PQ Encyclopedia
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Adjustable-Speed Drive
Technology and Power Quality Considerations

Chapter 9

Contents

WHAT IS AN ASD?

Electric motors that are connected line-to-line or line-to-ground operate at full speed. An adjustable-speed drive, as the name implies, allows a motor to operate at a continuous range of speeds.

A Large Bank of ASDs at a Non-Woven Fiber Plant

Motors and motor systems are not a minor concern. Motor systems are responsible for 63% of all electricity consumed by U.S. industry. Within the manufacturing sector, steel mills and blast furnaces account for 4.7% of all motor energy use. Motors larger than 50 horsepower make up only 8% of the motor population in primary metals industries, yet they account for over 80% of motor energy use in the typical plant. Fans, pumps, and blowers make up the largest driven load class and account for about 55% of motor drive energy [1].

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In early motor-driven processes, an electric motor would run in steady-state operation, fully "on"or a completely "off," with no states in-between.

A BRIEF HISTORY OF ASDS

A DC adjustable-speed motor, invented by John Lincoln around 1905, may have been the first type of adjustable-speed drive. Other drive designs over the years have used mechanical or hydraulic methods to vary the speed of motors or processes.

Early control systems prior to the modern adjustable-speed drive achieved regulation of fluid or material flows through mechanical means such as belt-driven conveyor systems, damper-controlled air circulation systems, and systems using valves, gears, flywheels, and so on. A process using an electric motor would have the motor in steady-state operation, fully "on" or a completely "off," with no states in-between. In the "on" state, flow control was achieved by throttling the flow of fluid or material somewhere down the line. This meant that the electric motor ran at top speed, drawing full load current to produce full-power output while, somewhere else, something else would gear-down or, in effect, apply brakes to control the process. Not until the development of sophisticated electronics and control systems would the modern ASD become possible.

MODERN DRIVE TOPOLOGIES

Adjustable-Speed Drives

In the modern industrial facility, ASDs are quickly replacing mechanical means of controlling process parameters such as speed, timing, and the flow rate of air and liquids. ASDs eliminate gear or belt arrangements that take up space and require maintenance. In office buildings throughout the world, ASDs are controlling motors that drive heating, ventilation, and air-conditioning systems. By efficiently controlling the speed and torque of induction motors, ASDs improve productivity and conserve energy that would otherwise be consumed by mechanical controls such as throttling and gear changing.

The ASD—also referred to as the variable-frequency drive (VFD), the adjustable-frequency drive (AFD), or the variable-speed drive (VSD)—is an electrical device that can control and vary the speed, torque, power, and direction of three-phase electric motors using fixed input voltage and frequency. While the ASD may be used for any kind of motor, the term *ASD* is commonly used for AC motor controllers. The types of AC motors that ASDs control include: induction, synchronous, synchronous wire wound, permanent magnet synchronous, and synchronous reluctance. DC motors include both brushless and those using brushes.

ASD classification, based on voltage, falls into three categories:

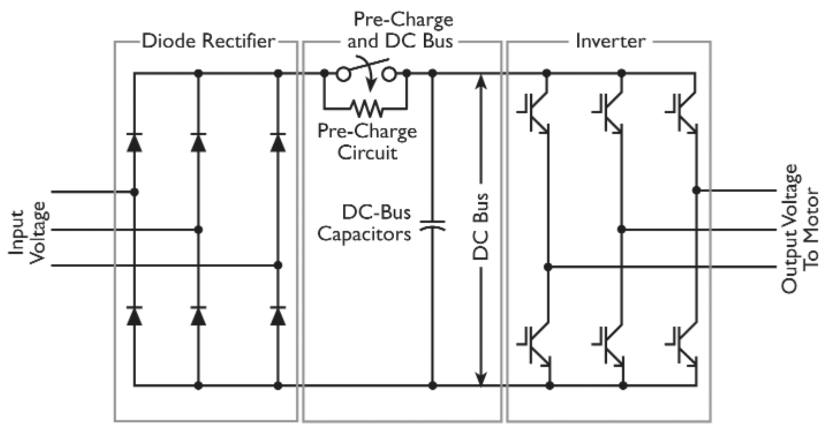
- Low-voltage drives (standard drives) of less than 2.3 kV
- Medium-voltage drives between 2.3 kV and 10 kV (usually 2400 V, 3300 V, 4160 V, and 6600 V)
- High-voltage drives greater than 6.6 kV

Industrial equipment incorporating the ASD include HVAC, circulating fans, pumps, blenders, crushers and mills, cranes, sanders, lathes, milling machines, mixers, compressors, washers, dryers, grinders, sorters, feeders, and extruders.

ASD Operation and Applications

The most common type of ASD used in the industry for controlling the speed of induction motors is the pulse-width modulated (PWM) voltage source inverter (VSI) AC drive. As shown in Figure 1, the first two stages of a typical PWM VSI drive include a three-phase diode bridge rectifier and capacitor filter to convert the incoming AC voltage to a low-ripple DC voltage. The voltage at the output of the bridge rectifier charges the DC-bus capacitors only when the instantaneous peak of the input voltage exceeds the voltage across the DC bus.

Figure 1. Typical Diagram of a PWM VSI Drive



Older designs of ASDs controlled the motor voltage by changing the voltage across the DC bus through controlled rectifiers. In modern PWM VSI drives, the voltage across the DC bus stays relatively constant. Instead of modulating the voltage across the DC bus, the operation of fast solid-state switching devices in the inverter control the magnitude, frequency, and shape of the inverter's voltage and the motor's current. By keeping the DC-bus voltage steady, the internal control circuits of a drive can be powered directly from the DC bus, which increases the ride-through of the ASD.

Precise and efficient control of electric motors is especially important in industrial processes. ASDs afford the fast response times required by industrial processes such as extruding, computer numerical control, and paper milling. ASDs are used to control the speed and torque of a motor as required by the mechanical load characteristics of a particular process. For example, ASDs can be used to take the place of mechanical controls such as dampers, throttles, and gear boxes. Instead of using a mechanical device to control the speed of liquid, air, or other material, an ASD can adjust the speed of the motor to accomplish this control. Depending on the duty cycle of the load, using an ASD instead of mechanical controls can save energy. Additionally, ASDs are used in high-precision processes, such as when the torque and speed of a motor must be precisely maintained.

A single process may have several ASDs working together to drive different process motors. Such systems are referred to as *coordinated-drive systems*. A typical coordinated-drive system can be found in the pulp and paper industry, where ASDs are used to control the processing of paper as it travels from stage to stage.

In addition to ASDs themselves, modern control systems may also include programmable logic controllers, distributed control systems, input/output racks, contactors, relays, and sensors. However, as with most electronics technologies, ASDs are sensitive to electrical disturbances. Moreover, the ride-through of the entire system is no better than the ride-through of the weakest system component. Therefore, it is important to consider the effects of power quality variations (especially voltage sags and momentary interruptions) on the entire system and not just the ASD.

Based on duty cycle, an ASD application falls into one of three categories: short-term duty, continuous duty, and intermittent duty [2].

The estimated total value of U.S. drive shipments for 2007 is $1.4 billion.

- **Short-Term Duty:** Short-time, constant-load operation with drive below thermal equilibrium. This category includes cranes, household appliances, and valves.
- **Continuous Duty:** Constant-load operation with thermal equilibrium reached. This category includes agitators, paper mills, compressors, conveyors, centrifugal pumps, and fans.
- **Intermittent-Periodic Duty:** Periodic load operation with thermal equilibrium never reached. This category includes pressing, cutting, and drilling machines.

Torque Characteristics

Certain processes allow a characteristic torque relationship to predominate. Applications where load torque increases with speed include those using pumps, fans, blowers, and compressors. Constant-load torque applications involve reciprocating compressors, positive-displacement pumps, conveyers, center winders, drilling/milling machines, crushers, drill presses, extruders, hoists, kilns, and mixers. Processes where load torque decreases with speed—constant-power processes—include traction drives, flywheels, lathes, and center-driven winders [3].

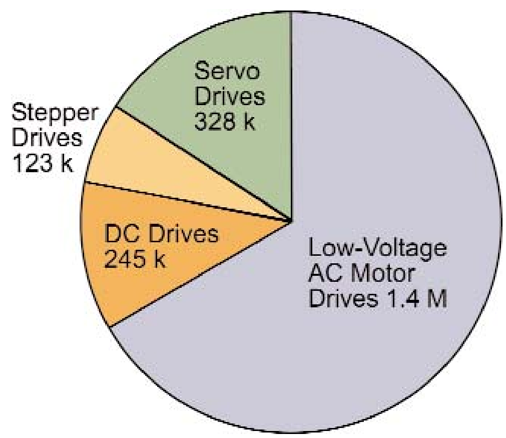
MARKET INFORMATION: DRIVES

ASD drives have five categories: Low-voltage AC motor, DC drives, stepper drives, servo drives, and medium-voltage drives. The compound annual growth rate range, or CAGR range, over the last 5 years is 3.6% (stepper drives) to 10.6% (DC drives), with the market average being 7.5%. The estimated total value of U.S. drive shipments for 2007 is $1.4 billion. ASD sales in the state of California are shown in Table 1. Figure 2 illustrates the installed base of ASD drives as of 2007 in the state of California.

Table 1. ASD Sales Data from California

Category	2007 Projected CA Unit Sales
Low-Voltage AC Motor	219,000
DC Drives	44,000
Servo Drives	16,000
Medium-Voltage Drives	45,000
Total	**324,000**

Figure 2. ASD In-Use Data from California



MODERN DRIVE TOPOLOGIES AND SENSITIVITIES

Figure 3 shows a simplified schematic of an adjustable-speed drive, including the power source and the driven motor. The main components of this typical ASD configuration are defined below:

- *Three-Phase Source:* AC voltage supplying power to the terminals of the ASD.
- *Diode Rectification:* AC line current becomes DC time-varying current.

- *DC Link:* The connection between the rectifiers and the inverter (the DC bus).
- *DC Link Choke:* Inductor/line reactor used to dampen transients from the AC line (optional, but very desirable).
- *DC Link Capacitor:* Charged by the rectified AC line current; provides DC voltage to inverter.
- *Motor:* Usually an AC induction motor.

Figure 3. ASD Components

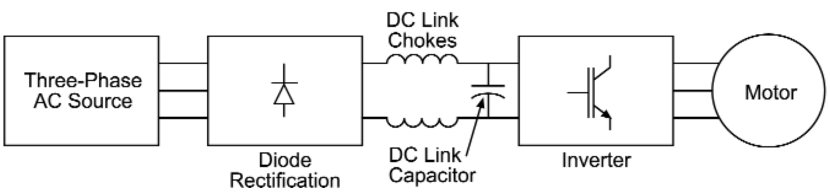


Figure 4. ASD with Diode Bridge Rectifier Topology

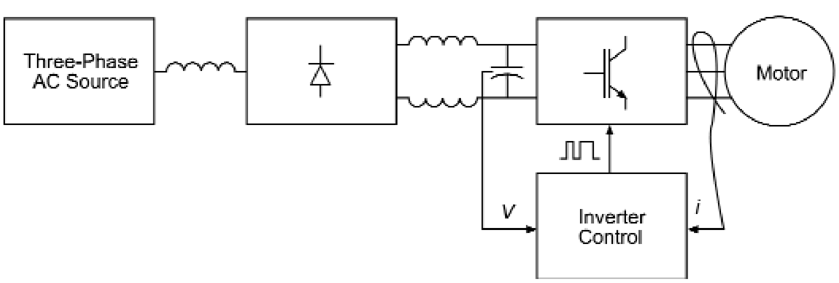
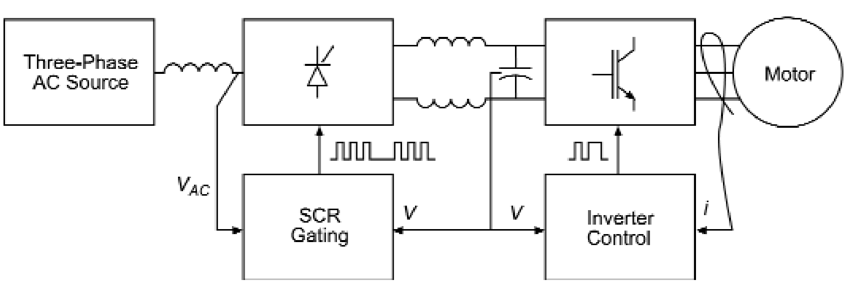


Figure 5. ASD with SCR



ASD with Diode Bridge Rectifier

The inverter control feedback loop shown in Figure 4 maintains bus voltage through control of motor speed. Controller monitors voltage level at DC bus along with current level at inverter output. Note that the line reactor between the power source and the ASD acts to dampen current spikes from the power source that may otherwise damage the ASD or cause it to malfunction.

ASD with SCR

The DC bus may experience overvoltage conditions during initial startup operations due to inrush current. Pre-charging with silicon-controlled rectifier (SCR) gating, shown in Figure 5, serves to limit inrush and protect the ASD.

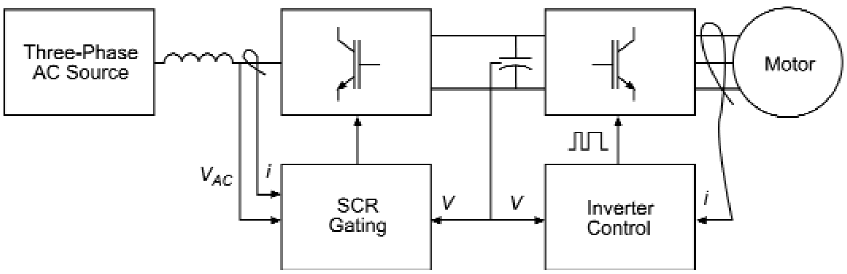
The gating circuit monitors the DC bus voltage level versus the AC voltage input level to produce a pulse-width-modulated (PWM) voltage that gradually elevates the DC bus voltage to the correct operating level and maintains that level. The SCRs synchronize firing angles with the AC input voltages.

During voltage sags, the gating loop reduces inrush current by retarding the SCR firing angle to track the DC bus voltage. This type of ASD may lose line synchronization due to rapid change in phase during a fault.

ASD with IGBT Rectifier

Rectifier control regulates the DC bus voltage to maintain output voltage and frequency through an insulated gate bipolar transistor (IGBT)-operated feedback loop, as shown in Figure 6. During voltage sags, the rectifier regulates the DC bus voltage at the desired set point. During heavy loads, the rectifier operates at or near the current limits of the DC bus should the voltage level of the DC bus drop.

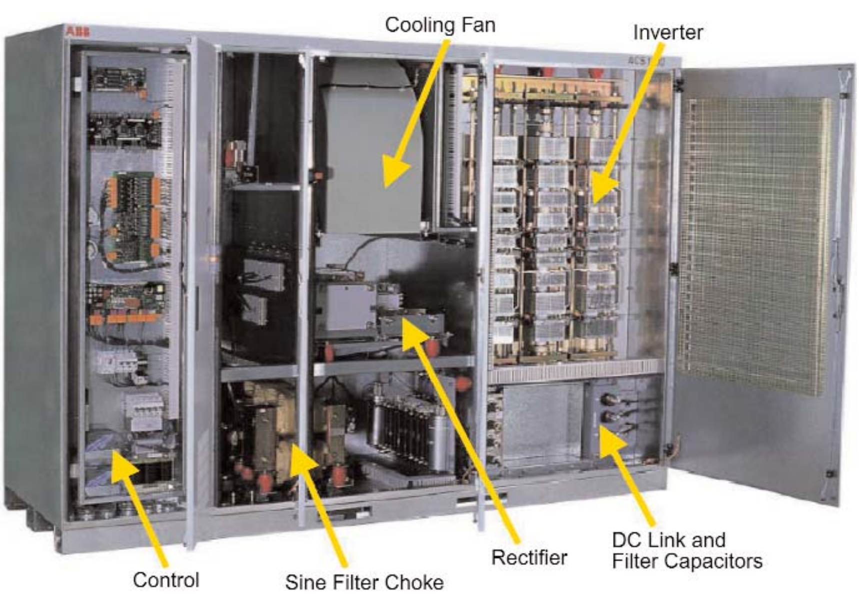
Figure 6. ASD with IGBT Rectifier



Should this ASD sense an overcurrent condition in either the inverter or rectifier, it will shut down. Should the ASD lose synchronization with the AC line voltage due to voltage sags, then the IGBT gate pulses will be disabled so the IGBT rectifier functions as a diode front end until ASD regains phase synchronization.

A large ASD installation is shown in Figure 7 below as it serves to illustrate the sections of an ASD [4].

Figure 7. A Representative Large ASD Installation

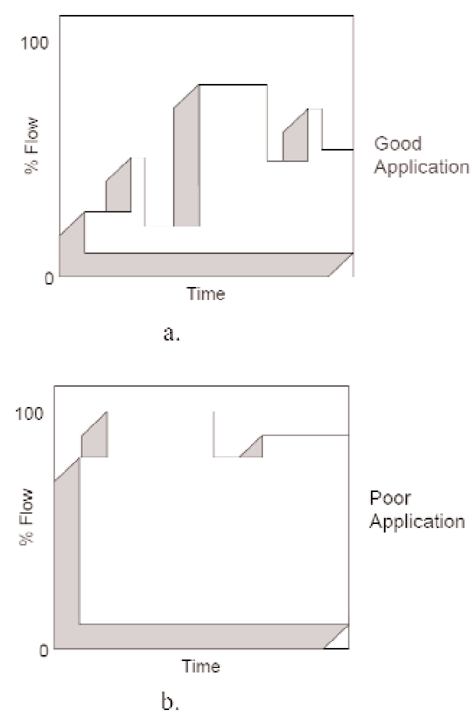


ASD APPLICATION: DUTY CYCLE CONSIDERATION

When should an ASD be used and when should it not be used? The answer to this question lies in the nature of the intended load: Is it a constant or variable load, and how much does it vary?

A preferred application for an ASD, shown in Figure 8a, is a constantly changing load that hovers around 50% and does not approach 90% over a long period of operation. A very poor application would be a near-constant load—90% or above. The economic justification for using ASDs, as opposed to a line-connected motor using mechanical dampers, gears, and so on, is that the mechanical losses for the latter greatly exceed those of the former at low-load conditions. Figure 8b shows a process that operates fairly close to 100% most of the time and would therefore not be a good candidate for ASD control [3].

Figure 8. ASD Application Based on Duty Cycle



Examining the duty cycle of the load would also provide an indication of whether or not a process should use ASD control. Figure 9 shows an example of one that should: The percent of rated flow peaks in percent operating hours at around 50%, diminishing gradually to a minimum at 85%, and never achieves 90% or higher.

Figure 9. Excellent ASD Candidate

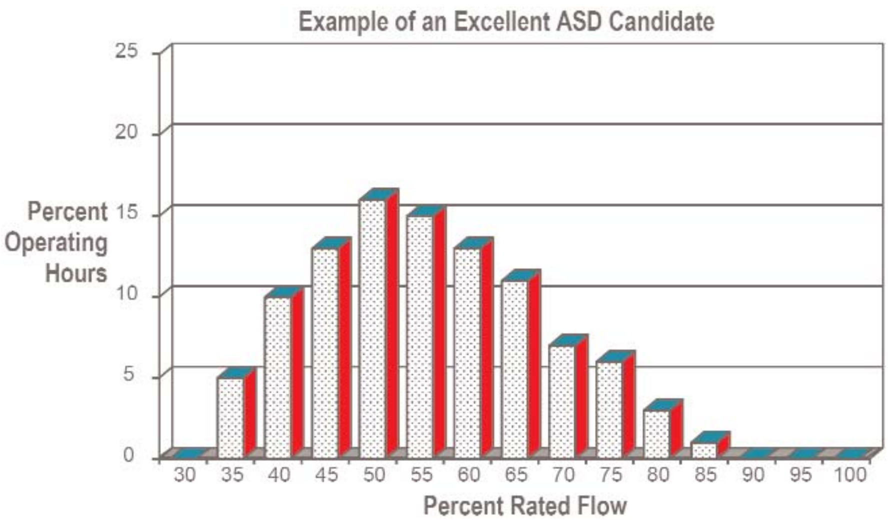
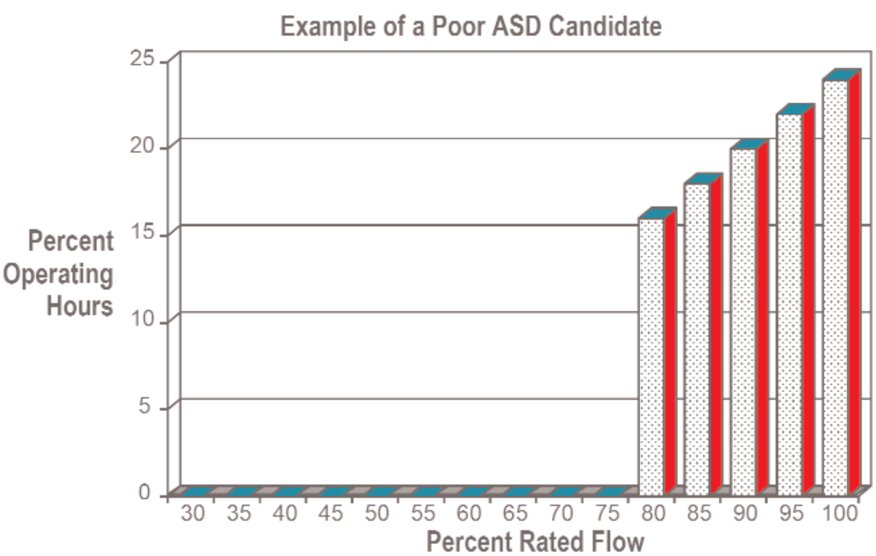


Figure 10. Poor ASD Candidate



On the other hand, Figure 10 provides an example of one that perhaps should not be considered for ASD control. Note that, most of the time, the process operates at 90% or higher of its percent of rated flow and never operates below 80%.

Costs for basic variable-torque drives start at around $520 per horsepower for a 1-HP drive and drop sharply to around $160 per horsepower for a 10-HP drive. Costs level off more slowly after that with 40-HP drives at about $100 per horsepower, and 500-HP drives down to about $70 per horsepower. Installation costs, electrical filters, and special features for constant torque, special controls, or diagnostics can easily more than double the cost of the ASD.

