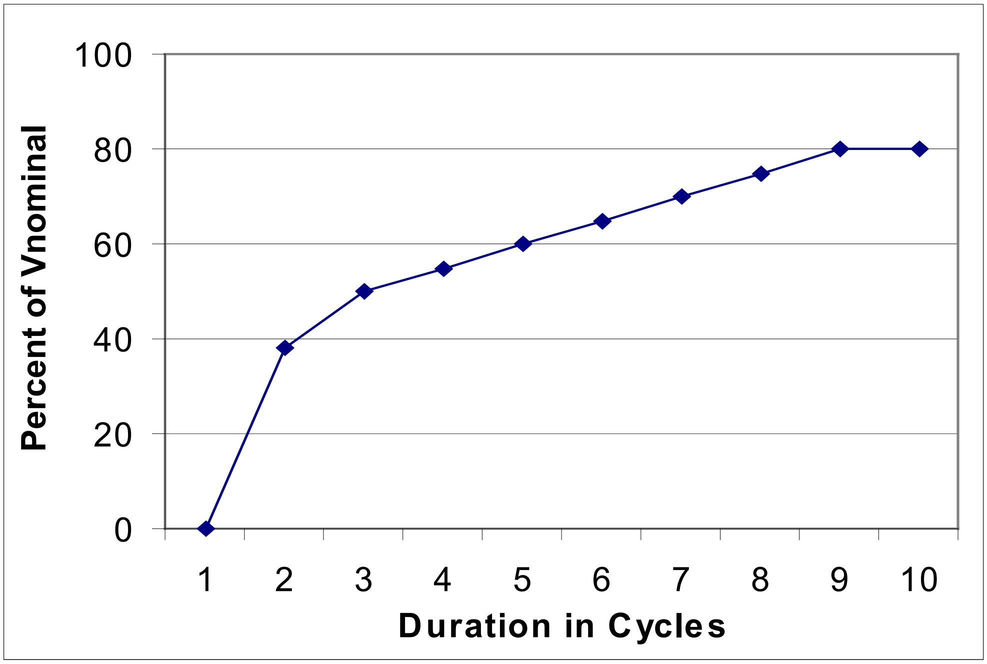

Figure 5-2
Voltage Tolerance Profile for the Wire Drawing Machines (Events Above the Curve Cause No Problem but Events Below the Curve Cause the Drawn Wire to Break)

A 1 kVA constant voltage transformer (CVT) was inserted in front of the DC power supply and the process sagged again to verify that a CVT would solve the problem. This 1 kVA CVT proved to be too small to support the DC power supply and keep the wire from breaking. Based upon the response of the CVT during applied voltage sags, it was initially assumed that a 2 kVA CVT would be necessary to provide an acceptable level of sag immunity. This acceptable level is defined as an ability to support the load during a one-half second sag to fifty percent on nominal line voltage. The 2 kVA CVT would additionally support all other components in the extrusion process, with the exception of the heating loads. While the above conclusion seems justified for a typical process application, there was a critical factor that was nearly overlooked, and is identified here as a “lesson to be learned” before drawing conclusions. The 1 kVA CVT was actually large enough to support the DC power supply from a total kVA perspective, and should have therefore been a viable solution. Monitoring the output voltage of the CVT during the sag testing indicated a serious oscillation of output voltage waveform. This oscillation was actually present even during steady state conditions. Simultaneous monitoring of the DC power supply input current provided the answer as to why the CVT oscillation was occurring. This power supply was half wave rectified, drawing current only during one-half of the sixty Hz voltage cycle. This presented a core saturation and waveshape unbalance problem for the constant voltage transformer. Because of this, even a 2 kVA CVT may not have been able to hold in the load during a voltage sag. Therefore, a CVT was not considered to be an appropriate and cost-effective solution for this process.

No Power Conditioning Required

It was clear that the process was sensitive to voltage sags. Additionally, it was clear that the torque transient between the capstan and the final spooler was causing the wire to break. Finally, it was clear that power conditioning the capstan power supply was not going to solve the problem. The question was how to reduce the torque transient, or at least minimize its impact. The solution turned out to be a screwdriver that the test team used to hold the wire down between the capstan and the spooler to simulate a shock absorber. During the preceding sags, the screwdriver and the arm of the technician holding the screwdriver would be forced upward, but the wire did not break. This shock absorber type solution (using the screwdriver) was validated for all induced sags and kept the wire from breaking even if the process completely stopped. By adding a properly designed guide wheel and spring assembly between the capstan and the spooler, the wire-snapping problem could be easily eliminated without the need of expensive power conditioning devices. The screwdriver with a spring and roller mechanism appeared to be the best solution to the problem. This solution is shown in Figure 5-3.

