Performance of AC Motor Drives During Voltage Sags and Momentary Interruptions

Introduction

In the modern industrial facility, adjustable-speed drives (ASDs) are quickly replacing mechanical means of controlling process parameters such as speed, timing, and the flow rate of air and liquids. 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 control such as throttling and gear changing.

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. However, as with most electronics technology, ASDs are sensitive to electrical disturbances.

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. Industries have reported losses as high as one million dollars 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. This PQ Commentary discusses the causes of ASD system shutdowns and ways to improve ride-through of processes controlled by ASDs.

ASD Operation and Applications

Basic Operation

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.

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.

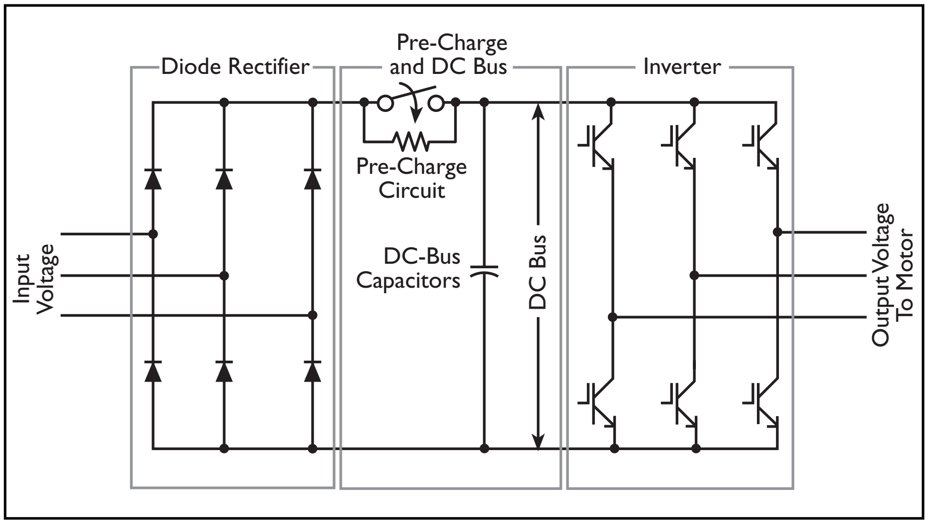


Figure 1. Typical diagram of a PWM VSI drive

Applications

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 fluid, 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, ASD control systems may include programmable logic controllers, distributed control systems, input/output racks, contactors, relays, and sensors. The ride-through of the ASD system is no better than the ride-through of the weakest ASD system component. Therefore, it is important to consider the effects of voltage sags and momentary interruptions on the entire ASD system and not just the ASD.

Voltage Sags and Momentary Interruptions

In most power systems, electrical disturbances are unavoidable. Generally, voltage sags and momentary interruptions are caused by system faults. Faults can be initiated by a number of events, including lightning, animals contacting power lines, and tree limbs contacting power lines. 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 percent of the nominal voltage lasting between 0.5 and 60 cycles. Figure 2 shows a voltage sag to 75 percent of the nominal peak voltage with a duration of five cycles. The IEEE defines a momentary voltage interruption as any low-voltage event of less than 10 percent of the nominal voltage lasting between 0.5 cycles and 3 seconds. Figure 3 shows a one-second momentary voltage interruption with a remaining voltage of five percent 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 (see sidebar on page 3). 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 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 (see *An Assessment of Distribution System Power Quality, Volume 2: Statistical Summary Report,* TR-106294-V2, May 1996). 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 4. The study also indicated that an average site will experience about 45 voltage sags and five momentary interruptions every