EFFICIENCY

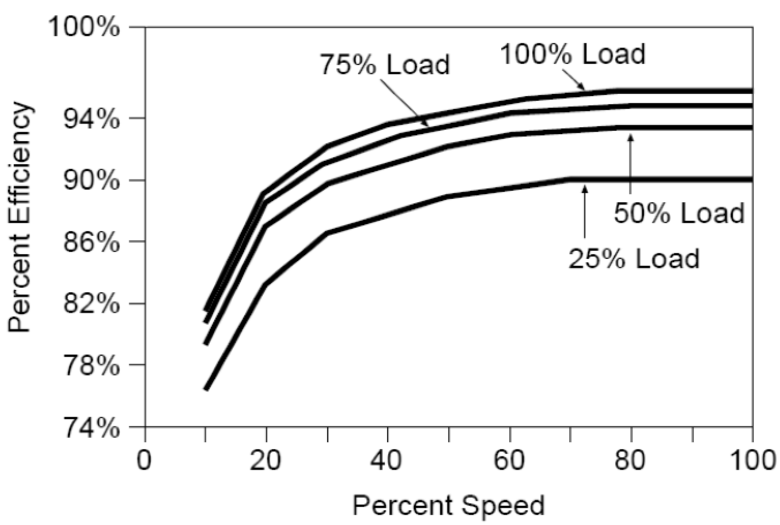
There are three main techniques to measure efficiency:

- Direct method: Digital direct-measurement devices can record, analyze the waveform, and compute efficiency. Measurement accuracy is a concern with this type.
- Calorimetric method: Calibrated insulated enclosures are used to compute drive losses. Very accurate results are obtainable with this method.
- Segregated loss method: With this theoretical technique, all losses are individually computed to arrive at estimated efficiency. This is the most widespread method.

The ASD operating efficiency for large motor drives (not the motors), according to one study, approaches 99% [4]. Typical loss components include the largest loss for the semiconductor inverter at 0.63%, followed by the DC link at 0.27%. The remaining loss factors include the semiconductor rectifier, rectifier snubber circuit, inverter snubber circuit, AC line choke, and the dv/dt filter.

ASD efficiency may also be measured using percent speed for a given load percentage, as shown in Figure 11. It may be seen that the percent efficiency for various loading is not affected to a great extent until percent speed drops below 30% [3].

Figure 11. Percent Efficiency versus Percent Speed



Yet another measure of ASD efficiency compares speeds and horsepower ratings of the drives. Table 2 indicates that higher power drives run more efficiently at a given speed than those of lower power [5]. Therefore, a good candidate process for ASD control would use motors with a moderate to high horsepower rating.

Losses in ASD/Motor System

Background

Always in search of ways to increase production efficiency, many industrial facilities rely on ASDs to control production processes that are driven by electric motors. Motors that drive variable-torque loads such as pumps and fans sometimes operate significantly below their full-load ratings. For example, during extreme temperature changes, a heating, ventilation, and air-conditioning system may require full air flow to heat or cool a building. During normal operation, the HVAC system may require only moderate air flow to maintain steady temperature.

When evaluating the benefit of using an ASD, additional system losses must be considered. Not only do losses in the ASD inverter add to the system losses, but motor

Table 2. Drive Efficiency Based on HP Rating

Variable-Speed Drive HP Rating	Percent of Full Operating Speed (% Torque)			
	25% (1.6%)	50% (12.5 %)	75% (42%)	100% (100%)
1	9.4%	44.2%	70.5%	82.5%
5	29.6%	74.7%	83.3%	92.4%
10	35.3%	79.0%	90.3%	93.5%
25	35.6%	79.4%	90.6%	93.8%
50	43.3%	83.5%	92.1%	94.4%
100	54.8%	89.1%	95.0%	96.6%
200	61.2%	91.3%	96.1%	97.3%

Quantifying the ASD losses and total motor losses in the system enables a more accurate estimation of savings when comparing ASD operation to other mechanical controls.

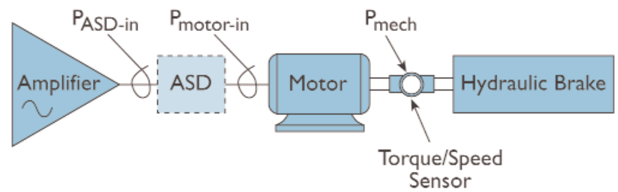
losses will increase when the motor is driven by an ASD. Quantifying the ASD losses and total motor losses in the system enables a more accurate estimation of savings when comparing ASD operation to other mechanical controls.

However, accurately evaluating such losses requires specialized equipment and facilities, such as that found at LTEE Hydro-Quebec Motor Testing Laboratory, capable of the task. Tests performed by Hydro-Quebec determined the additional system losses resulting from the use of an ASD in a motor-driven process.

Test Setup

A voltage-source inverter (VSI), pulse-width modulated (PWM) ASD rated at 150 horsepower was tested with a 150-horsepower, 460-volt motor. The motor was loaded using a 250-horsepower hydraulic brake. Figure 12 shows the test setup. Input voltage to the ASD was fed from a power amplifier, which supplied three-phase voltage (460 volts) with harmonic distortion maintained below 1%. All measurements were taken both with and without the ASD in the circuit. During each trial, technicians took power measurements from the ASD input ($P_{ASD\text{-}in}$) and output ($P_{motor\text{-}in}$) with a digital power analyzer, which recorded power consumption in kilowatts. Mechanical load power (Pmech) was derived by measuring the output torque and speed and then multiplying the torque and speed measurements. For each trial with and without the ASD in the circuit, the motor load was set at 25, 50, 75, or 100% of the rated full-load torque. For each trial with the ASD in the circuit, the ASD frequency was set at 15, 30, 45, or 60 hertz. The ASD output frequency determined the system speed: 60 hertz equaled 100% speed, 45 hertz equaled 75% speed, 30 hertz equaled 50% speed, and 15 hertz equaled 25% speed.

Figure 12. Test Setup



Results

Table 3 shows the measurements taken for each trial. The measurements were used to calculate losses and efficiency for the ASD, the motor, and the ASD/motor as a system. Motor efficiency was calculated by dividing P_{mech} by $P_{motor\text{-}in}$. For trials with the ASD in the system, the ASD efficiency was calculated by dividing $P_{motor\text{-}in}$ by PASD-in. In both cases, system efficiency was calculated by dividing P_{mech} by PASD-in ($P_{motor\text{-}in}$ when the ASD was not in the system).

Figure 13 shows how load level and ASD frequency affected motor efficiency with and without the ASD in the circuit. Figure 14 shows how load level and ASD frequency affected system efficiency with and without the ASD in the circuit. Figure 15 shows how the load level and ASD frequency affected the total power consumption of the system with and without the ASD in the circuit.

Table 3. Test Results for Motor, ASD, and ASD/Motor System

Freq.(Hz)	Load Torque (%)	PASD-in (kW)	$P_{motor-in}$ (kW)	P_{mech} (kW)	ASD Losses (kW)	Motor Losses (kW)	ASD Efficiency (%)	Motor Efficiency (%)	System Efficiency (%)
60 (No Drive)	100	-	119.6	112.4	-	7.2	-	94	94
	75	-	89.5	84.0	-	5.5	-	94	94
	50	-	60.8	569.4	-	4.4	-	93	93
	25	-	31.8	28.1	-	3.7	-	88	88
60 (Drive)	100	128.5	126.1	111.4	2.4	14.7	98	88	87
	75	99.2	97.5	84.9	1.7	12.6	98	87	96
	50	68.6	67.4	56.5	1.2	10.9	98	84	82
	25	37.8	37.0	28.4	0.8	8.6	98	77	75
45 (Drive)	100	94.8	92.7	84.0	2.1	8.7	98	91	89
	75	72.0	70.5	63.4	1.5	7.1	98	90	88
	50	49.1	48.1	42.3	1.0	5.8	98	88	86
	25	26.6	26.1	21.5	0.5	4.6	98	82	84
30 (Drive)	100	65.0	63.1	55.7	1.9	7.4	97	88	86
	75	49.1	47.7	42.0	1.4	5.7	97	88	86
	50	33.7	32.8	28.3	0.9	4.5	97	86	84
	25	18.4	18.0	14.3	0.4	3.7	98	79	78
15 (Drive)	100	34.7	33.0	27.4	1.7	5.6	95	83	79
	75	26.0	24.9	21.2	1.1	3.7	96	85	82
	50	17.5	16.6	14.2	0.9	2.4	95	86	81
	25	9.4	9.0	7.2	0.4	1.8	96	80	77

Figure 13. Motor Efficiency Based on Motor Load and ASD Frequency

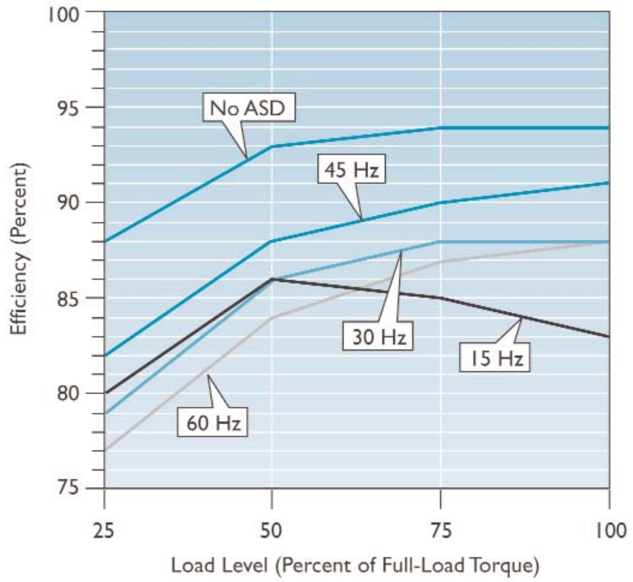
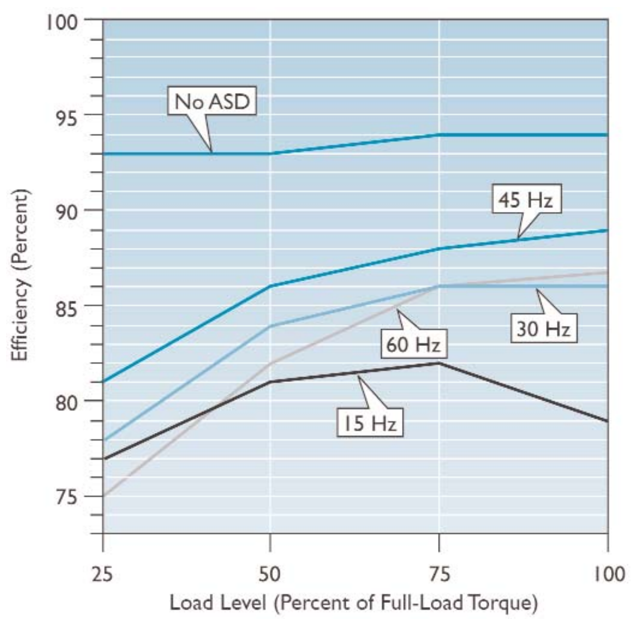


Figure 14. Efficiency of the Motor Alone (No ASD) and the ASD/Motor System Based on Load Level and ASD Frequency



Discussion

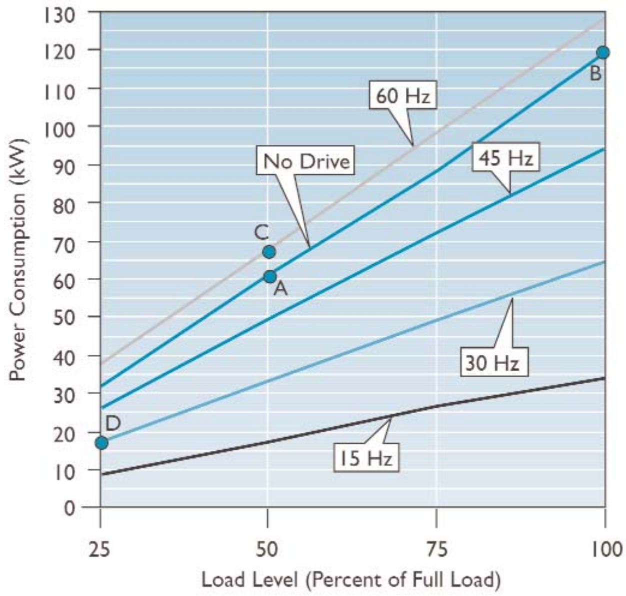
The data from Table 3 reveals that the motor had a lower efficiency when connected to an ASD than when directly connected to line voltage. This lower motor efficiency resulted from the non-sinusoidal voltages and currents characteristic of ASDs. At 60 hertz, motor efficiency decreased (anywhere from 6 to 11% depending on the motor load) when the ASD was in the circuit.

The ASD also contributed to system losses. As shown in Table 3, the losses in the ASD at 60-hertz operation were between 2.4 kW at full load and 0.8 kW at 25% load, with an ASD efficiency of 98% for an overall system efficiency of 87% compared to 94% with no ASD. The losses in the ASD were the result of the switching and conducting of the power-electronic components in the ASD. At lower speeds, the efficiency of both the motor and the ASD dropped, as shown earlier in Table 3. However, at lower ASD frequencies, the ASD/motor system consumed less power for the same load-torque level as the line-connected motor operating at 60 hertz.

Significance

Manufacturing companies continually seek ways to trim operating costs and increase production efficiency. Small energy savings incurred within one production process over the course of one day can be multiplied to reap significant savings throughout the year. When mechanical controls such as dampers and valves are replaced by ASDs, the system energy performance usually improves, especially for processes that require a partially closed damper or valve for a large portion of the total operation time. Determining whether an ASD will save energy requires careful consideration of process characteristics. In addition, quantifying all the losses incurred by adding an ASD to a motor-driven process will enable a more accurate estimate of potential energy savings.

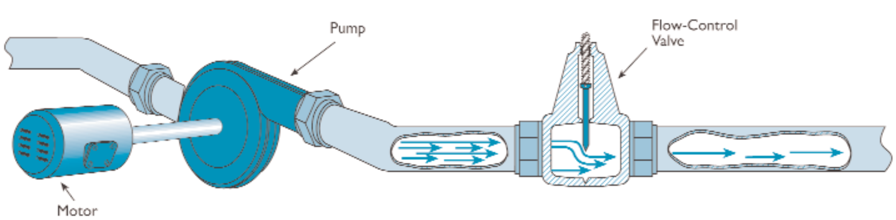
Figure 15. Power Consumption of the Motor Alone (No ASD) and the ASD/Motor System Based on Load Level and ASD Frequency



Potential Energy Savings with ASD Control

The efficiency of a motor driven by an ASD is always lower than that of a line-connected motor. Also, an ASD will contribute to system losses. So why use an ASD? Consider the motor-driven process illustrated in Figure 16. The liquid-coolant pump in this process is a variable-torque load on the motor. The flow rate of the liquid coolant transported by the pump is controlled by a flow-control valve. However, when the flow-control valve restricts flow, system efficiency decreases.

Figure 16. Motor-Driven Process Using a Flow-Control Valve to Control the Rate of Flow of a Liquid Coolant



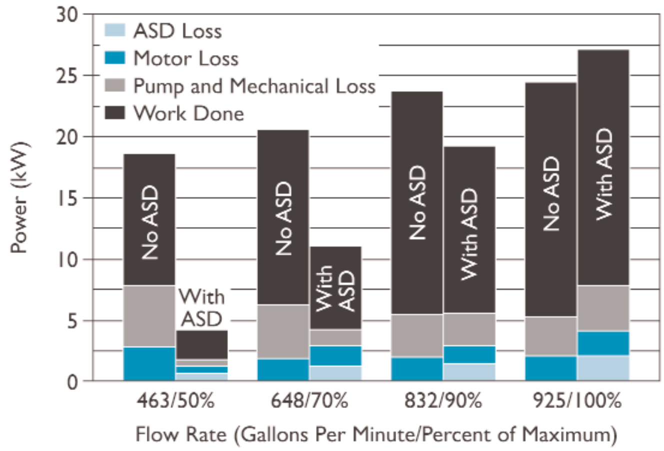
The function of a flow-control valve can be achieved with an ASD. By changing the output frequency of the ASD, the motor speed, and thus rate of flow, can be controlled. However, while losses in the flow-control valve are eliminated, additional losses in the motor and the ASD are introduced. As shown in Figure 17, these additional losses are small when compared with the losses in the mechanical control, especially at reduced flow rates. Therefore, if the process is operated at a reduced flow rate for most of the time, using an ASD instead of a mechanical control will likely yield significant energy savings, notwithstanding the additional losses in the ASD and motor.

No mechanical or electrical process experiences 100% efficiency. All along the way, energy dissipates, usually as heat, due to mechanical and/or electrical resistances and other characteristics of the process. In the case of Figure 17 on the following page, the motor, the pump, and other mechanical sources dissipate a good deal of energy without ASD control.

Fans and pumps consume power in a manner proportional to the cube root of shaft speed. Therefore, reducing the speed of rotation should also greatly reduce power consumption. However, reducing flow below 90% without an ASD (by mechanical means alone) becomes less and less efficient, even with decreasing losses due to the slower rotation of fans and pumps.

However, in an ASD-controlled pump process, if shaft speed is reduced by 10%, flow is reduced by 10%, while power consumption is reduced by 27%. Should speed be reduced by 20%, then power is reduced by 49%.

Figure 17. Losses in System Elements with Mechanical Control versus ASD Control at Four Different Flow Rates



An example process operating at 50% by mechanical means (the extreme left side of the Figure 17 above) experiences far greater losses than one controlled with as ASD due to the energy expended in the gear trains and/or baffles that throttle down the process while the motor runs at normal operating speed. The motor also uses more energy in the throttle-down state.

However, the ASD uses energy as well. On the opposite side of the graph, for the same process operating at maximum flow, the losses generated by the ASD add significantly to the total. Indeed, for flows at 90% or above in this example, the process receives little or no benefit from ASD control. In this case, the combined losses including the ASD would exceed significantly the combined losses without the ASD.

Several methods employed to reduce energy consumption to improve the efficiency of ASDs include:

Regenerative braking, where several drives use dynamic breaking rather than waste energy through braking resistors and mechanical brake arrangements. With regenerative braking, energy is generated and supplied back to the grid. This method requires an active front-end for bi-directional energy flow.

Soft start is an operation that reduces motor inrush current to save energy. Savings also occur due to optimal stop and start patterns.

Bypass contactors can be used to bypass the ASD drive when the motor is running at rated speed, thus saving energy through bypassing the ASD when not needed. This arrangement requires a complex control scheme to switch back and forth as required. One example is the Cutler Hammer IntelliDisconnect drive.

Table 4 below shows the approximate cost to operate ASDs of different ratings at different costs per kilowatt [5].

Table 4. Operating Cost Comparisons for Different-Sized ASDs

Rated HP	@US $0.03/kWh	@US $0.05/kWh	@US $0.07/kWh
50	$3,908	$6,913	$9,678
100	$8,828	$14,713	$20,599
200	$18,000	$30,000	$42,001

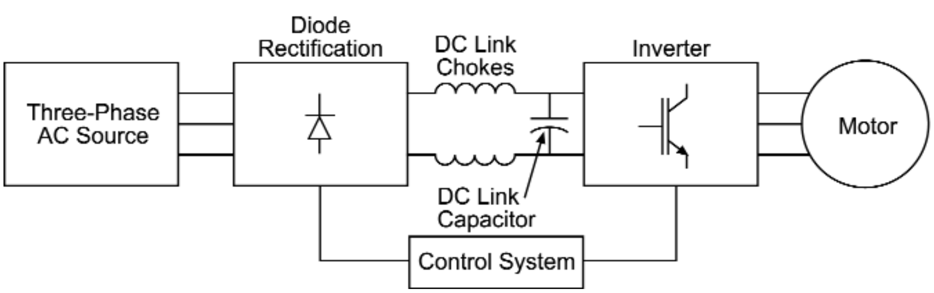
ASD POWER QUALITY CONCERNS

While adjustable-speed drives improve the flexibility and efficiency of manufacturing operations, a number of concerns remain regarding their application, such as:

- Harmonic distortion from the supply side as well as the motor side of the drive
- ASD tripping and/or component failures due to transient voltage (DC overvoltage)
- Nuisance tripping of ASDs due to voltage sags and momentary outages
- Nuisance tripping from overcurrent surges due to sags and momentary outages
- Notching and transient oscillations caused by power-electronics switching
- Motor overheating due to harmonic currents produced by ASDs
- Motor-winding failure caused by fast-front transient voltages associated with PWM inverter output and long cable lengths
- Audible noise caused by high-frequency (several kilohertz) components in the voltage and current.

These concerns must be addressed effectively at the time of ASD installation.

Figure 18. ASD System Schematic



ASD Characteristics

As illustrated again in Figure 18, an ASD system consists of three basic components—rectifier, DC link or DC bus, and inverter—as well as a control system.

The diode rectifier converts the three-phase 60-Hz AC input into a DC signal. Depending on the design, an inductor, a capacitor, or both smooth the DC signal to reduce voltage ripple in the DC link. The inverter circuit then converts the DC signal into a variable-frequency AC voltage to control the speed of the induction motor.

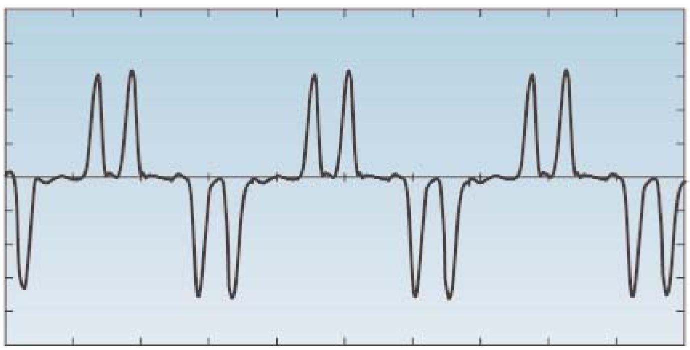
For power quality considerations, ASDs may be divided into two basic types:

- Voltage source inverter (VSI) drives are the most commonly used drive type for applications of less than 500 HP. A large capacitor in the DC link provides a relatively constant DC voltage to the inverter. The inverter then chops this DC voltage into a variable-frequency AC voltage supplied to the motor. VSI drives may be purchased off the shelf and employ PWM techniques to improve the quality of the output waveform.
- Current source inverter (CSI) drives are typically used for custom-designed applications greater than 500 HP. The DC link consists of a large inductor that maintains a relatively constant DC current. The inverter chops the DC current to provide the variable-frequency AC signal to the motor. While somewhat distorted, this current waveform is less distorted than that of the VSI drive.