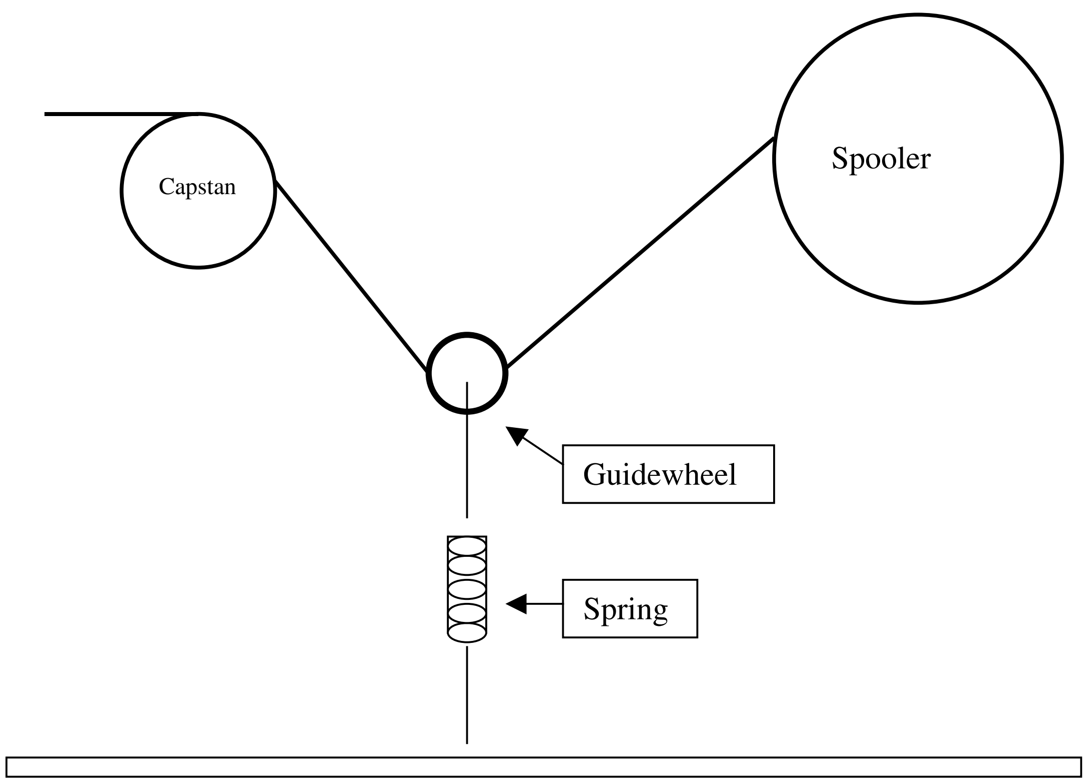

Figure 5-3
Drawing Detailing the Proposed Shock Absorber Solution

The estimated cost for the solution was approximately $50 per machine. In terms of cost-payback analysis, $50 each for 200 machines calculates to a $10,000 up-front investment. Based upon an average scrap and downtime cost per year of approximately $5,000 per dropout event, or at least $100,000 per year, the payback period is less than two months ($100,000 per year loss divided by $10,000 investment equals 0.1 years).

The process ride-through evaluation system proved to be extremely useful in identifying the root cause of the wire breaks. This unique solution to the process sag tolerance problem was not a standard fix and emphasizes a significant point. Mechanical process complexities and integration of multiple process elements rule out the potential of generic standard approaches to resolving sag susceptibility problems. A clear understanding of process interactions is necessary before recommendations should be made regarding power conditioning solutions for interlinked and mechanically complex processes. While an oversized power conditioning device to support the entire load at each wire drawing machine would have potentially solved the sag problems, the upfront costs to the customer would have been significant and definitely would have changed the cost-payback time significantly. The likelihood of an industrial customer being able to justify a multiyear cost-payback is not promising.