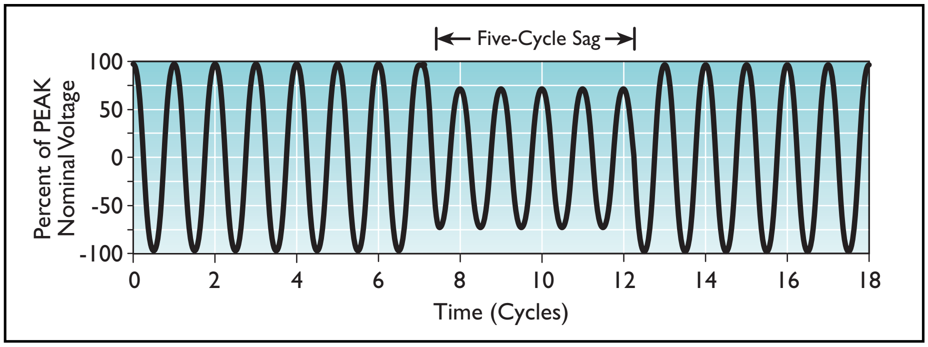


Figure 2. A voltage sag to 75 percent of nominal

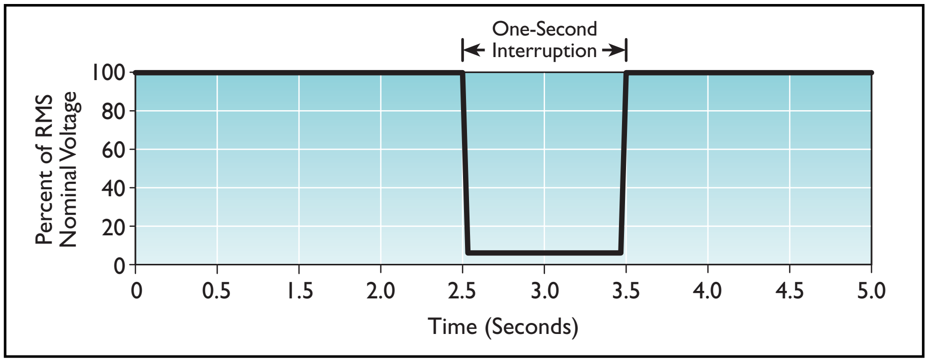


Figure 3. A momentary voltage interruption with five-percent remaining voltage

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

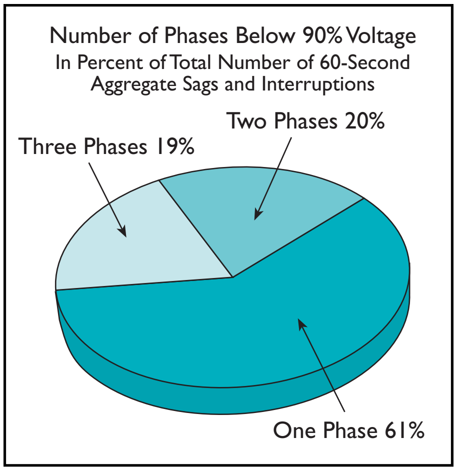


Figure 4. Number of single-phase, two-phase, and three-phase voltage sags as a percent of total voltage sags measured below 90 percent of nominal

Effects of Sags and Interruptions on ASDs

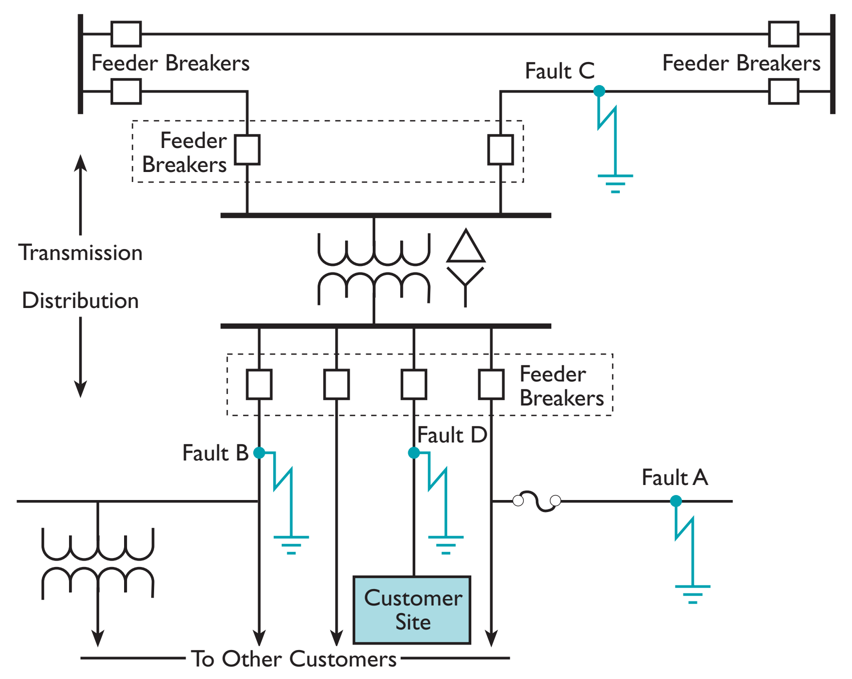
The response of an ASD to a voltage sag or momentary interruption varies widely. Whether or not the response of an ASD is acceptable depends upon the dynamic requirements of the process. For example, one process may not tolerate even moderate changes in torque and speed, while another may tolerate wide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

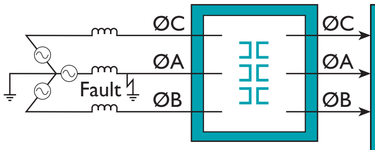
ASD DC Bus and Inverter Circuit

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

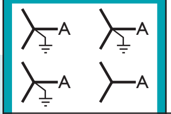
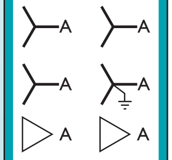
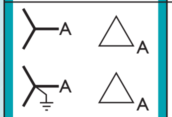
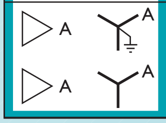
From Faults to Voltage Sags