Power Factor (PF)

The application of capacitors for power-factor correction may have unfortunate effects on ASDs due to the possibility of harmonic resonance and transient voltage magnification. The ASD input current waveform illustrated in Figure 19 shows the characteristic distortion that adversely affects power factor.

Figure 19. Current Pulses of an ASD



The power factor of nonlinear loads, that is, loads involving power electronics, differs from true power factor, one based on reactance and resistance. The nonlinear load employs what is called the *displacement power factor* (dPF) as opposed to the true power factor (PF). The dPF is determined using the cosine of the angle between the fundamental voltage and the fundamental current. The dPF equals the PF only for linear loads with sinusoidal voltages and currents. The power factor for nonlinear loads includes the effects of harmonics with values expressed as per unit (pu), normalized to maximum motor speed and ASD power rating.

The distortion, and therefore PF, of the VSI drive differs from that of CSI in that distortion for the VSI may be considerably worse. However, power factor for PWM drives typically vary between 95 and 99%.

Nuisance Tripping Due to Capacitor-Switching Transients

When a capacitor becomes energized, a transient voltage oscillation develops between the capacitor and the power system inductance. The resulting transient overvoltage may be as high as 2.0 pu of the normal voltage *at the capacitor location* unless dampened by system loads and losses. These transient events usually do not concern utilities because, on the utility side, they do not rise above a level that would activate surge-protection devices elsewhere in the system (1.5 to 2.0 pu). However, during a switching event involving a utility capacitor bank, the transient overvoltage may be magnified at the customer facility should the customer have employed low-voltage capacitor banks for power-factor correction. Should the frequency of a transient overvoltage match the series resonant frequency of the customer's transformer coupled with the customer's capacitor bank, then a low-impedance, high-current condition results at that resonant frequency.

The transient current resulting from utility capacitor switching produces a transient voltage that will appear, magnified or not, on the customer distribution bus affecting anything, such as ASDs, connected to the bus. The voltage transient results in a surge of current into the DC link capacitor at a relatively low frequency (300 to 800 Hz). This current surge charges the DC link capacitor, thus causing an overvoltage to occur. Whether or not the overvoltage results from a magnified transient, it may be sufficient to raise the voltage of the DC link beyond its voltage tolerance thresholds, thus causing the ASD to shut down. This

While effective against low-energy transients, metal oxide varistors (MOVs) may be destroyed by magnified capacitor-switching transients.

type of nuisance tripping may occur day after day, often at the same time of day.

The magnification of capacitor-switching transients becomes most severe under the following conditions:

- The reactive power (kVAr) for the capacitor on the higher-voltage side far exceeds that of the capacitor on the lower-voltage side, as with substation switching.
- The frequency of oscillation produced as the utility's high-voltage capacitor becomes energized is close to the resonant frequency formed by the series combination of the customer's step-down transformer and low-voltage capacitor.
- The low-voltage system offers little resistive load that would dampen the transient.

Ordinarily, neither utility nor customer power-factor-correction capacitors cause harmonic problems unless they create a resonance near the 5th or 7th harmonic. For resonance problems to occur, the total capacitor kVAr would have to exceed 25% of the transformer rating.

The total installed ASD power requirement should not exceed 30% of the transformer capacity. Should power-factor-correction capacitors be required, then a harmonic filter approach should be used to control the magnification of voltage distortion due to harmonic currents. The addition of series inductors to the power-factor-correction capacitors should shift the resonant frequency away from the harmonic frequency of concern.

Other Sensitivities

Many ASD drives contain power semiconductor switch assemblies made of SCRs with a peak inverse voltage (PIV) rating of 1200 volts. On a 480-volt distribution system, such a PIV rating equates to 177% of normal system peak phase-to-phase voltage. The switch assemblies carry on-board metal oxide varistors (MOVs) for protection against transient voltages. While effective against low-energy transients, MOVs may be destroyed by magnified capacitor-switching transients. ASDs prove to be particularly sensitive to the transient voltages described earlier due to the relatively low PIV ratings of the semiconductor switches and low ratings of MOVs used to protect the ASD power electronics. Therefore, high-energy MOV arresters and higher-rated SCRs should be used. A low-voltage capacitor solution for a poor power factor may be reconfigured as a filter through the addition of series inductors. This addition detunes the circuit to prevent magnification of the capacitor-switching transient.

The circuit configuration (topology) of the drive as well as the control system characteristics may also affect the sensitivity of the drive. For instance, VSI drives require smoothing of the DC link voltage, usually with a large capacitor, for proper operation. Inverter components, especially high-power field-effect transistors (FETs) and bipolar junction transistors (BJTs), require protection from overvoltage conditions such as voltage transients. Such protection requires constant monitoring of the DC link voltage. Should the DC link voltage level rise beyond a preset value, typically around 760 volts or 117% of the nominal, the drive will trip out of service (ideal DC voltage is at 0.955 Vpk, where Vpk is peak-source phase-to-phase voltage).

One effective and relatively inexpensive way to eliminate nuisance tripping of small drives is to isolate them from the power system using series inductors called chokes or line reactors.

Small ASDs, referring back to Figure 18, typically employ a diode rectifier to convert AC to DC. A capacitor in the DC link smoothes the rectified voltage. A PWM inverter converts DC voltage to AC voltage or current to operate the motor. Because the DC link's capacitor connects alternately across each of three phases, it may be extremely sensitive to overvoltage on the AC power side. The ASD control system protects against both DC undervoltage as well as overvoltage to operate in a fairly narrow bandwidth. Again, voltage over 1.17 pu, or 760 volts for a 480-volt application, will cause the ASD to drop off-line.

One effective and relatively inexpensive way to eliminate nuisance tripping of small drives is to isolate them from the power system using series inductors called *chokes* or *line reactors*. The series inductance along with the voltage drop across the inductor reduces the current surge into the DC link, thereby limiting the DC overvoltage.

The choke size must be carefully selected: Too much impedance may increase harmonic distortion levels as well as notching transients at drive terminals. Commercially available chokes range in size from 1.5 to 5% of the ASD impedance at various horsepower ratings. Determining the precise inductor size requires a fairly detailed transient simulation taking into account the utility capacitor size, transformer size, and so on. However, a size of 3% usually will suffice to avoid nuisance tripping due to capacitor-switching operations. Newer designs may even include an inductive choke in the DC link to reduce harmonics and prevent nuisance tripping. Therefore, additional choke inductance at the input of such drives should not be necessary. Standard isolation transformers may serve the same purpose as series choke inductance.

Harmonic Distortion Concerns

Due to the harmonics it creates, an ASD appears to an electric system as a generator of currents at frequencies other than 60 Hz. These currents interact with the system impedance frequency-response characteristics to create, through Ohm's law, harmonic voltage distortion. For the utility and customer, this distortion may cause malfunction of relays and controls, capacitor failures, motor and transformer overheating, and increased power system losses. Moreover, the application of power-factor-correction capacitors, especially at the customer site, may magnify harmonic distortion levels, thus compounding the problem. With these added capacitors, a parallel resonance occurs at a frequency determined by the capacitance and source inductance. Significant voltage distortion may be created should this parallel resonance create high impedance for one of the characteristic harmonic currents generated by the ASD, typically the 5th or 7th harmonic (because these are the largest harmonic current components). However, the eleventh and thirteenth harmonics may also cause problems for loads with a large percentage of ASDs.

The actual distortion level will be affected by the amount of resistive load on the system that will dampen the resonance. Lighting and heating loads provide most of the damping because motor loads resemble a shunt inductance at the harmonic frequency and thus provide very little damping.

Most power systems, fortunately, may absorb significant levels of harmonic currents without producing excessive levels of voltage distortion. Even without the application of power-factor-correction capacitors, transformers may be loaded to 30 to 40% of rating with ASDs while maintaining voltage distortion less than 5% for most conditions [1].

Adding capacitors to a system will introduce a parallel resonance (high impedance) at a frequency determined by the capacitance and source inductance. Should this parallel resonance create a high impedance for one of the characteristic harmonic currents generated by the ASD (such as the 5th or 7th), then significant voltage distortion may occur with equipment problems likely to occur. Note that a transformer may require derating due to high ASD harmonic currents because increased I^2R losses create additional heating within the transformer windings that may damage the insulation of the windings.

Figure 20. Frequency-Response Characteristic

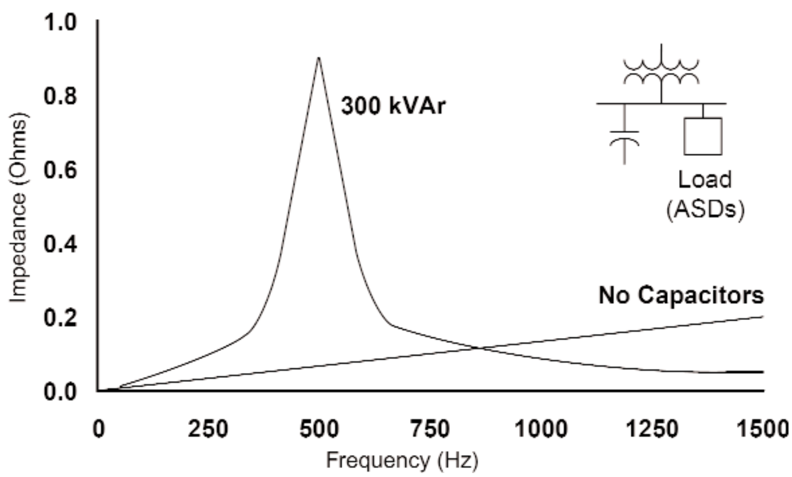


Figure 20 shows an example frequency-response characteristic for a 2000-kVA, 13.8/0.48-kV, 5.5% impedance transformer and a 300-kVAr, 480-volt capacitor bank.

A parallel resonance will occur at the frequency where the inductive source reactance becomes equal to the shunt capacitive reactance and may be expressed in terms of the 60-Hz values as follows:

$$h = \sqrt{\frac{X_c}{X_{sc}}} = \sqrt{\frac{kVA_{sc}}{kVAr_{cap}}}$$

Where:

h = parallel resonance frequency (x 60)

X_c = shunt capacitive reactance of capacitor

X_{sc} = short-circuit reactance of source

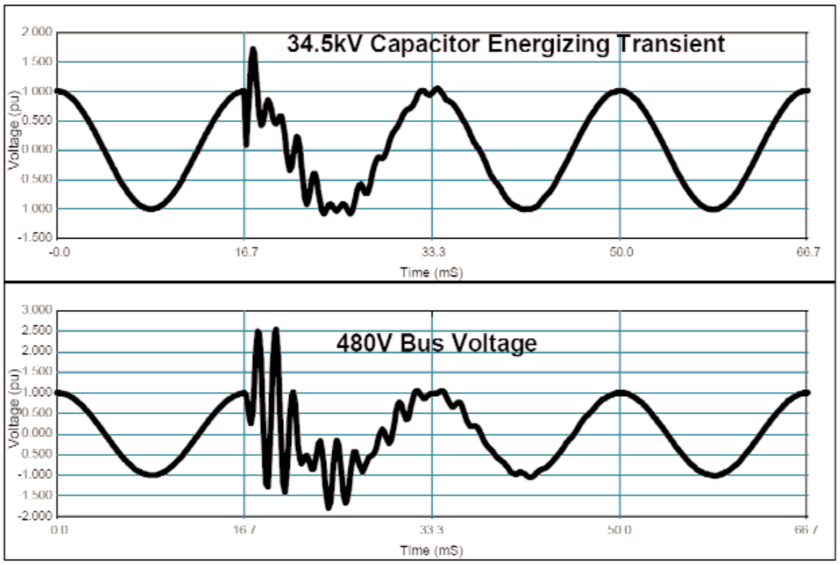
kVA_{sc} = short-circuit kVA of source

$kVAr_{cap}$ = total capacitor kVAr

One method of reducing harmonic distortion involves the implementation of harmonic filters along with the power-factor compensation. The inductors and capacitors in the filter, designed and specified based on the expected harmonic loading in combination with the reactive compensation (kVAR) supplied at the harmonic frequency, provide a low-impedance path for the harmonic currents and thus prevent problems with harmonic voltage distortion. Such filters may be tuned slightly below the harmonic frequency of concern to allow for tolerances in the filter components and also to prevent the low filter impedance from becoming a short circuit for the offending harmonic current. While not completely effective against nuisance tripping for small drives, harmonic filters prove very effective in preventing component failure.

Magnified transients, as illustrated in Figure 21, may occur in the range of 3.0 to 4.0 pu with energy sufficient to cause failure of protective devices (MOVs), electronic equipment (silicone-controlled rectifiers and so on), and capacitors.

Figure 21. Capacitor-Switching Transient



Magnified transients may be controlled in a number of ways:

- Energize the capacitor bank using vacuum switches with synchronized closing control.
- Provide high-energy MOV protection (at least 1 kJ) on the 480-volt buses.
- Use tuned filters for power-factor correction instead of shunt capacitor banks.

Other ASD Effects

Notching of the input voltage waves occurs due to the power electronic switching of the rectifier for a continuous-current operation. Current must be commutated or switched from one diode or silicon-controlled rectifier (SCR) to another. Phase-controlled rectifiers such as SCRs differ from uncontrolled rectifiers such as diodes in that the DC voltage may be varied by adjusting the firing angle of the SCR. During this aforementioned commutation, a phase-to-phase short circuit momentarily exists on the input, producing a notch in the voltage waveform.

The commutation time, a function of the total source reactance seen by the rectifier and the point on the wave (POW) at which the commutation occurs, determines the notch width. Phase-controlled rectifiers produce more severe notching due to the delayed SCR firing (conduction). The delay results in commutation at a point where the phase-to-phase voltage is higher. Caused by the ASD itself, voltage notching may require an isolation transformer or series choke to effectively isolate a drive from the rest of the system.

Notching may interfere with control circuits and communications. Often, notching causes crosstalk interference with the controls of other nearby ASDs. Applying a choke or isolation transformer on the drive input provides a simple solution. While the additional inductance makes the notching worse at the drive input (notch area increases with increasing input inductance), most of this notching voltage transient will appear across the added inductance. The notch appearing on the source side of the inductance will be less severe and will not affect other loads.

Motor-Side Harmonic Concerns

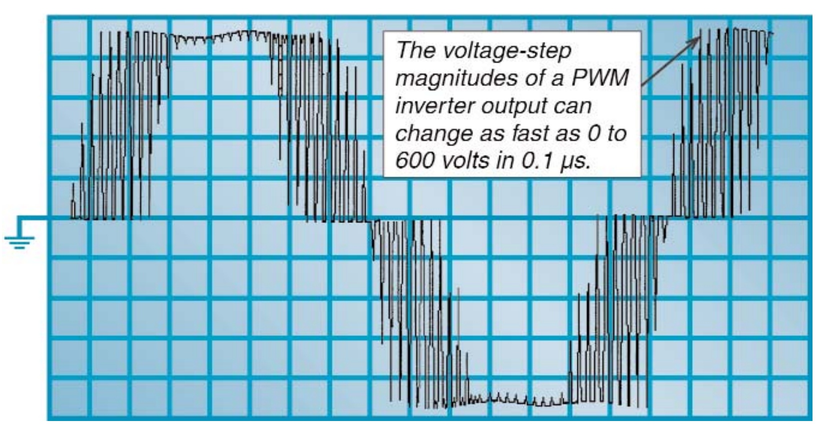
ASD manufacturers pay most attention to controlling harmonics on the motor side rather than the input side. These harmonics depend on the specific design of the inverter. Current-source inverters normally build a six-step current waveform similar to the input current waveform to the drive. The voltage waveform at the motor depends on the motor impedance at the harmonic frequencies. Such inverters produce relatively high current distortion of around 30 to 40% in the motor. This current distortion produces additional heating losses (I^2R) in the motor windings, which must be sized to withstand the additional heat so that the winding insulation does not suffer damage. In very large installations, 12-pulse designs may be used to reduce the harmonic levels for the 5th and 7th harmonics.

Most VSIs use PWM technology to supply the motor with relatively "clean" voltage. PWM reduces the impact of harmonic heating in the motor yet can create audible noise due to the modulation frequency of several kilohertz. An output choke may be used to reduce the higher-frequency harmonics in the motor, thus reducing the audible noise.

Motor-Side Transient Concerns

The output of some ASDs may adversely affect the motors that they drive. For instance, voltage transients as high as 2.0 pu may be detected at the terminals of a motor driven by PWM-type ASDs. Most ASDs designed to operate 460-volt induction motors incorporate VSIs, which create motor voltages at a switching frequency anywhere from 2 to 20 kilohertz using PWM technology. As shown in Figure 22, the output voltage of such an ASD is composed of voltage pulses with extremely quick changes in voltage magnitude.

Figure 22. Output Voltage of a Typical VSI-PWM ASD

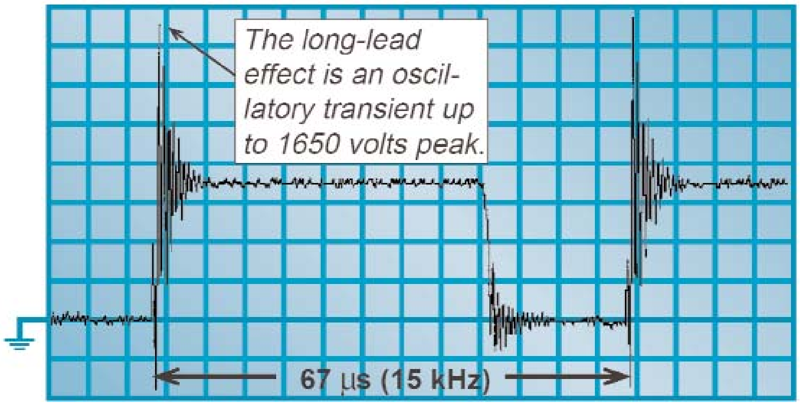


In many industrial applications, an ASD and the motor that it drives are separated by tens or even hundreds of feet, which requires long cables, called *motor leads*, to connect the two together. These motor leads behave like transmission lines for voltage pulses, which can be amplified (reflected) at the motor terminals as much as two times or more. If the surge impedance of the motor matches the surge impedance of the motor leads, then the amplification will be zero. However, exact matching of surge impedance is rarely the case. The amount of voltage amplification at the motor terminals generally depends upon the size of the motor and the length of the leads. The smaller the motor and the longer the leads, the greater the voltage amplification at the motor terminals. The resulting phenomenon, a large oscillatory transient known as the *long-lead effect* (see an example in Figure 23), can stress and consequently degrade the stator insulation system of a motor.

For most small- to medium-sized induction motor drives, voltage source inverters may provide variable-frequency AC output. A series of step-like functions generate the inverter output waveform, a steep-front waveform characteristic of a high-frequency-operation VSI. Modern VSIs employ IGBT technology. These inverters operate at a switching frequency ranging from ten to tens of thousands of hertz.

One advantageous outcome of the high-switching-frequency inverter—reduced low-order harmonics—may reduce the requirement for an output filter. A disadvantageous outcome due to the fast-changing voltage would be severe insulation problems for an induction motor.

Figure 23. The Long-Lead Effect



Voltage magnitude as well as the rate of change of voltage affects motor insulation integrity because voltage with a high rate of change will become unevenly distributed along a motor's winding. This uneven distribution causes a significant over-stress across ending turns, resulting in turn-to-turn insulation failure. The most harmful effects for the outputs of PWM ASDs occur with a connection cable relatively long with respect to the wave front of an incidental voltage wave coupled with a high ratio of machine and cable characteristic impedance, which sometimes doubles the magnitude of the inverter's voltage pulse measured at the induction motor terminals. Manufacturers may specify a particular cable length for their ASDs, as is shown in Table 5.

Table 5. Critical Cable Lengths of One Manufacturer

Inverter Technology	Critical Cable Length
IGBT	100 to 200 ft.
Bipolar	250 to 500 ft.
GTO	600 to 1000 ft.
SCR	600 to 1000 ft.

While measurement of the voltage transition at the output of the PWM VSI drive would indicate no overshoot, measurements at the motor terminals may typically show an overshoot of 1.7 p.u. As much as 85% of the peak transient voltage will be dropped across the first turn of the first coil of the motor phase winding.

While the inter-turn insulation is unlikely to fail at the first surge impact, repeated surges over time will accelerate the aging process of the dielectric material, thus weakening the insulation, especially at the ending region of the machine winding.

Lead-Length Experiment

EPRI undertook a test to explore the significance of lead length at its Knoxville Power Quality Test Facility using an ASD to control a 460-V AC induction motor. The objectives of the tests performed there were to 1) determine the correlation between peak motor voltage and the length of motor leads and 2) determine the correlation between peak motor voltage and the switching frequency of the ASD.

Test Setup

EPRI engineers tested three five-horsepower VSI-PWM ASDs from three different manufacturers. Each was rated for three-phase, 460-volt operation. As shown in Figure 24, each test required one of the ASDs to be connected to a 460-volt, five-horsepower induction motor by way of fourteen-gauge leads ranging from ten to 500 feet. An eddy-current brake connected to the motor was set to 50% loading at 60 hertz. During the tests, to determine the rise times of peak motor voltages and the effect of lead length on peak motor voltage, the switching frequencies of the three ASDs were set to their default values. A digitizing oscilloscope measured the rise time and peak voltage at the motor terminals.