6 CONCLUSIONS

SCR controlled DC motor drives and their peripheral controls are by far the most voltage sag sensitive electronic devices used in industry today. The sensitivity is magnified even further when the system utilizes regenerative braking during process operation. The chopper and single-phase DC drives also described in this report are not as sensitive as the SCR topology, but these drives still require power conditioning or application modifications to operate through the majority of voltage variations. These systems and the processes they control can be made less sensitive to voltage sags by following some of the recommendations contained in this report. The five basic categories of recommendations that were detailed include:

- Retrofit solutions
- Control power solutions
- Programming solutions
- Embedded solutions
- DC drive replacement with AC technology

A number of recommended practices have also been presented within Section Four of this document. These recommendations, when followed, can generally ensure that success is achieved with any of the implemented solutions. A summary of the most important recommendations include:

- Steady state nominal voltage at or slightly above the equipment nameplate rating can reduce the number of nuisance trips by one-third to one-half, and is recommended as the first step in DC drive sensitivity reduction.
- It is a recommended practice to always apply power conditioning solutions to the drive controls, control power circuit, and to the field winding for the DC drive any time power conditioning is applied to the primary drive input.
- When looking at reprogramming options to improve drive power quality performance, regardless of whether this programming involves disabling the firing of SCRs or reprogramming the logic controller to wait a few seconds before reacting to relay contact fault signals, the same thought process must be used. This thought process (in order of priority) involves answering the following questions:

  1. Safety – If I change the reaction of this piece of equipment so that it does not trip during voltage variations lasting less than a second or so, will the change compromise (or possibly enhance) any aspect of personnel or plant safety?

2. Performance – If I make the changes, will the process now have the ability to ride-through these momentary voltage variations that otherwise would result in lost production and scrapped or reduced quality product?

3. Cost/Benefit – Will the changes be justified in terms of reasonable payback if the number of process interruptions is reduced?

- If the process requires constant speed and constant torque at rated load, then the process is not a very good candidate for programmed ride-through. For any other processes, programmed ride-through should be considered and is a viable solution to minimize the number of trips experienced by the DC drive.
- For all DC drive controlled processes it is a recommended practice that for any new drive installation or replacement applications, AC drives should be seriously evaluated as the technology of choice.

As a final recommended practice, equipment procurement specifications have been emphasized for both new and retrofit applications. A good, generic equipment procurement specification will consider not only the drive, but also the controls and any ancillary support processes such as steam, instrument air, lighting, etc. Following is a sample procurement specification that is presented in Section Four that can help in obtaining “power quality friendly” DC drives and support processes.

- Specify the equipment’s response to switching voltage transients as follows: “The equipment shall not trip as the result of transient overvoltages (impulsive and oscillatory) that can be as high as 2.0 per unit (of normal input voltage) at a damped frequency in the range of 300 to 800 Hz for one cycle. These transients may have significant energy associated with them but should not cause failure of the equipment’s protective devices and other components that make up the equipment.”
- Specify the equipment’s response to voltage sags as follows: “At rated load, the electronic equipment shall be able to ride-through voltage sags down to fifty percent input voltage for thirty cycles without causing any disruption to the equipment and its associated loads.”
- Specify the requirements for the equipment’s input line-current total harmonic distortion as follows: “The equipment shall have appropriately sized AC line reactors, chokes, or equivalent impedance input isolation device to limit the equipment’s input-current total harmonic distortion to under forty-five percent at full load.”
- Specify the need to evaluate the equipment’s potential to be interfered with by RFI/EMI generated by other facility electronic and switching loads. Ask the equipment manufacturer about any special electronic equipment, separation and shielding of the input power line, cable separation and shielding, and grounding requirements. Also, request if there are any special cabling recommendations for all the equipment’s control and process signal wires.
- Specify that the lighting and other support processes, such as steam and instrument air, have the ability to either “hold in” or restart if power returns to normal within two seconds of an electrical disturbance.

With this arsenal of specifications and solution opportunities, there is a good probability of developing a series of recommendations and power conditioning solutions that will yield a cost-payback of less than two years, when comparing the cost of the solutions with the cost of process losses and downtime. In some cases, the payback can just a few months. The key to understanding the best options for solving drive power quality problems is to first understand exactly which type of electrical variation is occurring to upset the drives, and to then encourage dialogue between the utility power quality personnel, the process engineers, and the drive manufacturer application engineers.

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