As shown in the figure below, short circuits (faults) occurring in adjacent feeders in the distribution system (Fault A and Fault B) and in the transmission system (Fault C) can cause voltage sags at the customer site. However, only when a fault occurs on the same feeder (Fault D) does the customer experience a momentary interruption. Therefore, the customer is much more likely to experience voltage sags than interruptions. In fact, according to the 1996 EPRI Distribution System Power Quality (DPQ) Study, a customer at a given site in the United States is nine times more likely to experience a voltage sag than a momentary interruption.





Certain types of transformer connections may transform a single line-to-ground fault into a phase-to-phase or three-phase voltage sag. As shown to the right, transformer configuration and the connection of the load determines the type of voltage sag at the equipment. As shown in the figure, a single line-to-ground fault upstream of a transformer can cause two- or even three-phase sags at the equipment terminals.

Transformer Connection	Per Unit Voltage					
	Phase-to-Phase			Phase-to-Neutral		
	V_{AB}	V_{BC}	V_{CA}	V_{AN}	V_{BN}	V_{CN}
	0.58	1.00	0.58	0.00	1.00	1.00
	0.58	1.00	0.58	0.33	0.88	0.88
	0.33	0.88	0.88	-	-	-
	0.88	0.88	0.33	0.58	1.00	0.58

the 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.

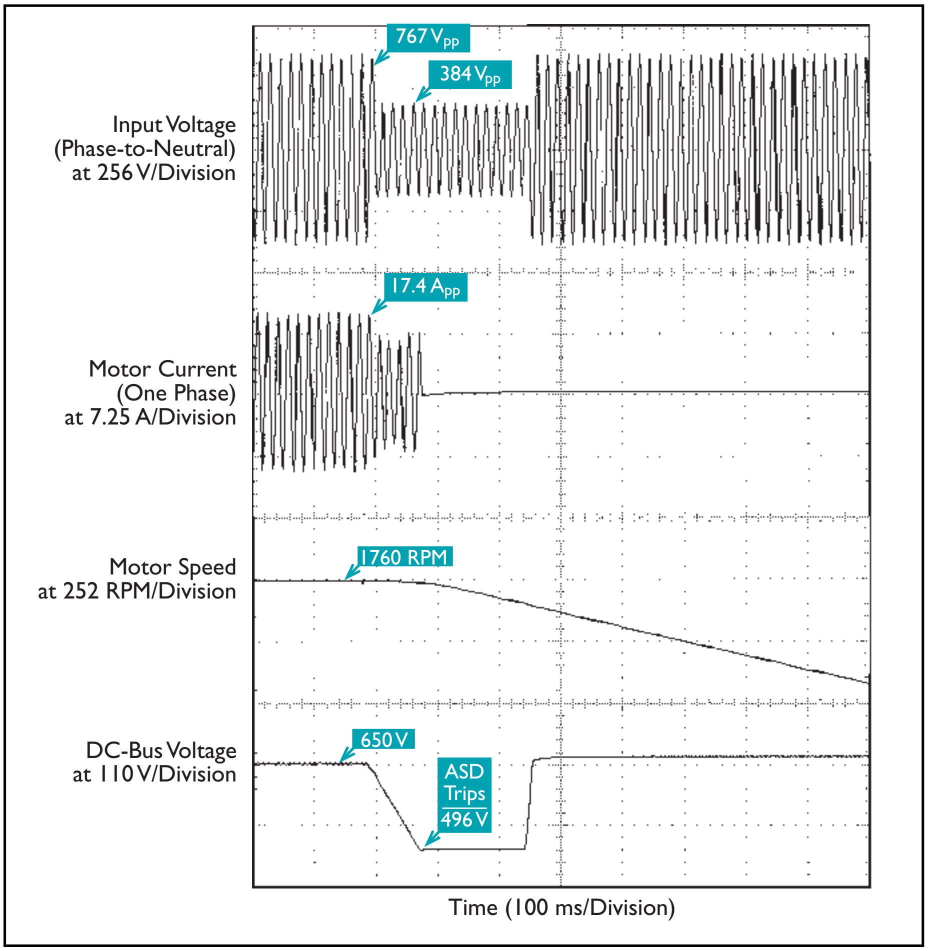


Figure 5. Typical ASD shutdown caused by a 15-cycle, three-phase voltage sag to 50 percent of nominal

Figure 5 shows the effect of a 15-cycle, symmetrical three-phase voltage sag to 50 percent 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 continues 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.