Figure 24. Test Setup

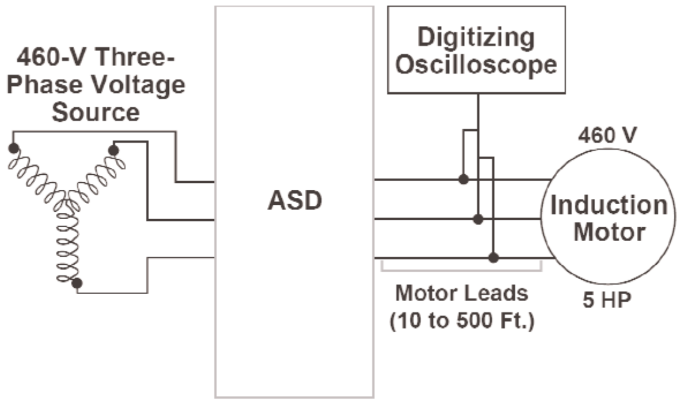
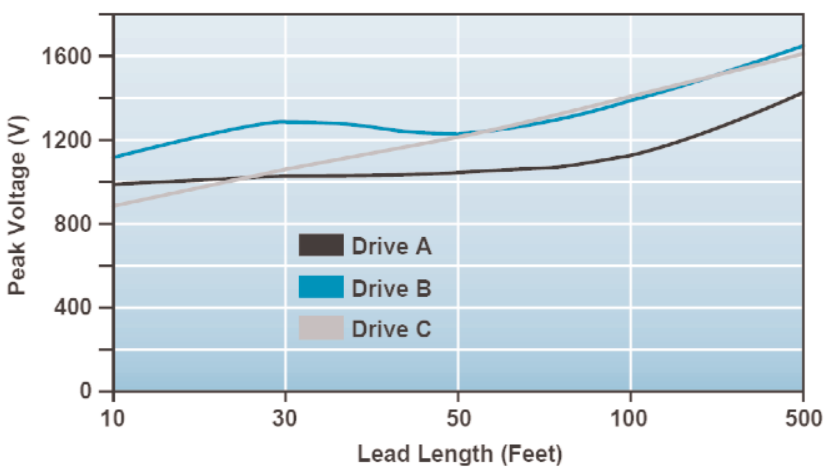


Table 6. Rise Times of the Three ASDs

Drive	Default Switching Frequency (kHz)	Rise Time (ns)
A	4.5	458
C	4.8	130
C	15	35

Figure 25. Peak Voltage versus Lead Length



Test Results

Voltage Rise Time

With each ASD connected to the motor by way of ten-foot leads, the rise times of the peak motor voltages were measured at the motor terminals. As shown in Table 6, the default switching frequencies of the ASDs ranged from 4.5 to 15 kilohertz, and the rise times ranged from 35 to 458 nanoseconds.

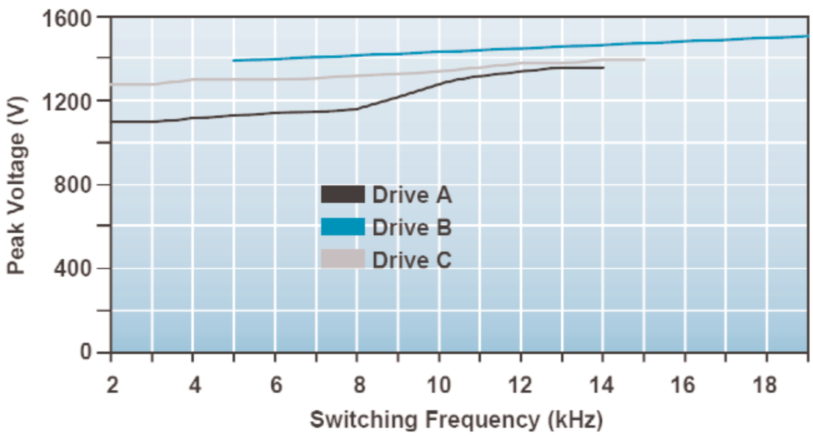
Lead Length

The length of the motor leads varied from ten to 500 feet, with peak motor voltage being measured at various length intervals during normal motor operation. Figure 25 shows the peak motor voltages for each ASD ranging from 890 volts for the ten-foot lead length to 1650 volts for the 500-foot lead length.

Switching Frequency

To determine the correlation between ASD switching frequency and peak motor voltage, the frequency of each ASD was varied according to its particular frequency options. The switching frequency of Drive A was varied from two to 14 kilohertz in nine steps, Drive B from 4.8 to 19.2 kilohertz in two steps, and Drive C from two to 15 kilohertz in ten steps. Motor leads of varying lengths connected each ASD to the motor. As shown in Figure 26, the peak motor voltage increased as the ASD switching frequency increased. The peak voltage of Drive A increased about 9% over a range of 12 kilohertz. The increase was about 24% over a range of about 14 kilohertz for Drive B and about 9% over a range of 13 kilohertz for Drive C.

Figure 26. Peak Voltage versus Switching Frequency



Discussion

Test results demonstrated a strong correlation between peak motor voltage and lead length: The peak motor voltage increased with increasing lead length. However, the average peak motor voltage at lead lengths as short as ten feet measured at around 1000 volts, exceeding the voltage rating of the typical 460-volt motor by nearly 18%. The test results also demonstrated a correlation between switching frequency and peak motor voltage: The peak motor voltage increased as the ASD switching frequency increased.

Significance

Although reducing the length of motor leads will decrease peak motor voltages, these voltage peaks remain at levels that will lead to stress-related failure of a typical induction motor. Higher switching frequencies of VSI-PWM ASDs require motors designed to withstand such voltages as well as even higher voltages resulting from the long lead effect.

Mitigation techniques for the overvoltage problem at the motor terminals include:

- Install a line choke on the output of the PWM drive in series with the connection cable.
- Install a capacitor in parallel with the motor at the motor terminals. This capacitor requires a significant cable length to prevent interaction problems with the drive. Drive manufacturers do not recommend installing capacitors.
- Install an LC filter at the drive output. Basically a combination of the previous two techniques, this filter, a series inductor with a capacitor in parallel, is installed at the output of the PWM drive, usually by the manufacturer.
- Specifying a motor with additional insulation in the first few turns of the motor windings or the addition of an LC filter at the output of the PWM drive should solve the problem.

Voltage Sags and Momentary Interruptions

In most power systems, electrical disturbances such as voltage sags are unavoidable. Many electronic devices show sensitivity to voltage sags. Depending on the specific controls, ASD drives show sensitivity to momentary outages or voltage sags of only a few cycles.

Of all categories of electrical disturbances, the voltage sag and momentary interruption are the nemeses of the automated industrial process. When an ASD shuts down during a voltage sag or momentary interruption, the process it controls often requires manual reset and restart. Moreover, extensive cleanup and equipment repair may delay restart for a significant time. Every minute that a scheduled process is shut down, the manufacturer loses revenue. Some industries have reported losses as high as one million dollars or more for a single electrical disturbance that caused a critical process shutdown. With the possibility of several such shutdowns per year, it is no wonder that ASD users are eager to improve the ability of ASDs to ride through voltage sags and momentary interruptions.

The sag itself has many origins. Generally, voltage sags and momentary interruptions are caused by system faults. Should a fault occur on the transmission or distribution system, then a voltage sag or interruption will occur. Faults can be initiated by a number of events, including lightning, animals contacting power lines, and tree limbs contacting power lines. The fault persists until cleared by a protective device, usually 3 to 30 cycles depending on the fault location. Should the fault occur on the same feeder as the customer, power may be completely interrupted until fault clearing and reclosing operations conclude.

Figure 27. A Voltage Sag to 75% of Nominal

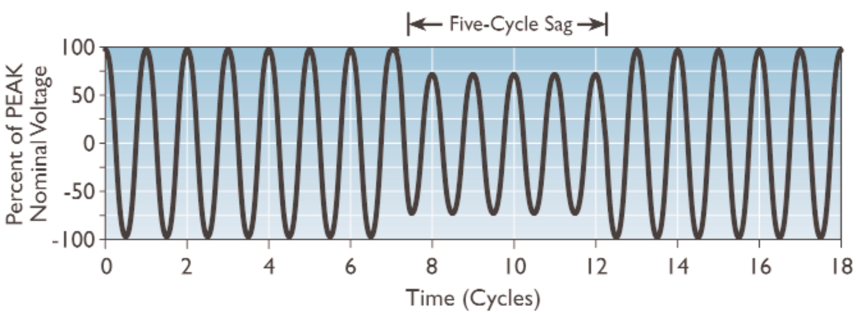
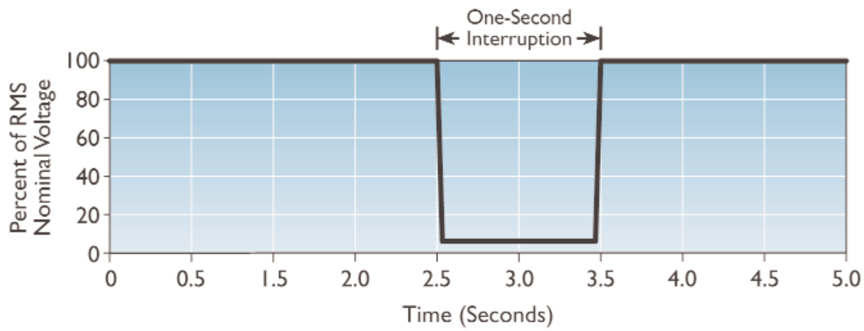


Figure 28. A Momentary Voltage Interruption with 5% Remaining Voltage



In IEEE Standard 1159, the Institute of Electrical and Electronics Engineers (IEEE) defines a voltage sag as any low-voltage event between 10 and 90% of the nominal voltage lasting between 0.5 and 60 cycles. Figure 27 shows a voltage sag to 75% of the nominal peak voltage with a duration of 5 cycles. The IEEE defines a momentary voltage interruption as any low-voltage event of less than 10% of the nominal voltage lasting between 0.5 cycles and 3 seconds. Figure 28 shows a one-second momentary voltage interruption with a remaining voltage of 5% of the nominal RMS voltage.

Some voltage sags are caused by faults in the utility transmission and distribution system. When a fault occurs on one power system feeder, the voltage on the bus to which the feeder is connected will decrease. The other feeders connected to this bus will experience a voltage sag, while the faulted feeder will be isolated by a fault-clearing device, thereby experiencing an interruption. The voltage sag on adjacent feeders persists until the fault is isolated or cleared. The depth of a voltage sag at the terminals of an ASD depends upon the fault current, the distance between the ASD and the fault, and the impedance of the intervening cables (including transformers and feeders), among other factors. The duration depends upon the clearing time of the interrupting device.

The EPRI Distribution System Power Quality (DPQ) Study monitored nearly 300 sites in the United States between June 1993 and

August 1995 [6]. Results of this study indicate that most voltage sags in the United States are caused by single-phase line-to-ground faults, as shown in Figure 29. The study also indicated that an average site will experience about 45 voltage sags and five momentary interruptions every year.

Figure 29. Number of Single-Phase, Two-Phase, and Three-Phase Voltage Sags as a Percent of Total Voltage Sags Measured below 90% of Nominal

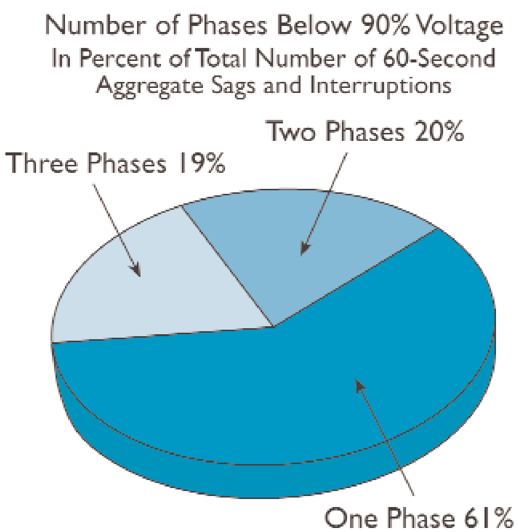
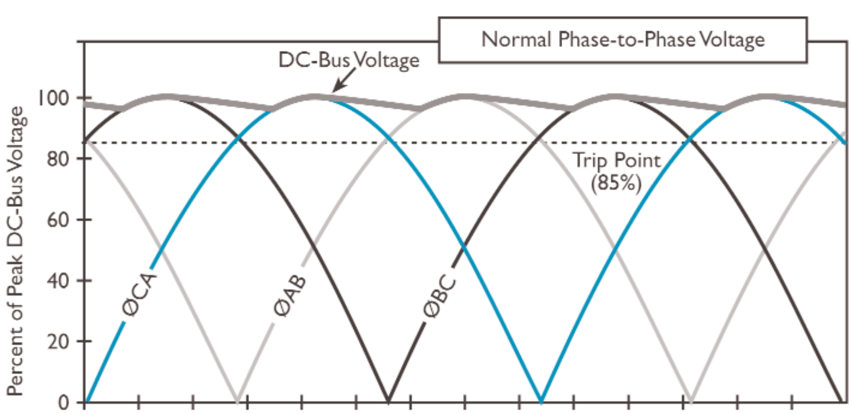


Figure 30. DC Bus during Normal Phase-to-Phase Voltage



However, of the 45 voltage sags, only about 14 will be deeper than 70% of nominal.

Effects of Sags and Interruptions on ASDs

The response of an ASD to a voltage sag or momentary interruption varies widely. Whether or not the response of an ASD is acceptable depends upon the dynamic requirements of the process. For example, one process may not tolerate even moderate changes in torque and speed, while another may tolerate wide momentary swings in torque and speed. In fact, for some processes, a drive may shut down yet continue to meet the operational requirements of the process because the drive enables automatic restart or because the process does not require continuous control.

PWM VSI Drives

ASDs are delta-connected loads. That is, they use phase-to-phase instead of phase-to-neutral voltages. In Figure 30, all phase-to-phase voltages are normal. The voltage across the DC bus follows the input voltage, while the DC capacitors charge and then decrease until the next phase-to-phase voltage exceeds the level of the DC bus. The charging and discharging of the DC-bus capacitors create a slight ripple, so that the RMS voltage is very close to the peak voltage across the DC bus.

During a phase-to-neutral voltage sag in the electrical service supply, an ASD will likely experience a phase-to-phase sag on two phases. Based on monitoring data compiled for the EPRI DPQ Study, over 60% of all voltage sags affect only one phase-to-neutral voltage. Therefore, although most voltage sags involve only one phase-to-neutral voltage, most voltage sags at a delta-connected load will involve two phase-to-phase voltages. Figure 31 shows how a single line-to-neutral voltage sag to 50% of nominal can become a sag to 76% of

Figure 31. Effect of Line-to-Neutral Sag (VAN) on Phase-to-Phase Voltages (VAB and VAC)

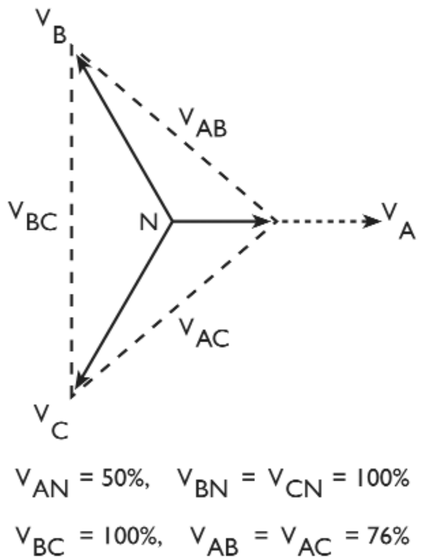


Figure 32. DC Bus during a 50% Voltage Sag on Phase A

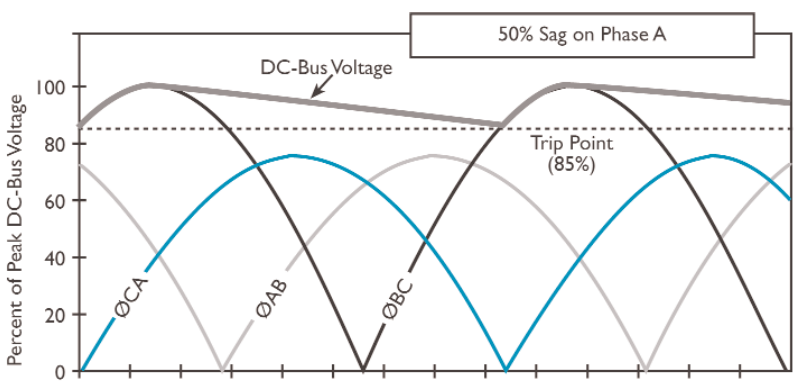
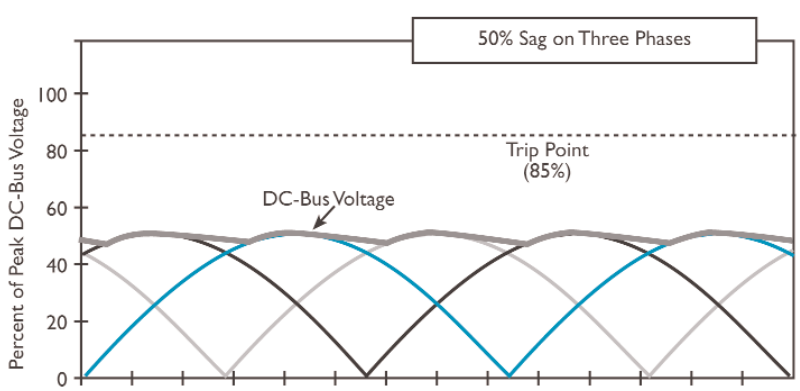


Figure 33. DC Bus during a 50% Symmetrical Voltage Sag on All Three Phases



nominal on two phase-to-phase voltages, while the third phase-to-phase voltage remains normal.

As shown in Figure 32, the peak of the highest phase-to-phase voltage determines the peak of the voltage across the DC bus. In this example, the voltage between phase B and phase C determines the peak of the DC voltage. Note that no matter how low the other two phase-to-phase voltages fall, the DC-bus capacitors will charge to the peak of the voltage between phase B and phase C.

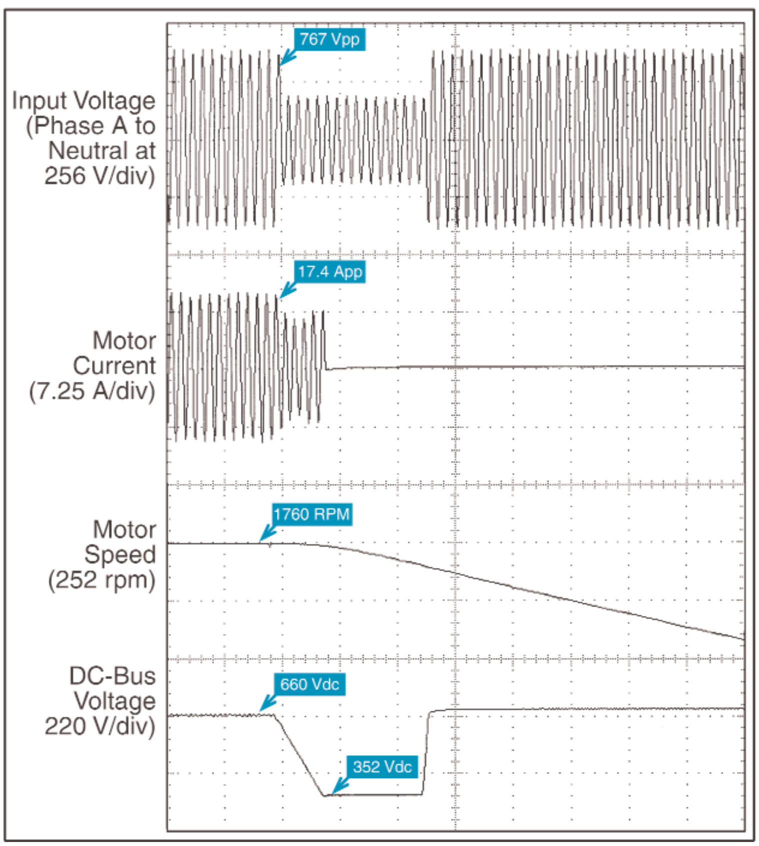
How fast the DC-bus capacitors discharge depends mostly upon amount of motor load and the amount of capacitance in the DC bus. The DC-bus voltage in Figure 32 was calculated for a five-horsepower ASD at full load with 370-mF of capacitance, which is typical of a five-horsepower ASD. In this case, the drive is fully loaded, which represents a worst-case scenario. However, the DC-bus voltage still remains above the undervoltage trip point by one volt. If the ASD were less loaded—which is typically the case—the DC-bus voltage would be even higher during the single-phase voltage sag.

When all three phase-to-phase voltages sag equally, the DC-bus voltage falls proportionally to the peak of the sagged phase-to-phase voltages. Figure 33 shows a symmetrical three-phase voltage sag to 50% of nominal. Because the DC-bus capacitors can charge only to the highest peak of the three phase-to-phase voltages, the voltage across the DC bus is about 50% of the normal DC voltage, well below the undervoltage trip point of the ASD, which will cause the drive to shut down on "DC Bus Undervoltage."

Besides the sensitivity of the drive itself, individual motor contactors, relays, emergency motor shut-off (EMO) circuits, and other devices in the control circuit may trip due to voltage sags or momentary outages. Therefore, the ASD requires specific protection against voltage sags and momentary outages. This may be accomplished using any of several devices on the market that must be sized for the particular load. If possible, only the control system of the ASD should be protected because it should be a much smaller load compared to that of the entire motor.

Changes to the trip settings of the ASD may allow the ASD to ride through sags of a certain magnitude. While the ASD may not trip for the lower voltage level on the DC bus in this case, it may trip for an overcurrent situation caused by the sudden recharging of the depleted DC bus capacitor.

Figure 34. Typical ASD Shutdown Caused by a 15-Cycle, Three-Phase Voltage Sag to 50% of Nominal



ASDs exist having a 3-cycle ride-through capability that will prevent false tripping. Additional protection is possible with the application of voltage-sag-mitigation devices such as the constant-voltage transformer (CVT), the dynamic sag corrector (DySC), and the uninterruptible power supply (UPS).

ASD DC Bus and Inverter Circuit

During a voltage sag or momentary interruption, the diodes in an ASD rectifier bridge will not conduct if the peak line voltage drops below the level of the DC bus. While the ASD is still controlling the motor and its load, the motor and motor load will draw energy from the DC bus capacitors, which will cause the DC bus voltage to decrease. If the DC bus voltage falls below the ASD's undervoltage trip point before the line voltage returns, then the control circuit will respond according to the drive's program, perhaps shutting down the drive.

Figure 34 shows the effect of a 15-cycle, symmetrical, three-phase voltage sag to 50% of nominal on motor current, motor speed, and the DC-bus voltage of a typical ASD/motor system. At the onset of the voltage sag, the DC-bus voltage begins to drop from a nominal 650 volts and will continue to drop until it reaches the ASD undervoltage trip point of 496 volts. At that point, the ASD shuts down, and the motor current decreases to zero. Without a recovery capability, the ASD cannot remain active or restart on its own to supply energy to the motor, and the motor speed then gradually falls to zero.

Most PWM VSI drives use a fixed undervoltage trip point that is typically set at 70 to 85% of the nominal DC-bus voltage. Among other reasons, ASDs are set to shut down during DC-bus undervoltages to protect diodes in the bridge rectifier from capacitor inrush current in the DC-bus during voltage recovery. For a

650-volt DC bus, the typical trip point ranges from 455 to 553 volts. Should a voltage sag or interruption involve all three phases, the voltage at the DC bus will usually decrease in proportion to the decrease in line voltage. For example, a three-phase voltage sag to 90% of nominal would cause the voltage at the DC bus to decrease from 650 volts to about 585 volts.

ASD Contactors and Control Circuits

Many drive installations include a line-side contactor that connects the drive to the voltage source. A line-side contactor connected to an ASD may be a leftover starter contactor used for the motor prior to drive installation. Contactors and related control relays may be used as part of local emergency-stop circuit or a transfer switch to bypass the ASD. Even motor-side contactors are sometimes used with ASDs.

Figure 35. Voltage Sag at the Terminals of an ASD Connected Directly to the Voltage Source

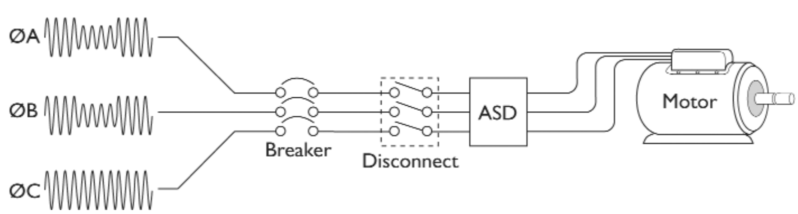
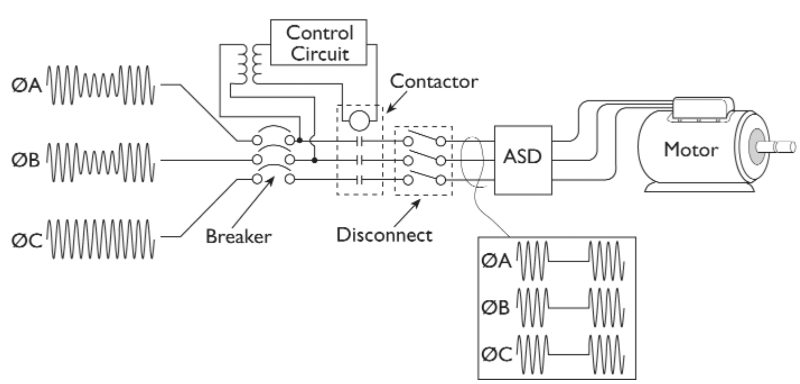


Figure 36. Voltage Sag at the Terminals of an ASD Connected to the Voltage Source through a Contactor



These contactors can affect the ride-through, restart, and control of an ASD. In some cases, the protection components of a drive can be damaged because of the operation of a line-side contactor. For example, one drive manufacturer states the following: "The drive is intended to be controlled by control input signals that will start and stop the motor. A device that routinely disconnects and reapplies line power to the drive for the purposes of starting and stopping the motor is not recommended." NEC Article 430 provides information about specifying protection and control of ASDs. The article requires simply that each branch circuit connected to an ASD or motor must have a disconnect means, short-circuit protection, and overload protection.

Although the NEC provides the rules to ensure safety in building wiring and installation of ASDs, it does not address performance or reliability issues related to using disconnect means with an ASD. In fact, using a line-side contactor as a control device for an ASD can decrease the ride-through of the ASD system. Consider the scenario in Figure 35, where the ASD is connected directly to the voltage source via an overcurrent-protective device (breaker) and a local disconnect switch. In this case, the ASD will likely ride through the voltage sags shown on phases A and B because there is no contactor to remove voltage from the drive during the sag.

Now consider the scenario in Figure 36. When a contactor is installed between the ASD and the overcurrent-protective device, the ride-through of the ASD system is no better than the ride-through of the series-connected contactor. As shown in Figure 37, a typical contactor has a dropout point around 50% of the nominal voltage during voltage sags lasting longer than 5 cycles, and a typical relay has a dropout between 60 and 70% of the nominal voltage during voltage sags lasting longer than 1 cycle.

Figure 37. Ride-Through of a Typical Contactor and Relay

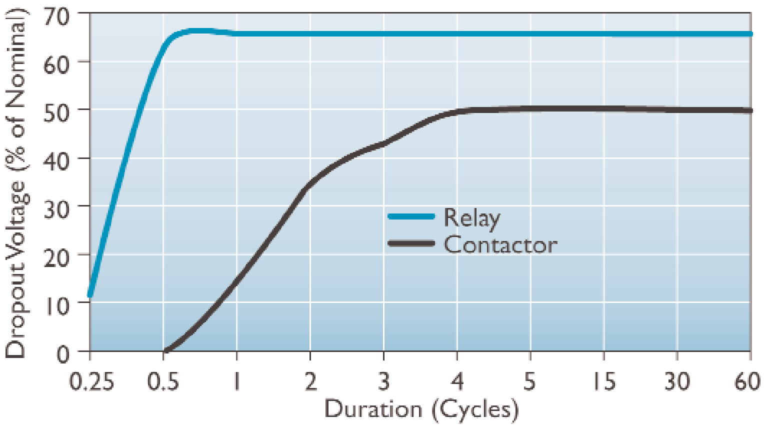
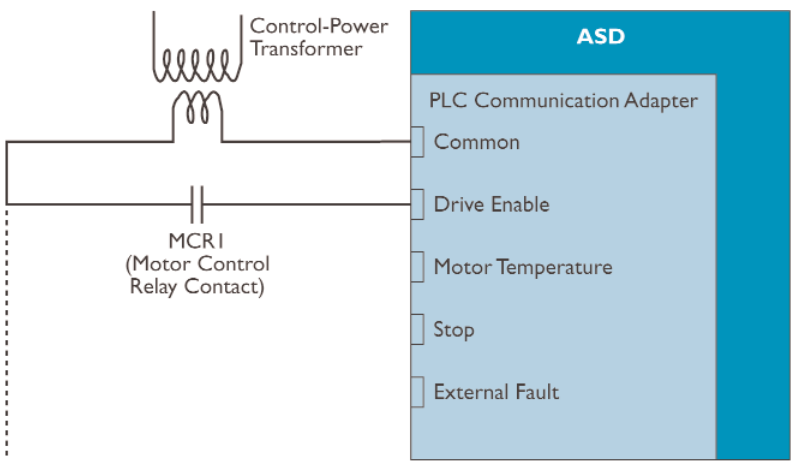


Figure 38. Typical Connection of an ASD to PLC Control Signals

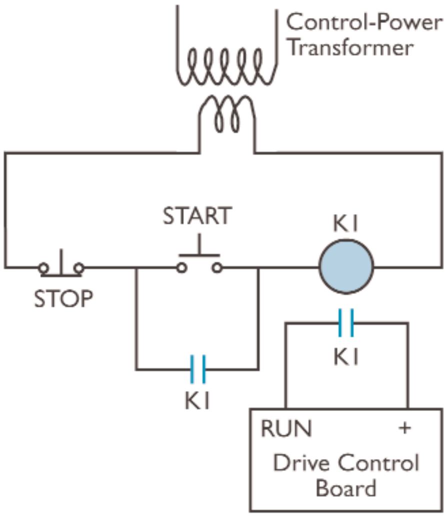


When the voltage on phases A and B in Figure 36 sags, the coil of the contactor drops out. Instead of experiencing a phase-to-phase voltage sag, the ASD experiences a three-phase momentary interruption for the duration of the voltage sag, which may cause the ASD to shut down. Cascading ASD control devices such as line-side contactors can compound this problem.

External motor-control circuits and programmable logic controllers (PLCs) often provide enable, start, stop, and speed signals to I/O terminals on the drive control board. These signals are critical to drive operation, and loss of a signal can cause the drive to shut down. Drive installers also use relay contacts to provide the drive-enable signal. Figure 38 shows a typical connection of a drive-enable signal to an ASD PLC communication adapter. The drive-enable signal typically derives from the contact (MCR1) of a motor control relay (MCR), whose coil is powered from a logic circuit (not shown). Voltage sags can cause the MCR to drop out, opening the MCR1 contact, disconnecting the drive-enable signal from the ASD, and causing the ASD to shut down.

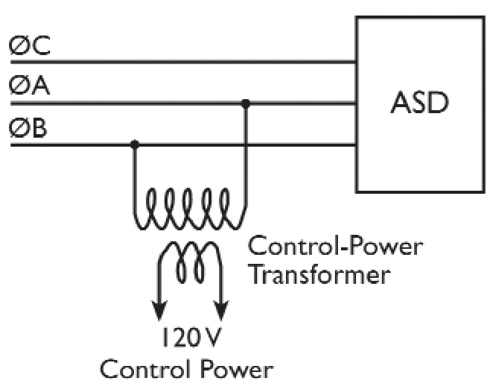
Start/stop circuits for ASDs may also account for ASD shutdowns. For example, Figure 39 shows how a typical start/stop circuit connects voltage (+) to the RUN terminal of an ASD. To start the ASD, the normally open START button must be pressed. Then, the coil of the normally open contactor K1 becomes energized, latching the start button closed and connecting the RUN terminal to the RUN voltage terminal (+) on the drive control board. Pressing the STOP button disconnects the coil of contactor K1 from the voltage source and thereby unlatches the start button, shutting down the ASD. A voltage sag of significant depth and duration can also de-energize the coil of contactor K1. Once the contact K1 opens, the START button must be pushed to manually restart the ASD.

Figure 39. Simplified Start/Stop Circuit for an ASD



In early versions of ASDs, the control power was derived from the AC line instead of the DC bus, as shown in Figure 40. A step-down transformer, usually connected to the 480-volt source on the primary, supplied 120 volts of control power at the secondary. With this control design, the older-generation drives are particularly sensitive to voltage sags and momentary interruptions because the voltage supplied to the logic circuits changes immediately with changes in the supply voltage. The control power shown in Figure 40 is vulnerable to either single-phase sags or multi-phase sags involving phase A, phase B, or both. The worst-case scenario for this type of control voltage is a sag involving both phase A and phase B. Such a sag would be directly transformed to the secondary of the transformer at the same magnitude as the two sagged phases.

Figure 40. Source of Control Power in Early ASD



When control power is derived from the AC line, voltage sags and interruptions can disrupt information processing by the ASD logic circuits, resulting in faulty decisions or a complete shutdown. For example, a logic circuit responsible for activating overcurrent protection may malfunction, resulting in damaged ASD components. Undervoltage detection may also be compromised by malfunctioning logic circuits.

In modern ASDs deriving control power from the DC bus, ride-through time for the control circuits may be several seconds. The amount of ride-through depends upon the size of the DC-bus capacitors in the drive and the level of motor load. Also, modern control circuits are powered by switch-mode power supplies, which provide better ride-through for control circuits than linear power supplies.

Inrush Current During ASD Recovery

Because of the capacitors in the DC bus, PWM VSI drives can draw significant inrush current following a voltage sag. During deep three-phase voltage sags or momentary interruptions, the DC-bus voltage may drop significantly should the undervoltage trip point be set low. When the AC line voltage abruptly recovers, the DC-bus capacitors will draw a large inrush current to recharge up to the peak of the AC line voltage. The peak of the inrush current can be three to four times the full-load current of the ASD. High inrush currents can damage input rectifiers and blow input protection fuses. Figure 41 shows the inrush current at the end of a three-phase voltage sag to 50% of nominal.

Figure 41. Inrush Current after a Three-Phase Symmetrical Voltage Sag to 50% of Nominal

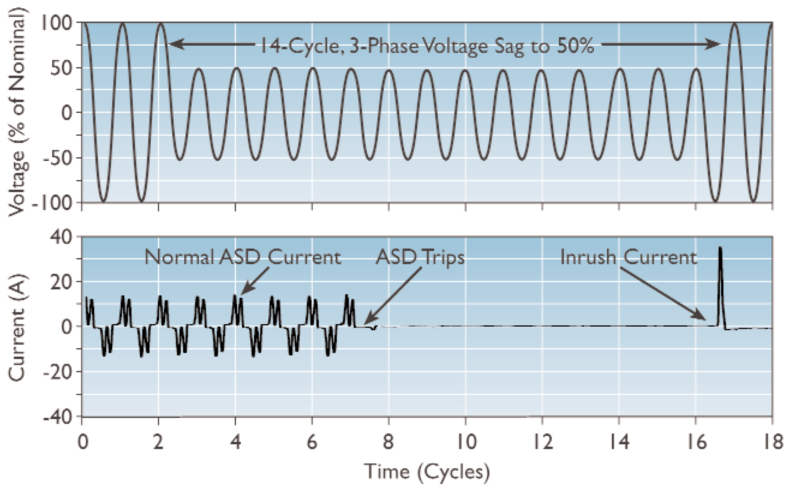
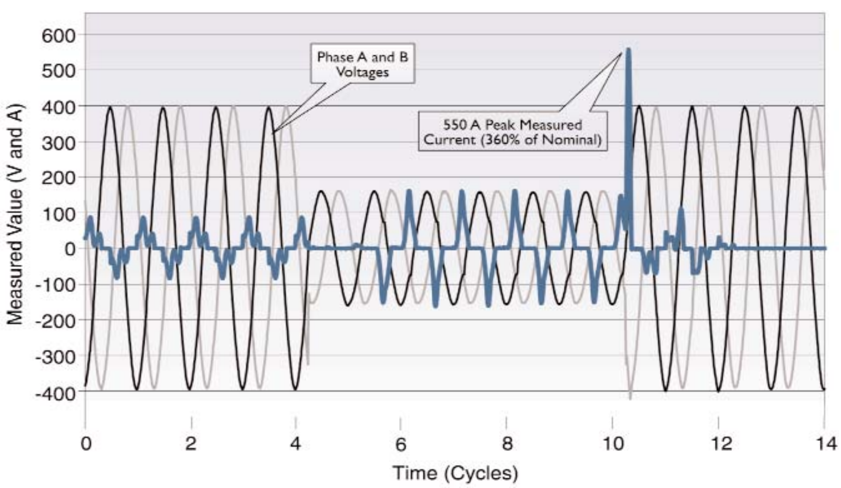


Figure 42. Voltage Sag and Inrush Current in ASD



In Figure 42, the ASD recovered from the sag, experienced the inrush at the end of the voltage sag, and shut down due to the inrush. The peak current value is quite large and could damage sensitive components in the ASD or anywhere else in the electrical system carrying the inrush current.

ASD manufacturers recommend ultrafast-acting semiconductor fuses to protect rectifiers from overcurrent damage during transient electrical disturbances. Such fuses protect the drive rectifiers and DC-bus capacitors. However, they may blow during post-sag inrush current, shutting down the ASD.

The magnitude and duration of the inrush current, which is the amount of energy required to charge the DC-bus capacitors, depend upon the source impedance and magnitude of the voltage across the DC bus when the line voltage returns. Only two phases will carry the inrush current. Therefore, blown fuses and component damage caused by inrush current are usually limited to two phases.

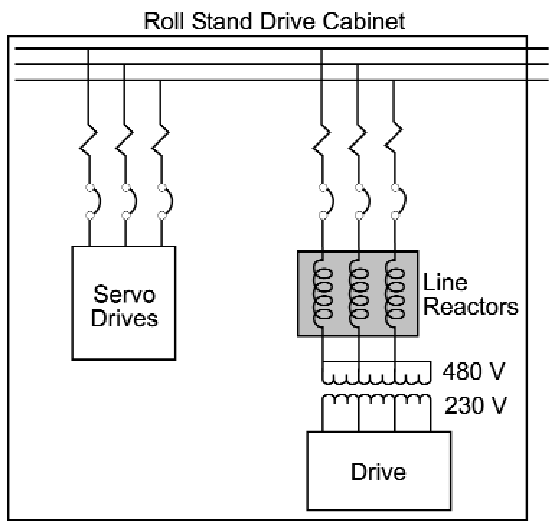
Protection Against Inrush Current

As stated earlier, inrush current can blow fuses and damage ASD components. For many years, manufacturers of PWM VSI drives have incorporated pre-charge resistors into their drives to limit the inrush current when a drive is first powered up (see Figure 1). Now, some manufacturers are also using pre-charge resistors to limit the inrush current that follows a voltage sag or momentary interruption. The resistor is bypassed during normal operation and is inserted into the circuit when the DC bus drops below a preset level.

Also, a line-side inductor—which has many benefits such as limiting harmonic currents, improving the power factor, and reducing the sensitivity of ASDs to voltage unbalance and capacitor-switching transients—can limit inrush current. The effect of the inductor, also called a line *reactor* or *choke*, works on the DC bus for both line transients such as capacitor-switching events, where the excess voltage will drop across the line reactor, as well as for overcurrent or inrush current conditions where the inductor will resist momentary changes in current, keeping the peak inrush below the level that would trip the ASD or cause damage to sensitive components.

Drive input reactors normally range from 3% to 5% based on drive horsepower rating. For instance, a motor operating at 238 V and pulling 3 amps at full load would correspond, in The National Electrical Code (NEC), to 0.75 HP, 230 V, 3.2 FLA (full-load amps). The required reactor inductance in this case is determined to be 5.5 mH.

Figure 43. Application of Line Reactors



Referring to Table 7 [7, page 19], the reactor closest to 5.5 mH would operate at either 3 or 6 maximum amps. Because 6 amps would cover any expected full-load current level for these motors, the RL-00402 reactor at 6.5 mH, 6 maximum amps was selected.

The location of the line reactor (also a typical application of a line reactor) is illustrated in Figure 43, between the 240-V source and the drive supply terminals. While the line reactor should reduce drive tripping due to capacitor-switching transients, it will not have any effect on tripping due to voltage sags.

Voltage Unbalance and ASDs

Background

A phase-voltage unbalance occurs when the voltages of a three-phase supply are not equal. Maintaining an exact voltage balance at the point of use is virtually impossible because of three main factors: (1) single-phase loads are continually connected to

Table 7. MTE Reactor Technical Data

TECHNICAL DATA
Standard Type "RL" AC Line/Load Reactors

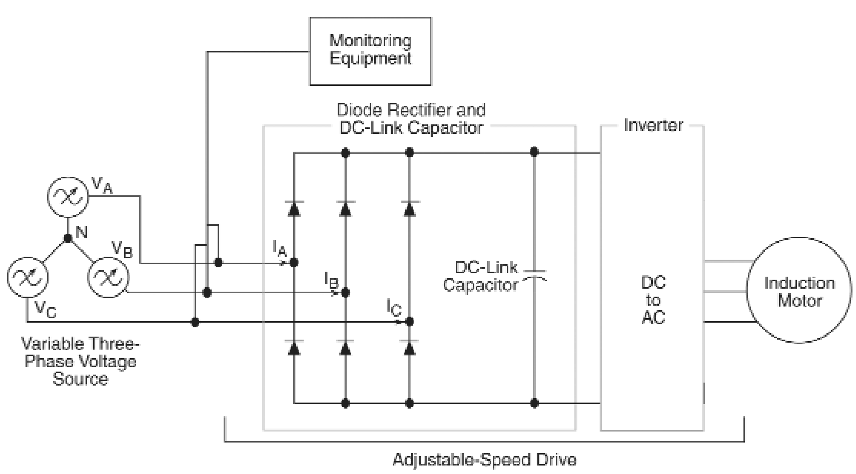
Catalog Number	Watts Loss	Terminal Data			Weight Mass			Fund Max	
		Type	Wire Range (AWG)	Torque (in-lbs)	lbs	Kg	mH	Amps	Amps
RL-00201	8	TB	22–14	4.5	4	2	12	2	3
RL-00202	12	TB	22–14	4.5	4	2	20	2	3
RL-00203	16	TB	22–14	4.5	4	2	32	2	3
RL-00204	11	TB	22–14	4.5	3	2	6	2	3
RL-00401	15	TB	22–14	4.5	4	2	3	4	6
RL-00402	20	TB	22–14	4.5	4	2	6.5	4	6
RL-00403	20	TB	22–14	4.5	5	3	9	4	6
RL-00404	21	TB	22–14	4.5	6	2	12	4	6

and disconnected from the power system, (2) single-phase loads are not evenly distributed between the three phases, and (3) power systems may be inherently asymmetrical. ANSI C84.1-1989 recommends that electrical supply systems should be designed and operated to limit the maximum voltage unbalance to 3% when measured at the electric utility revenue meter under no-load conditions. IEC (the International Electrotechnical Commission) recommends 2%. However, for some modern three-phase power-electronics equipment, such as the adjustable-speed drive, a 3% voltage unbalance may cause excessive current in one or two phases, which can trip overload-protection circuits. Tests performed at EPRI determined the effects of steady-state phase-voltage unbalances upon the phase-current unbalance and harmonic distortion of commercially available three-phase ASDs powering an induction motor.

Test Setup

Testing involved thirteen different models of 5-HP AC adjustable-speed drives rated for three-phase, 460-VAC operation. Figure 44 shows a diagram of the test setup. The user-selectable features of each ASD model remained at the factory default settings. The input of each ASD connected to a variable three-phase voltage source. The output connected to a three-phase, 5-HP induction motor with an eddy-current brake to control the ASD load. Line-to-line, steady-state voltage unbalances were created by adjusting the voltage of one phase to a voltage slightly lower than the other two phases. A digitizing signal analyzer and digital power monitor were used to monitor and record the ASD input current, voltage, and current waveforms of all three phases. For all tests, the eddy-current brake was set for 75% loading.

Figure 44. Test Setup



Test Results

Each ASD was subjected to three steady-state phase-voltage conditions: (1) virtually balanced phase-to-phase voltage (about 270 volts from each phase to neutral), (2) unbalanced voltage created by reducing the voltage between phase A and neutral by 10 volts, and (3) unbalanced voltage created by reducing the voltage between phase A and neutral by 20 volts. Generally, as the voltage unbalance increased from 0.6 to 2.4%, the current unbalance increased from 13% to a maximum 52%. Whereas the total harmonic current distortion and the 5th harmonic component increased moderately as the voltage unbalanced increased, the 3rd harmonic component increased dramatically, as much as 13 times. Moreover, the level of each harmonic component was different for each phase. Table 8 shows the resulting line-to-line voltages, voltage unbalances, line currents, and current unbalances measured for one of the typical ASDs. Table 9 shows the resulting total harmonic current distortion and its 3rd and 5th harmonic components. Table 10 shows the phase-current waveforms for each of the three voltage conditions.

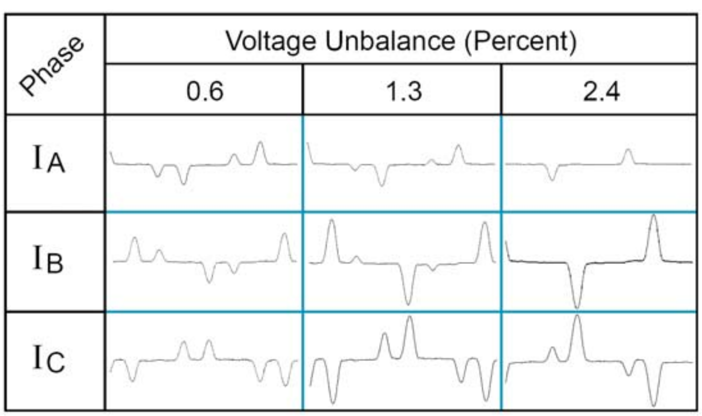
Table 8. ASD Input Line-to-Line Voltage, Voltage Unbalance (Vub), Line Current, and Current Unbalance (Iub) During Virtually Balanced and Two Unbalanced Phase-Voltage Conditions

V_{AB} (Volts)	V_{BC} (Volts)	V_{CA} (Volts)	V_{ub} (%)	I_{ARMS} (Amps)	I_{BRMS} (Amps)	I_{CRMS} (Amps)	I_{ub} (%)
463	11	467	0.6	5.1	5.7	6.5	13.0
455	15	460	1.3	3.9	5.9	7.2	31.2
448	20	450	2.4	3.1	8.0	8.4	52.3

Table 9. ASD Total Harmonic Distortion, 3rd Harmonics, and 5th Harmonics During Virtually Balanced and Two Unbalanced Phase-Voltage Conditions

V_{ub} (%)	I_{ATHD} (%)	I_{A3} (%)	I_{A5} (%)	I_{BTHD} (%)	I_{B3} (%)	I_{B5} (%)	I_{CTHD} (%)	I_{C3} (%)	I_{C5} (%)
0.6	127	25	86	130	30	85	122	5	84
1.3	144	55	80	137	67	81	121	27	82
2.4	179	94	90	147	91	79	124	64	79

Table 10. Phase-Current Waveforms During Virtually Balanced and Two Unbalanced Phase-Voltage Conditions



Determining Voltage Unbalance

At this point, some discussion would be in order as to how to determine the voltage unbalance. A three-phase ASD, such as the one in the test setup in Figure 44, is powered line-to-line (VAB, VBC, VCA) and is not connected to the neutral of the three-phase power source. To determine the voltage unbalance of a three-phase load, the line-to-line voltages must be measured. From those measurements, the voltage unbalance can be calculated according to IEEE Std 100-1992. For instance, in the previous experiment, the participants decreased the line-to-neutral voltage of one phase (VA) but calculated the voltage unbalance based upon measurements taken from line to line and then entered into the following formula:

$$\%\text{Unbalance} = \frac{\text{Maximum Deviation from Average}}{\text{Average of Three Phase-to-Phase Voltages}} \times 100$$

Decreasing VA to neutral by 20 volts, for instance, yields the following voltage unbalance: VAB = 448, VBC = 465 and VCA = 450

$$\text{Average} = (448 + 465 + 450)/3 = 454 \text{ volts}$$

$$\text{Max Deviation} = 465 - 454 = 11 \text{ volts}$$

$$\%\text{Unbalance} = \frac{11}{454} \times 100 = 2.4\%$$

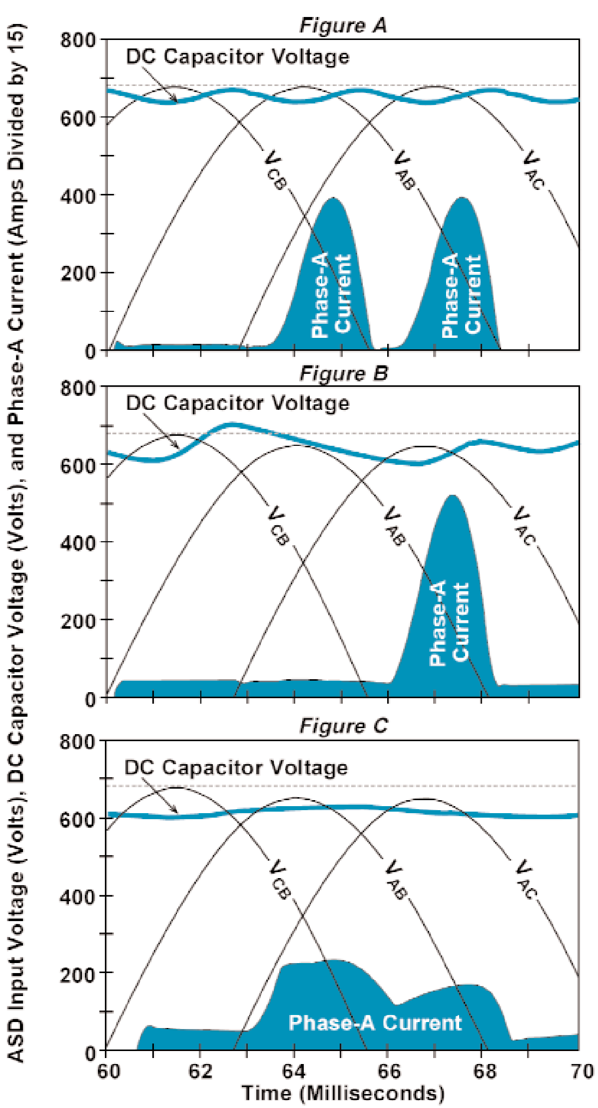
Discussion

The test results demonstrate that ASD phase-current unbalance is sensitive to voltage unbalance. Even if the ANSI-recommended 3% limit for voltage unbalance is met, current unbalance may be higher than 50%, enough to trip overload protection and shut down critical processes. The test results also demonstrate that ASDs generate more harmonic currents with increasing voltage unbalance. Also, voltage unbalance can cause ASDs to generate a significant amount of 3rd harmonics, which are uncharacteristic for a three-phase load.

Significance

A high current unbalance may trip overload-protection circuits and cause ASDs to generate uncharacteristic triplen harmonics that flow into the utility system. The different levels of harmonic components in each phase make it difficult to design tuned harmonic traps for ASD-generated harmonics. The degree of current unbalance depends on the amount of loading on the ASD, size of the DC-link capacitor, and line impedance. Therefore, optimizing these parameters makes an ASD less vulnerable to voltage unbalance and more reliable.

Figure 45. ASD Input Voltage, Capacitor Voltage, and Phase A Current



Voltage Unbalance, 3rd Harmonics, and Reactors

When the input voltage is balanced, the current drawn by an ASD without any reactor will typically have two pulses for each phase, each pulse reflecting a large current draw as the rectifier diodes conduct and the DC-link capacitor charges (see Figure 45A, balanced condition). In order to conduct, each diode must be forward-biased. That is, each phase voltage must be at least 0.7 volts higher than the voltage across the DC-link capacitor. However, when the phase voltages are unbalanced, a low phase voltage may not be high enough to forward bias any of the diodes. In Figure 45B, for instance, VAB is 20 volts lower than VCB, which has charged the DC capacitor to a level significantly greater than VAB. When VAB reaches its peak, the DC-link capacitor is already fully charged by the other phases. The phase-A current, therefore, has only one pulse. The absent pulse indicates a reduction of phase-A current and a significant increase in 3rd harmonics. Adding both an AC-line and a DC-link reactor reduces the DC voltage enough to equalize the phase currents by enabling all three phase voltages to forward-bias the diodes (see Figure 45C).

Input Performance of an ASD with AC and DC Reactors During Supply Voltage Unbalance

Background

Test results demonstrated that for a stiff power source, a steady-state voltage unbalance caused a dramatic increase in harmonic distortion and phase-current unbalance, which could trip the overload-protection circuit of an ASD. AC-line reactors and DC-link reactors may reduce current harmonics, increase the power factor, and increase ASD tolerance to capacitor-switching transients, which can trip DC overvoltage-protection circuits. Further test results determined how AC-line reactors and DC-link reactors affect ASD current unbalance and the level of harmonic distortion during a voltage unbalance.

Objective

Tests performed at EPRI determined the effects of an AC-line reactor and DC-link reactor on current unbalance and harmonics of a commercially available three-phase ASD during a steady-state voltage unbalance.

Test Setup

One 5-HP AC adjustable-speed drive was tested. Figure 46 shows a diagram of the test setup. The ASD was rated for three-phase, 460-VAC operation. Its user-selectable features were set to the factory default settings before testing began. A switchable three-phase, 4-mH AC-line reactor with an iron core (a 3% reactor) connected to the input of the ASD. A switchable three-phase, 7-mH DC-link reactor with an air core connected between the bridge rectifier and the inverter. A variable three-phase power source connected to the switchable AC-line reactor. The ASD output connected to a three-phase, 5-HP induction motor with an eddy-current brake to control the ASD load. A line-to-line, steady-state voltage unbalance resulted from adjusting the voltage of one phase (line-to-neutral) to a voltage lower than the other two phases. A digitizing signal analyzer and digital power monitor recorded the ASD input current and voltage on all three phases. A digital voltmeter monitored the voltage across the DC-link capacitor. The eddy-current brake was set for 75% loading.

Test Results

A steady-state, 2.4% phase-voltage unbalance resulted from reducing the voltage between phase A and neutral from 270 to 250 volts, while phases B and C to neutral remained at 270 volts each. Line-to-line voltage, voltage across the DC-link capacitor, line current, and harmonic distortion were measured for the four different reactor configurations listed in Table 11 (see Figure 46 for locations of reactor switches). Tables 12 and 13 show the test results for the 2.4%, steady-state voltage unbalance. Generally, connecting either the AC line reactor or the DC-link reactor reduced the voltage at the DC capacitor but did not affect the current unbalance. Connecting both reactors cut the current unbalance in half. On the other hand, connecting either reactor by itself or connecting both reactors significantly decreased the RMS line current, as well as current distortion and its 3rd and 5th harmonic components.

Figure 46. ASD Test Setup

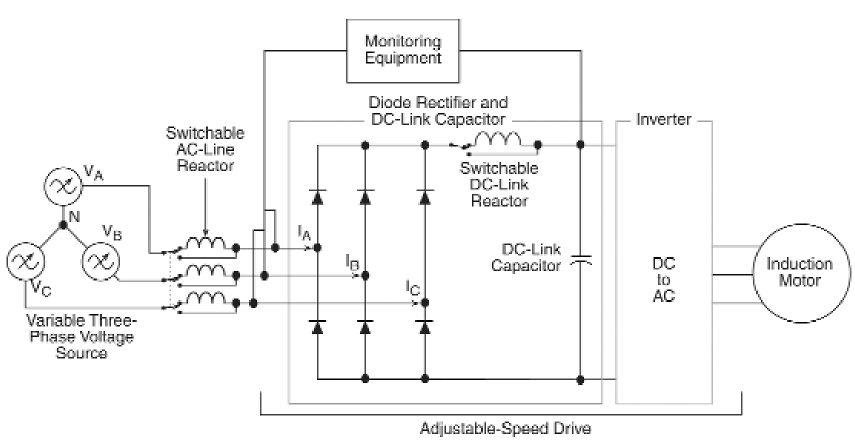


Table 11. Four Reactor Configurations

Configuration	AC-Line Reactor	DC-Link Reactor
No. 1	Switched Off	Switched Off
No. 2	Switched On	Switched Off
No. 3	Switched Off	Switched On
No. 4	Switched On	Switched On

Table 12. ASD Input Line-to-Line Voltages, DC Capacitor Voltage (VDC), Line Currents, and Current Unbalance (Iub) Measured During a 2.4% Voltage Unbalance

Config	V_{AB} (Volts)	V_{BC} (Volts)	V_{CA} (Volts)	V_{DC} (Volts)	I_{ARMS} (Amps)	I_{BRMS} (Amps)	I_{CRMS} (Amps)	I_{ub} (%)
No.1	449	465	450	664	5.8	8.7	10.4	30.5
No.2	448	465	451	620	3.1	5.6	5.4	33.4
No.3	448	465	452	620	3.3	5.7	5.2	30.8
No.4	447	465	450	604	3.6	4.8	4.2	14.5

Table 13. ASD Total Harmonic Current Distortion, 3rd Harmonics, and 5th Harmonics Measured for All Three Phases During a 2.4% Voltage Unbalance

Config	I_{ATHD} (%)	I_{A3} (%)	I_{A5} (%)	I_{BTHD} (%)	I_{B3} (%)	I_{B5} (%)	I_{CTHD} (%)	I_{C3} (%)	I_{C5} (%)
No.1	136	86	84	145	87	80	111	24	74
No.2	72	22	63	48	33	29	61	36	46
No.3	75	40	55	42	31	23	69	42	46
No.4	77	39	57	45	33	25	70	42	48

Discussion

The test results show that connecting both the AC-line and DC-link reactors to the ASD had the greatest effect on phase-current unbalance, reducing it by more than half. Even though either reactor alone did not reduce the current unbalance, either reactor alone mitigated current distortion and reduced the RMS line current, which reduced the risk of overload caused by voltage unbalance. For a stiff system, such as the power source used in the test setup, both the AC-line reactor and DC-link reactor were necessary to reduce the DC capacitor voltage to a value that balanced the line currents.

Significance

Reactors can mitigate the adverse effects of phase-voltage unbalance on ASDs. With a 2 to 2.5% voltage unbalance, the application of both AC-line and DC-link reactors will reduce phase current levels, phase-current unbalance, and cut triplen harmonics in half. DC-link reactors alone may be used to improve the power factor. Often, AC-line reactors alone are used to mitigate ASD-generated harmonic distortion and the effects of transients caused by routine capacitor switching. Sometimes a properly sized isolation transformer can provide the same benefits as an AC-line reactor. Many industrial utility customers apply reactors as add-on features of today's ASDs.

Years ago, magnetic components such as a front-end transformer and DC-link choke were standard on ASDs. The front-end transformer was essential to match the input voltage to the rating of the diodes in the bridge-rectifier stage. These early power-electronics devices did not have nearly the power rating of today's devices. But as silicon-based devices became more robust and ASDs more widely used, ASD manufacturers made an economic decision to reduce the amount of magnetics in their products. Soon, ounces of cheap silicon began to replace pounds of expensive copper and iron. Today, very few off-the-shelf ASDs have AC-line reactors, and even fewer have DC-link reactors. Both field experience and test results indicate that wholly removing magnetics from ASDs was perhaps a hasty economic decision that rendered the backbone of the process industry more vulnerable to voltage unbalance, transients, sags, and the effects of harmonic currents. ASD buyers should consider reactors—with all their benefits—as cost-effective magnetic solutions to many ASD problems.

ASDs may exhibit shutdown problems during voltage sags and momentary interruptions, but sensitive peripheral circuits are usually more likely to cause an ASD to shut down than the drive itself.

IMPROVING THE RIDE-THROUGH OF ASD SYSTEMS

ASDs may exhibit shutdown problems during voltage sags and momentary interruptions, but sensitive peripheral circuits are usually more likely to cause an ASD to shut down than the drive itself. Therefore, the ride-through of contactors and control circuits, as well as the ride-through of ASDs themselves, should be evaluated.

Ride-Through of Contactors and Control Circuits

Contactors and control circuits may have less ride-through than ASDs, depending on the manufacturer and connection scheme. One way to resolve the ride-through problems of line-side contactors is simply not to use them in an ASD control scheme. However, should the use of line-side contactors become necessary, then single-phase power conditioners and support devices may be installed to extend the ride-through of contactor coils and related control circuits. In cases where a coil is used as a pilot relay for a main contactor, power to the coil of the pilot relay should also be conditioned. If the control power for the control circuits of a drive is derived from the line side instead of the DC bus, then the control power should also be conditioned. The four major types of ride-through devices for industrial control applications are:

- Uninterruptible power supply (UPS). For more information on sizing UPSs, see *PQTN Application No. 5: Sizing Single-Phase Uninterruptible Power Supplies*, TA-105721, 1995.
- Constant-voltage transformer (CVT). For more information on sizing CVTs, see *PQTN Application No. 10: Sizing Constant-Voltage Transformers to Maximize Voltage Regulation for Process Control Devices*, TA-109233, 1997.
- Momentary ride-through device. For more information about momentary ride-through devices, see *PQ Brief No 48: Performance of a Momentary Ride-Through Device for Control Circuits*, PB-112208, 1999.
- Contactor coil hold-in circuits. For more information about coil hold-in circuits, see *PQ Brief No. 46: Performance of a Hold-In Device for Relays, Contactors, and Motor Starters*, PB-111613, 1998.

The first three of the four ride-through devices provide AC power and can be installed at the control transformer. A CVT can even replace the control transformer to effectively lower the dropout points of a control circuit, while a UPS will maintain a control circuit during any level of input AC power. The contactor coil hold-in circuit is installed at the relay or contactor terminals.

When a standby power conditioner such as a UPS or momentary ride-through device is used, a relay may drop out during the time it takes to switch from the AC line to internal energy storage. Among the many types of standby power conditioners, there is a wide range of transfer times. The small “ice-cube” relay is particularly sensitive and may drop out during this transfer time if the power conditioner is not selected carefully.

In some cases, UPSs and momentary ride-through devices can interfere with safety circuits. For example, during a complete loss of voltage, a contactor may be used safely to disconnect process elements from the voltage source. The use of a UPS or momentary ride-through device may keep the contactors closed regardless of the duration and magnitude of the voltage sag or interruption. In such cases, a time-out circuit in conjunction with the power conditioner may eliminate this safety concern.

Fast restart enables the ASD to restart a spinning motor after the line voltage has been restored without waiting for the motor and load to coast to a stop.

Ride-Through of ASDs: ASD Motor Restarting

Most modern PWM VSI drives have one of two basic restart schemes. Time-delayed restart enables the drive to be restarted a short time after it shuts down and after all process inputs are verified to be within acceptable limits. Usually, the motor must coast to a stop before the ASD restarts it. This type of ASD restart is appropriate for processes that do not require continuous operation. For example, an ASD used to drive a pump motor or a fan can be interrupted by a voltage sag and automatically restarted without significantly affecting the process.

However, other processes may not be able to tolerate a complete motor stop. For these processes, a faster restart feature may be ideal. Fast restart enables the ASD to restart a spinning motor after the line voltage has been restored without waiting for the motor and load to coast to a stop. When the DC bus voltage rises above the DC-bus trip point after a voltage sag, the drive restarts, determines the speed of the motor, and accelerates the system back to the original speed. Some drive manufacturers call this type of restart *flying restart*.

An ASD with *non-synchronous* flying restart can restart after the motor has significantly slowed but not stopped. A newer type of ASD with a *synchronous* flying restart feature promises to restart much more quickly than an ASD with non-synchronous flying restart. However, because the term “flying restart” is used to describe both types of ASD, end users may be confused about the ride-through abilities of the different models.

Although the motor and load may not come to a complete stop during a flying restart, they may slow considerably, depending on the duration of the sag, system inertia, load torque, and the restart algorithm used in a particular ASD. Therefore, flying restart is not appropriate for processes that require precise regulation of speed and torque. To determine whether flying restart should be enabled, a process engineer who understands the speed/torque requirements of the mechanical load and a drive engineer who understands the dynamic response of the drive and the motor should be consulted.

The restart algorithm that determines the motor speed at which an ASD restarts varies from manufacturer to manufacturer. Some manufacturers will have more accurate algorithms than others. Thus, one ASD model may afford smoother restarting than another.

EPRI tested two models of 5-HP AC adjustable-speed drives with different flying restart features. Figure 47 shows a diagram of the test setup. The ASDs were rated for three-phase, 460-VAC operation. Model A, which had a synchronous flying restart option, used a sensorless voltage-vector-control pulse-width-modulation (PWM) technology to control motor speed. Model B, which had a non-synchronous flying restart option, used a sine-wave PWM technology. The flying restart option of both drives was enabled during the test. The input of each ASD was connected to a variable three-phase voltage source (three single-phase variable transformers).

Each output connected to a three-phase, 5-HP induction motor with an eddy-current brake to control the ASD motor load. A computer-controlled transfer switch created voltage sags of defined duration and magnitude by switching from one tap of the transformers to another. Set for 75% loading, the eddy-current brake was equipped with a tachometer generator to measure the shaft speed. Digitizing signal analyzers recorded the ASD input voltage, DC bus voltage, motor speed, and motor current during the test.

Figure 47. Test Setup

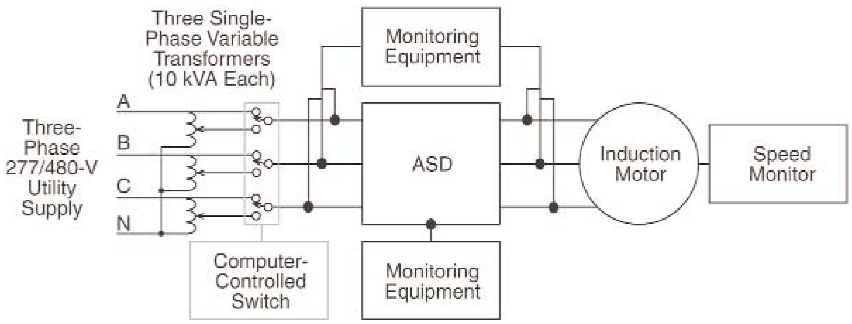
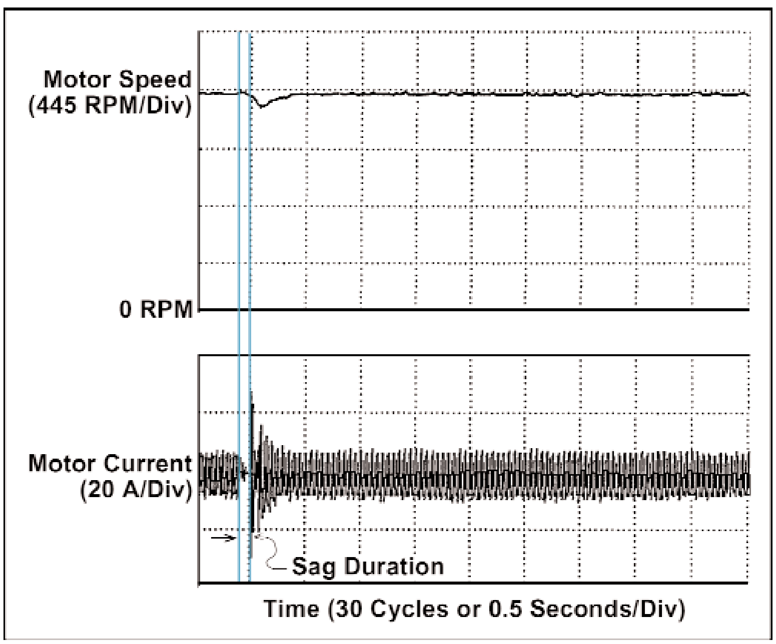


Figure 48. Motor Speed and Current for Model A (Synchronous) Before, During, and After a 5-Cycle, 50% Voltage Sag



Test Results

With the ASD speed set at 1740 RPM, each ASD experienced a balanced three-phase, 50% voltage sag lasting 5 cycles. Figure 48 shows the speed and current of the motor connected to model A (synchronous) before, during, and after the voltage sag. Figure 49 shows the speed and current of the motor connected to model B (non-synchronous). Although the voltage sag tripped model A off-line, the ASD came back on-line almost instantly after the sag, with very little decrease in motor speed. However, model B tripped off-line for almost one second after the voltage sag. During this time, the ASD cut off the power to the motor, and the motor speed decreased from 1740 RPM (point A in Figure 49) to about 1160 RPM (point B), when the ASD came back on-line. However, because model B was not synchronized with the residual voltage of the motor, the motor speed continued to drop for another one-half second, from 1160 RPM to about 180 RPM (point C). At point C, the ASD inverter re-synchronized with the motor, accelerating it to 1740 RPM in about two and a half seconds (point D).

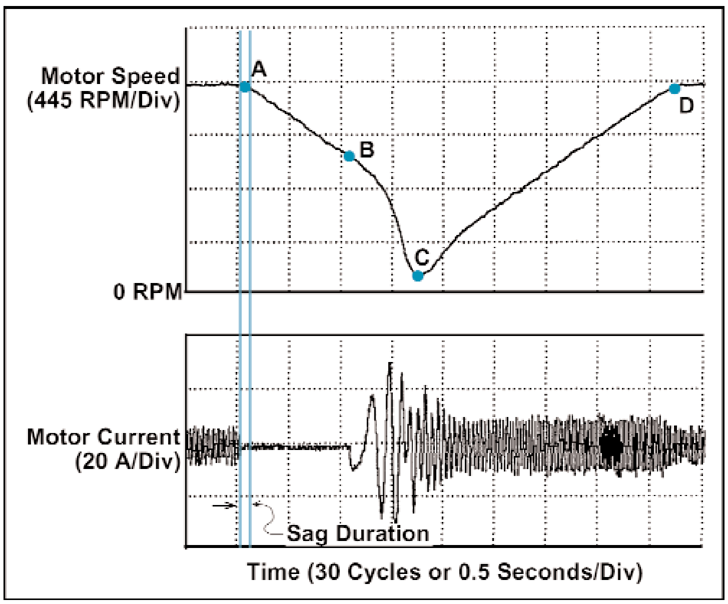
Discussion

The test results indicated that when the ASD with flying restart tripped off-line, its ability to quickly restore motor speed depended upon whether it had synchronous or non-synchronous flying restart. Model A, the ASD with synchronous flying restart, allowed only a 5% decrease in motor speed and took less than half a second to restore motor speed. The ASD with non-synchronous flying restart allowed a 90% decrease in motor speed and took about four seconds to restore motor speed. For processes that can withstand such a decrease in motor speed, both drives may be considered immune to a 50%, 5-cycle sag because they both automatically restarted the motor. However, only the model with the synchronous flying restart can sustain a critical process that requires nearly constant motor speed and torque.

Significance

Tolerance to voltage sags may be one of the most important criteria for specifying ASDs to control speed- and torque-sensitive processes. End users have many options to consider for increased ride-through. One option offered by many ASD manufacturers is a guaranteed ride-through time of two to ten seconds. However, sometimes this feature refers to the ASD logic power, not to the ASD output that controls the process motor. Adding power-conditioning equipment—such as uninterruptible power supplies, magnetic storage, or capacitor-based storage—can increase ride-through. However, these devices are usually more expensive than the ASDs themselves.

Figure 49. Motor Speed and Current for Model B (Non-Synchronous) Before, During, and After a 5-Cycle, 50% Voltage Sag



In both test cases, motor speed slowed during the shutdown. However, the speed change of the motor connected to Model A (Figure 48) was minimal, whereas the speed change of the motor connected to Model B (Figure 49) was significant. The restart algorithm accounts for the different changes in motor speed during voltage sags with the same duration and magnitude.

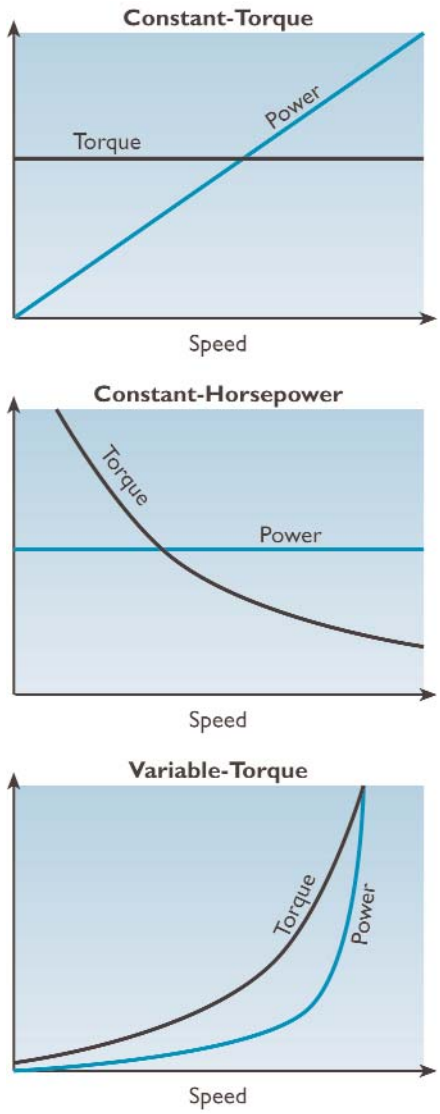
To ensure economical ride-through, end users should heed the cliché *caveat emptor* (let the buyer beware). A more expensive ASD does not necessarily mean a longer ride-through than a less expensive one, and the performance of an ASD during voltage disturbances cannot be determined from nameplate or specification data. Before purchasing an ASD, end users should ask the manufacturer about specific speed and torque performance during and after a voltage sag to determine restart characteristics.

Effect of Load Type and Inertia on Ride-Through During Restart

Many industrial processes require precise and accurate control over process system parameters such as torque, speed, pressure, temperature, and flow rate. The torque and speed of the motor control these parameters, and the ASD enables precise control of motor torque and speed. Although the ASD, motor, and motor load are serially connected, they constitute a dynamic system, with each one affecting the other two. For example, the characteristics of the motor-driven load can affect the ride-through of an ASD during restart.

A mechanical load has three basic characteristics: inertia, torque, and speed. The load inertia during acceleration or deceleration and the steady-state load torque are used to describe the dynamic characteristics of a load. During steady-state operation, the load is neither accelerating nor decelerating, at least not at any rate of consequence. For most loads, torque and speed are used to describe the steady-state characteristics of a load. As shown in Figure 50, ideal torque-speed characteristic curves describe how the steady-state load torque changes over the load's speed range, while power-speed characteristic curves describe how the steady-state load power changes over the load's speed range.

Figure 50. Torque-Speed and Power-Speed Characteristic Curves for Three Load Categories



Mechanical loads can be divided into three steady-state torque-speed categories: constant-torque, constant-horsepower, and variable-torque. Each of these three load types has a particular effect on ASD ride-through during restart, resulting in different speed changes. For constant-torque motor loads, such as conveyors, positive displacement pumps, and extruders, the load torque remains constant throughout the entire speed range of the mechanical load, as shown in Figure 50. The power required by a constant-torque load varies linearly with speed. As the speed increases, the power consumed by the load increases.

Constant-horsepower loads, such as cranes, lathes, and center winders, require a constant power to operate over the load's entire speed range. As shown in Figure 50, torque decreases as speed increases. The power required by the constant-horsepower load does not vary with speed.

For variable-torque loads, such as fans, blowers, centrifugal pumps, and compressors, torque also varies as a function of speed. However, the relationship between torque and speed is markedly different from the relationship for constant-horsepower loads. As shown again in Figure 50, the torque increases as the speed increases. The power required by variable-torque loads varies as a cubic function of speed in applications with no static pressure or head. Therefore, this type of load consumes less power than constant-torque and constant-horsepower loads as the speed decreases.

Figures 51 and 52 show the effects of load type and load inertia on speed change during the shutdown and flying restart of an ASD. The constant-horsepower load has the greatest effect on speed change, and the variable-torque load has the least effect on speed change.

Load inertia also affects the amount of speed change during ASD coasting and restart. The greater the system inertia, the less the speed changes during restart.

Figure 51. Typical Effect of Load Type on Motor Speed during a 20-Cycle, Three-Phase Voltage Sag ("Flying Restart" Enabled)

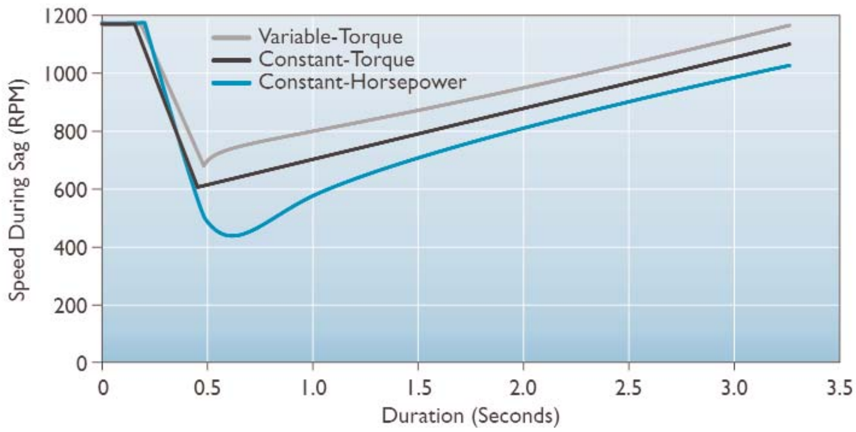


Figure 52. Typical Effect of Load Inertia on Motor Speed during a 20-Cycle, Three-Phase Voltage Sag ("Flying Restart" Enabled)

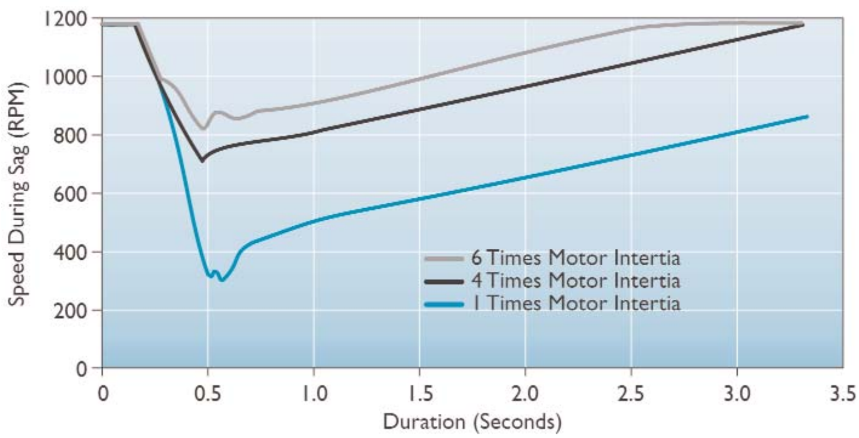
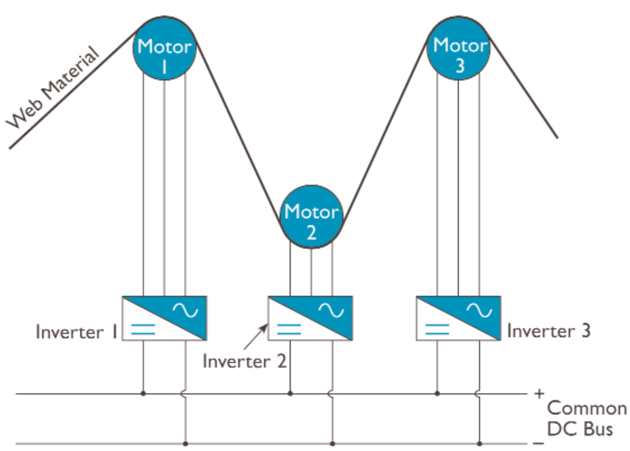


Figure 53. Coordinated-Drive System with a Common DC Bus Used to Control a Web Process



Kinetic Buffering

One disadvantage of a fast-restart feature is that the ASD loses control over the motor-driven process when it shuts down during a voltage sag. During this loss of control, the speed of the process drops according to the load type and inertia. In a coordinated-drive system, where multiple motors in a process are synchronized, different motors may have different levels of inertia. Therefore, the speed of the different motors will drop at different rates after the ASD shuts down. This uneven speed change may tear web process material such as paper or textiles.

To better control motor speed, some ASDs have a feature called *kinetic buffering*. Once the ASD senses a voltage sag or momentary interruption, this feature enables the motor and load inertia to transfer energy back to the DC bus of the ASD, allowing the inverter to control the rate at which the motor speed drops during the sag.

Kinetic buffering enables the user to program the same deceleration rate for multiple motors in a coordinated-drive system. Kinetic buffering is often implemented for coordinated-drive applications where multiple motors may be connected to multiple inverters from a common DC bus, as shown in Figure 53.

Fortifying the DC Bus

Processes that cannot tolerate even a slight change of speed and torque require an ASD with good ride-through performance. However, flying restart and kinetic buffering are not good candidates for such processes because both methods entail a change in motor speed when the ASD shuts down. One way to prevent the shutdown of an ASD is to fortify its DC bus by either adding energy storage or installing a standby boost converter, both of which connect directly to the DC bus.

Upon sensing that the voltage across the DC bus is approaching the undervoltage trip point, a boost converter rectifies the remaining line voltage and boosts the DC voltage to maintain the DC bus above the undervoltage trip point. However, boost converters require at least 40% remaining voltage during a voltage sag. Therefore, they cannot support the DC bus during deep three-phase voltage sags or momentary interruptions.

The DC bus can also be fortified by adding an energy-storage module, such as super or standard capacitors. Table 14 shows six methods of fortifying a DC bus against voltage sags and momentary interruptions: batteries, super capacitors, super-conducting magnetic energy storage (SMES), flywheels, fuel cells, and standard capacitors [8].

Table 14. Energy-Storage Devices for DC Buses

	Batteries	Super Capacitors	SMES	Fly-wheels	Fuel Cells	Standard Capacitors
Efficiency	70-90%	90%	95%	90%	40-55%	90%
Power Range (W)	5 kW-10 MW	5-100 kW	300 kW-1000 MW	1 kW-10 MW	10 kW-2 MW	5 kW-100 kW
Charge Time	Hours	Seconds	Minutes-Hours	Minutes	Continuous	μSeconds-mSeconds
Capital Cost ($/kW)	100-200	500	700-1000	300	1500	300

While ASDs can improve the productivity and efficiency of motor-driven processes, drive users must take steps to ensure the reliable operation of ASDs during voltage sags and momentary interruptions. First, verify a robust ride-through of external control circuits and peripheral equipment such as PLCs, control relays, and start/stop circuits. Low-cost single-phase power conditioners can be applied to these circuits and equipment to enhance ride-through.

Next, choose an ASD ride-through option based upon how much torque and speed variation a process can tolerate. Table 15 shows the various ASD ride-through options discussed in this chapter and their recommended applications. By understanding the technical requirements of a process and by collaborating with drive manufacturers, drive users and process operators can maximize the ride-through of ASD-controlled processes.

Performance of an ASD Ride-Through Device During Voltage Sags

Background

ASDs often have a low tolerance to voltage sags. During a voltage sag, the DC-bus capacitor of a typical ASD discharges and the voltage at the DC bus decreases. Depending on the setting of the drive's undervoltage protection (called the *trip point*), the drive may trip after the DC-bus voltage decreases below the trip point. In testing activities conducted at EPRI, 17 commercially available 5-HP ASDs were characterized for voltage-sag tolerance. Ninety percent of the tested drives tripped during a 5-cycle voltage sag down to 50% of the nominal supply voltage. Since those tests, a number of potential remedies for ASD tripping during voltage sags have been investigated, including a flying-restart technology. EPRI engineers tested a device designed to maintain the DC-bus voltage during voltage sags and thereby enhance the voltage-sag tolerance of an ASD-driven process.

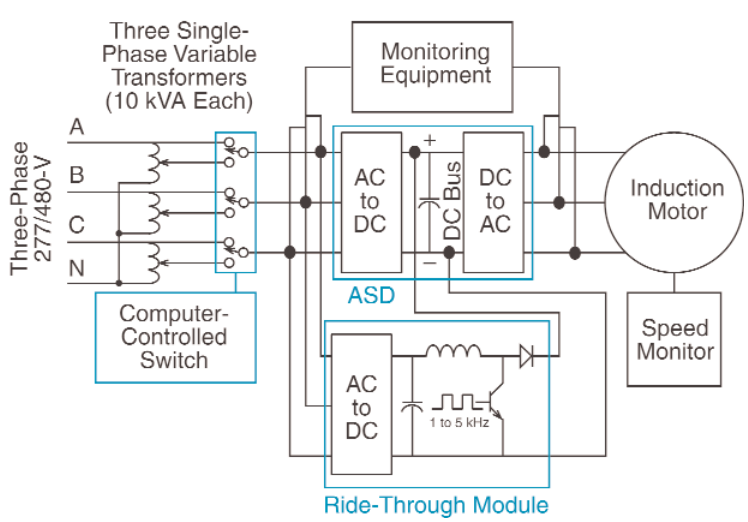
Test Setup

Figure 54 shows a diagram of the test setup. A 480-volt, 24-kilowatt ride-through device

Table 15. ASD Ride-Through Options and Their Applications

Ride-Through Option	Use This Option If...	Applications
Time-Delayed Restart	The ASD-driven motor can be completely stopped before restarting after a time delay without significantly affecting the process.	Wastewater Pumps • Non-Critical Process Motors • HVAC Systems
Fast or "Flying" Restart	The process can tolerate slight changes in torque and speed, but the motor speed cannot fall below a critical minimum speed required by the process.	Exhaust and Intake Fan Motors in Paint-Spraying Booths and Clean Rooms • Plastic Extruders
Boost Converter on DC Bus	The process torque and speed must be precisely maintained and voltage sags are known to be the primary cause of ASD tripping.	Motors for Grinders, Polishers, and Conveyors • Machine Tools • Winders and Unwinders
Energy Storage on DC Bus	The process torque and speed must be precisely maintained and momentary voltage interruptions are known to be the primary cause of ASD tripping.	Motors for Grinders, Polishers, and Conveyors • Machine Tools • Winders and Unwinders
Kinetic Buffering	A process uses a coordinated-drive system to transport web material and the process can tolerate slight (and even) changes in torque and speed.	Paper Machines • Plastic Extruders • Winders and Unwinders

Figure 54. Test Setup



containing four 6-kilowatt modules was tested. Each module is designed to be installed between the three-phase power source and the ASD DC bus and consists of a three-phase AC-to-DC rectifier, a filter capacitor, and a boost converter (inductor-and-chopper regulator). The ride-through device continuously monitors the DC bus of the ASD. During a voltage sag, if the voltage at the DC bus drops below a user-adjustable trip point, then the device switches on. The device does not store energy but transfers the energy remaining in the incoming AC line to the ASD DC-bus to maintain it above the trip point.

To match the power rating of one module, the output of one module was connected to the DC bus of a 5-HP ASD. A 5-HP induction motor loaded with an eddy-current brake was used as the ASD-driven load. Set for either 100% or 50% loading, the eddy-current brake, equipped with a tachometer, measured the speed of the motor shaft. The inputs of the ASD and the ride-through module connected to a variable three-phase voltage source (three single-phase variable transformers). A computer-controlled transfer switch created voltage sags of defined duration and magnitude by switching from one tap of the transformers to another. Digitizing signal analyzers recorded the ASD input voltage, DC-bus voltage, motor speed, and motor current during the tests.

Test Results

Figure 55 shows the input AC voltage, motor current, motor speed, and DC-bus voltage at 100% loading during a 15-cycle voltage sag to 50% of the nominal voltage without the ride-through device. At the onset of the voltage sag, the DC-bus voltage began to drop from a nominal 660 volts. The DC-bus voltage continued to drop until it reached the ASD undervoltage trip point of 352 volts.

Figure 55. Typical ASD Shutdown Caused by a 15-Cycle, Three-Phase Voltage Sag to 50% of Nominal

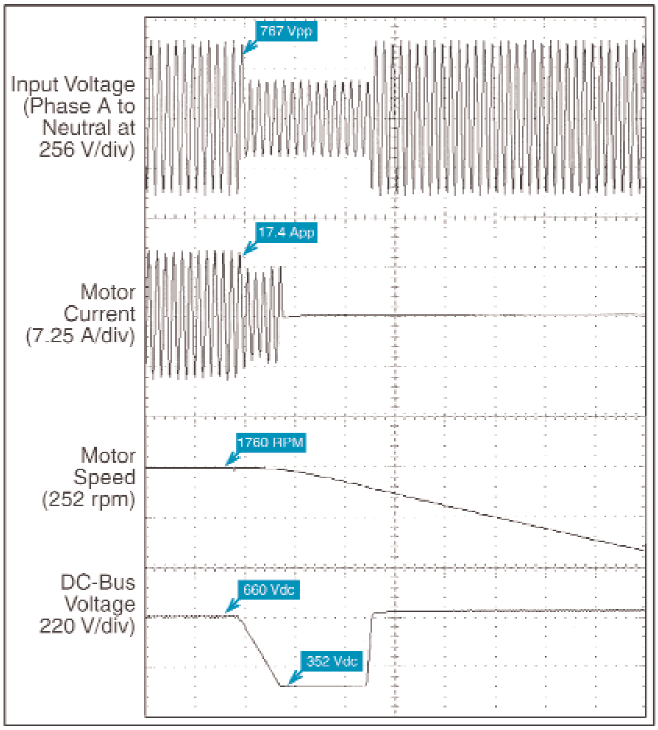
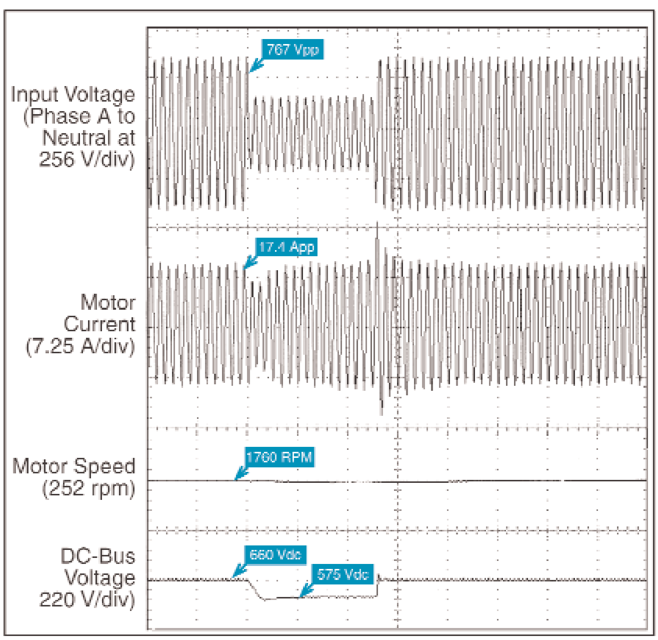


Figure 56. Sag with Ride-Through Device



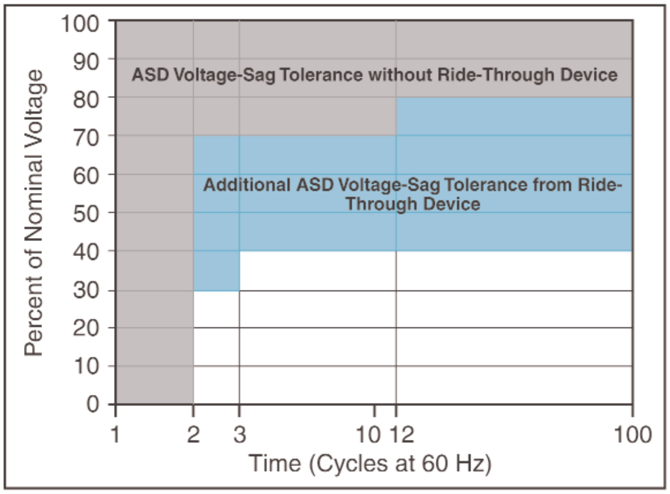
At that point, the ASD tripped and the motor current decreased to zero. Figure 56 shows the same measurements taken during the same conditions for the ASD with a ride-through device connected. During the voltage sag, the DC-bus voltage dropped from 660 volts to about 575 volts, at which point the ride-through device switched on to maintain the DC bus at 575 volts during the sag, thus maintaining the motor current and speed. When the input voltage returned to normal, the ride-through device switched off and the DC-bus voltage returned to nominal 660 volts.

To create a sag-tolerance envelope for a typical ASD with and without the ride-through device, test engineers subjected the ASD to voltage sags ranging from 0% to 90% of the nominal voltage and from 1 to 100 cycles. These sags were applied at 50% loading and at 100% loading, with and without the ride-through device. With the device installed, the steady-state (longer than 100 cycles) voltage tolerance increased from 80% of nominal to 40% of nominal. Figure 57 presents the test results in a CBEMA-type curve.

Discussion

The ride-through device greatly increased the ASD voltage-sag tolerance. Because it does not store energy, it could not provide protection against voltage sags below 30% of nominal voltage. However, recent power quality surveys indicate that in almost 80% of all voltage sags, the lowest phase voltage is greater than 50% of the nominal voltage. Motor load affected the ASD voltage tolerance more significantly for voltage sags to zero than for sags above 30% of nominal voltage. As the load increased, the ASD voltage tolerance decreased—with and without the ride-through device.

Figure 57. Sag-Tolerance Graph



Significance

Most continuous processes require adjustable-speed drives to control motor speed precisely. However, voltage sags and interruptions can trip a typical, unprotected ASD. Lowering the trip point will slightly increase sag tolerance. Recent advances in ASD technology make it possible to restart an ASD driving a spinning motor as soon as voltage recovers. However, when changing the undervoltage trip point or enabling the restart parameter of an ASD is not a viable option, then a ride-through device such as the one tested may prove to be an effective way to increase sag tolerance. Such ride-through technology is offered as an add-on feature by most ASD manufacturers but may also be purchased separately and retrofitted to an existing ASD. The device tested, available in sizes from 4 to 200 kilowatts, costs less and is smaller than energy-storage options such as add-on capacitors, batteries, uninterruptible power supplies, and motor/generator sets. However, unlike energy-storage devices, the tested ride-through device requires a residual AC input voltage and therefore cannot protect ASDs against momentary interruptions of power.

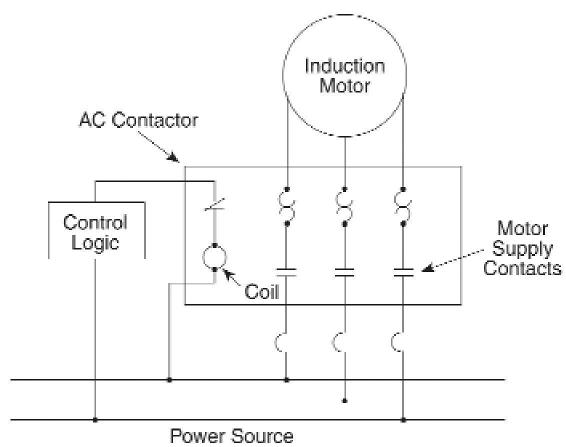
Low-Voltage Ride-Through Performance of AC Contactor Motor Starters

Another problem affecting adjustable-speed drives originates not in the ASD itself but in contactor motor starters.

Background

Faults in the power supply system typically cause momentary low voltages. The duration and severity of a low voltage depends on the type and location of the fault and the time required to remove it. Voltage sags lasting from 5 to 15 cycles (83 to 250 ms) are the most common momentary low voltages and can adversely affect end-user equipment. Because AC contactor motor starters (contactors) control induction motors, their performance during periods of low voltage is a significant concern for industrial users that rely on continuous processing. (Figure 58 illustrates a typical industrial application of an AC contactor motor starter.) In many cases, the control voltage for the contactor coil is supplied from the plant distribution system. Therefore, the contactor coil experiences the same voltage disturbance as the motor. If the disturbance is sufficient to cause the motor supply contacts to open momentarily, the plant process may be disrupted and equipment may be damaged.

Figure 58. Schematic of AC Contactor Motor Starter Connected to an Induction Motor

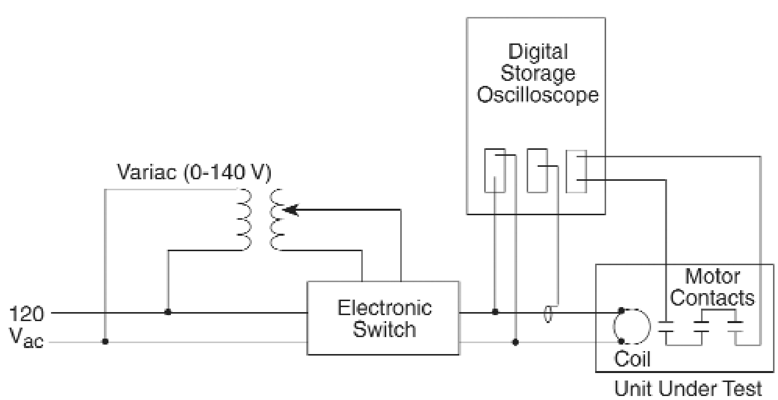


Tests performed at EPRI's Power Quality Test Facility characterized the performance of different-sized AC contactor motor starters during typical low AC voltages.

Test Setup

Three different sizes of three-pole, 480-VAC, open-type contactors were tested: NEMA size 0 (rated 0 to 5 HP @ 480 VAC), size 1 (rated 0 to 10 HP @ 480 VAC), and size 3 (rated 0 to 50 HP @ 480 VAC). All contactors were equipped with 120-VAC coils. Voltage sags were created by electronically switching from the 120-VAC line to a reduced-voltage source and then back. Voltage sags were timed at zero-crossings and adjusted in half-cycle increments. Varying the magnitude and duration of the sags determined which combinations would cause the contactor to open the motor supply contacts. During a voltage sag, the source was not disconnected from the contactor, which simulated the low source impedance of the power system during a fault. High-impedance interruptions and open circuits were not considered. Two channels of a digital storage oscilloscope monitored and recorded contactor coil voltage and current; another channel monitored and recorded continuity of the motor supply contacts. Figure 59 shows the diagram of the test setup.

Figure 59. Test Setup



Test Results

Steady-State Low-Voltage Dropout Test

This test determined the source voltage at which the motor supply contacts would open (drop out). Initially set at nominal 120 V_{AC}, the source voltage was decreased incrementally until the motor supply contacts dropped out. Among the three contactors tested, the dropout voltage ranged from 65 to 70 V_{AC}.

Voltage Sag Response Test

Each contactor coil experienced voltage sags lasting from 0.5 to 8 cycles (8.3 to 133 ms), and with magnitudes ranging from 0 to 120 V_{AC}. Monitoring the motor supply contacts during each of these voltage sags determined which combination of duration and magnitude would cause the contacts to open. Figures 60, 61, and 62 illustrate the area of closed-contact operation for the different-sized contactors during sags initiated at the zero-crossings of the AC input voltage. With the variable AC source (variac) adjusted to give an output of 0 V_{AC}, the size 0 and size 1 contactors kept their motor supply contacts closed for 4 and 3.5 cycles (67 and 58 ms), respectively. The size 3 contactor kept the motor supply contacts closed for 7 cycles (117 ms) because its larger coil retained a stronger magnetic field.

Figure 60. Size 0 AC Contactor Characteristics

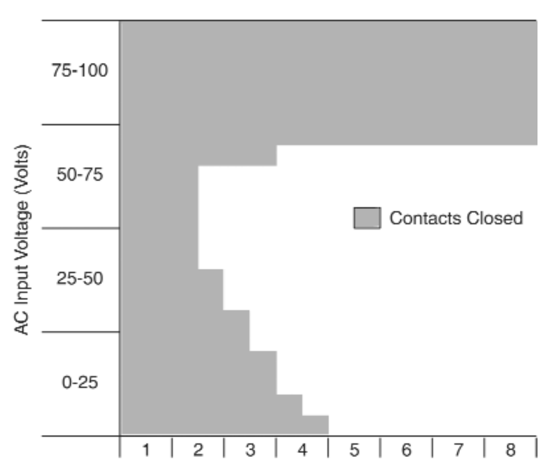


Figure 61. Size 1 AC Contactor Characteristics

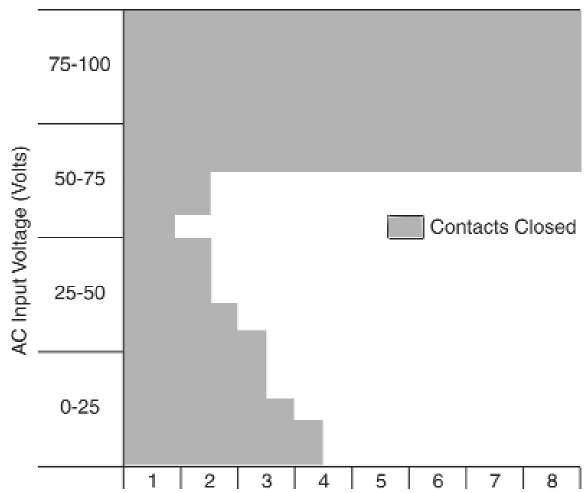
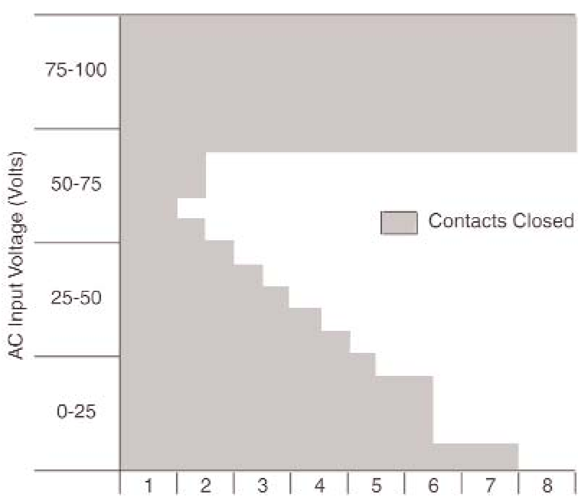


Figure 62. Size 3 AC Contactor Characteristics



Further testing revealed that the ride-through performance during a sag to zero volts (short circuit) also depended on the phase angle of the voltage waveform at the onset of the sag. The size 1 contactor could ride through a 3.5-cycle sag when the onset of the sag occurred at the zero-crossing (see Figure 61) and could only ride through about a 0.5-cycle sag when the onset occurred at the peak (not shown). Because the voltage across and current through a contactor coil are 90 degrees out of phase, coil current and the associated magnetic flux peak at the voltage zero-crossing. When a sag occurs at this phase angle, the peaked magnetic field tends to hold the motor supply contacts closed longer than when sags occur at other phase angles.

The line impedance of the source voltage also determined contactor ride-through time. During sags to zero or near-zero volts, the test setup—approximating real-world fault conditions in a power system—was nearly a short circuit, which allowed maximum current and magnetic flux. As a result, contactor ride-through time was longer for sags to zero or near-zero volts than for sags below but near the trip limit (the minimum steady-state AC voltage required to keep the motor supply contacts closed).

Discussion

Contactor dropout characteristics during voltage sags vary with the size of the coil, voltage phase angle at the onset of the sag, the magnitude of the sag, and the line impedance during the sag. In general, however, contactors are expected to tolerate low voltages less than a typical induction motor load. Therefore, contactors may be the “weak link” in a plant process system’s tolerance to voltage sags. One method to improve contactor ride-through performance is to modify the magnetic circuit using a rectifier, capacitor, and DC coil, which provide stored energy to keep the motor supply contacts closed during most voltage sags.

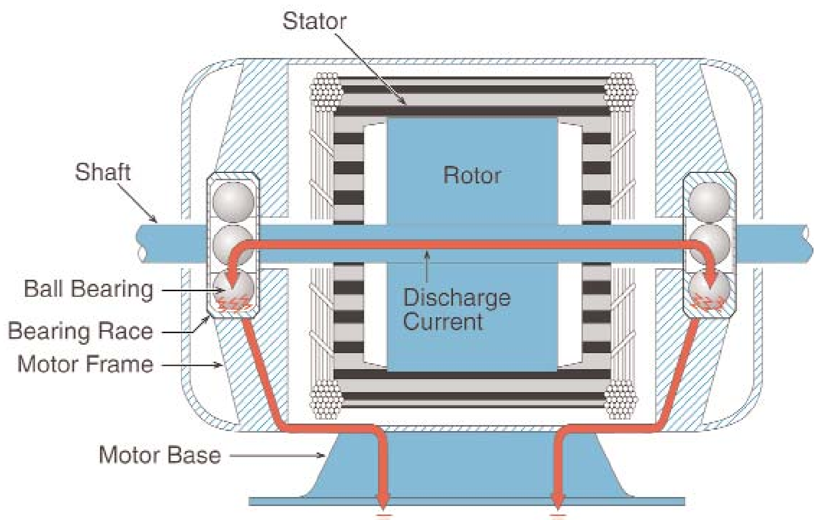
Significance

Because the AC contactor controls the connection of the induction motor to the power distribution system, it is crucial for continuous plant processing. Unwanted opening of motor supply contacts while the motor is under a load can disrupt a process or initiate an overall trip command from the process controller, or both. Disruption of the plant process may result in loss or damage to the product. As process disruptions resulting from low voltages increase, so does the need for investigating the effects of low voltages on all motors and contactors to identify weaknesses in plant processing systems.

PREMATURE FAILURE OF BEARINGS WHEN USING ASDS

Originally, ASDs with PWM inverters had switching rates between 1 and 8 kHz. To eliminate the audible motor noise caused by such low switching frequencies, manufacturers developed ASDs with switching frequencies as high as 20 kHz. The faster switching frequencies did reduce motor noise audible to humans, but they also created a side effect: excessive motor-shaft voltage and current that can discharge across the motor bearings.

Figure 63. The Paths of Motor-Bearing Discharge Currents in a Typical Three-Phase Motor Driven by a PWM ASD



ASDs that use insulated-gate bipolar transistors (IGBTs) as high-frequency switches are most likely to cause bearing-discharge current. The high switching frequency and fast rise times of an IGBT inverter output can cause induced voltage in the rotor to be capacitively coupled to the motor shaft. As shown in Figure 63, this shaft voltage can exceed the dielectric strength of the lubricant in the shaft bearings. The resulting current flows from the shaft, through the bearing lubricant, and to the grounded motor frame, which causes pitting—or *fluting*—in the bearing races. The resulting high rolling resistance leads to premature failure of the shaft bearings.

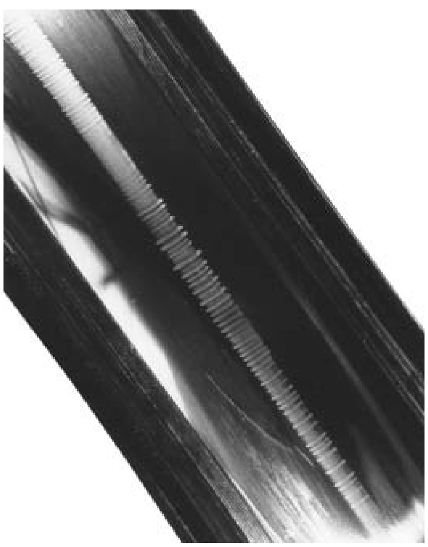
What To Observe

Audible motor noise and vibration usually present the first obvious symptoms of premature bearing failure. Because excessive noise and vibration may be symptomatic of other motor problems, maintenance personnel frequently misdiagnose problems caused by fluting. Usually, the current arcing across the bearings will first damage the smaller idle bearing opposite the end of the shaft connected to the motor load. Idle-bearing failure can occur as soon as six months after the motor has been installed.

Discharge current may also damage the bearings of other equipment connected to the motor shaft, such as direct-connected tachometers and gear boxes. In many cases, discharge current will damage the tachometer bearings instead of the motor bearings because the smaller tachometer bearings offer the path of least resistance. Damaged tachometer bearings can cause the tachometer to vibrate, resulting in an erratic signal from the tachometer.

A shaft voltage as low as six volts can cause arcing through the bearing lubricant, depending upon the type of bearing lubricant and the clearing between the race and the ball bearings. Excessive shaft voltage may be verified in two ways. One way, which requires a specialized shaft-monitoring device, is to measure the shaft-to-ground voltage. Should motor bearings have already failed, then inspection of the bearing races for fluting should take place. Bearing races appearing similar to that in Figure 64, for a PWM-type ASD driving the motor with a switching frequency above 10 kHz, indicate that the shaft voltage is most likely excessive.

Figure 64. Fluting of the Bearing Race Caused by Current Discharged through the Bearing Lubricant



Preventing Premature Bearing Failures when Using ASDs

Install a Shaft Grounding System

Minimizing the magnitude of the shaft voltage reduces the chance of electrical arcing through bearing lubricant. Grounding the motor shaft with a system of brushes creates a low-impedance path to ground for otherwise damaging discharge currents. A number of brush systems are commercially available. Soft carbon brushes are usually not suitable because they may create a nonconductive film that prevents electrical contact between the brushes and shaft. Brushes made of special materials—such as brass and stainless steel—do not create this film. Also, a sealed grounding system is recommended for a clean-room environment, which may be contaminated by airborne particles from a standard grounding-brush system. During maintenance, ensure that the brushes are in electrical contact with the shaft, regardless of the type of grounding system that you select.

Install Insulated Motor Bearings

Although insulated motor bearings may stop the flow of discharge current through the main motor bearings, they will not prevent damage to the bearings of other shaft-connected equipment, such as tachometers and fans. Also, the voltage on the shaft of a motor with insulated bearings and without shaft-connected equipment may pose a risk of a mild shock to anyone who touches the rotating shaft.

Decrease the ASD Switching Frequency

The switching frequency of most PWM ASDs may be set by the operator. By decreasing the switching frequency of an existing ASD, the premature failure of motor bearings may be prevented. Although shaft voltages will be present at lower switching frequencies, industry experience to date indicates that problems caused by discharge current begin mostly when the ASD switching frequency is greater than 10 kHz. Therefore, switching frequencies above 10 kHz should be avoided when shaft grounding systems or insulated bearings prove to be impractical options. If a higher switching frequency must be used, then motors with warranties against bearing failure caused by discharge current should be obtained.

Quick Check List

- Look for signs of premature bearing failure such as audible motor noise, vibration, and localized heating.
- Look for fluting in the races of damaged bearings from motors and other shaft-connected equipment such as tachometers, pumps, fans, and gear boxes.
- Reduce shaft voltage by installing a shaft grounding system.
- Stop current from discharging through motor bearings by replacing existing motor bearings with insulated bearings or by decreasing the switching frequency of the ASD that drives the motor.
- Purchase new motors with bearings guaranteed against premature bearing failure.

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