Most PWM VSI drives use a fixed undervoltage trip point that is typically set at 70 to 85 percent 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 inrush current during voltage recovery. For a 650-volt DC bus, the typical trip point ranges from 455 to 553 volts. If a voltage sag or interruption involves all three phases, the voltage at the DC bus will usually decrease in proportion to the decrease in line voltage (see the sidebar on pages 6 and 7). For example, a three-phase voltage sag to 90 percent 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.

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 assure 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 6, 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 7. 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 8, a typical contactor has a dropout point around 50 percent of the nominal voltage during voltage sags lasting longer than five cycles, and a typical relay has a dropout between 60 and 70 percent of the nominal voltage during voltage sags lasting longer than one cycle.

When the voltage on phases A and B in Figure 7 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 9 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.

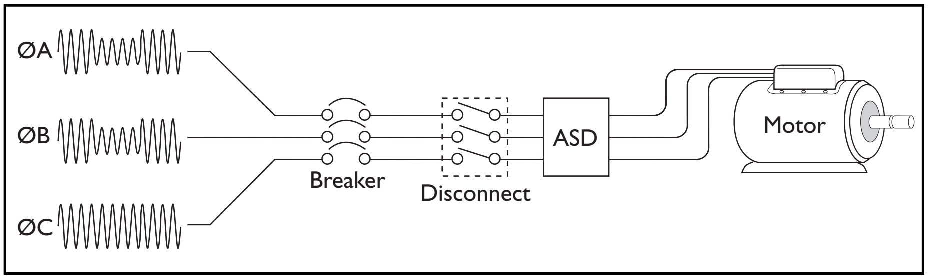


Figure 6. Voltage sag at the terminals of an ASD connected directly to the voltage source

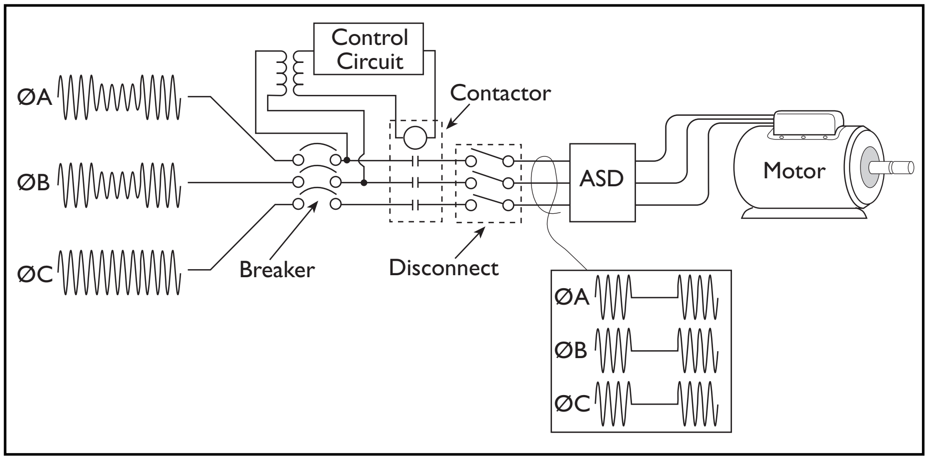


Figure 7. Voltage sag at the terminals of an ASD connected to the voltage source through a contactor

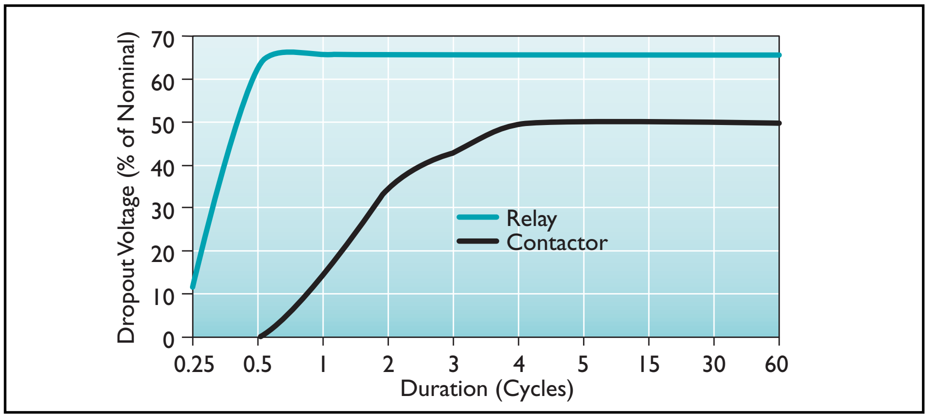


Figure 8. Ride-through of a typical contactor and relay

Start/stop circuits for ASDs may also account for ASD shutdowns. For example, Figure 10 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.

In early versions of ASDs, the control power was derived from the AC line

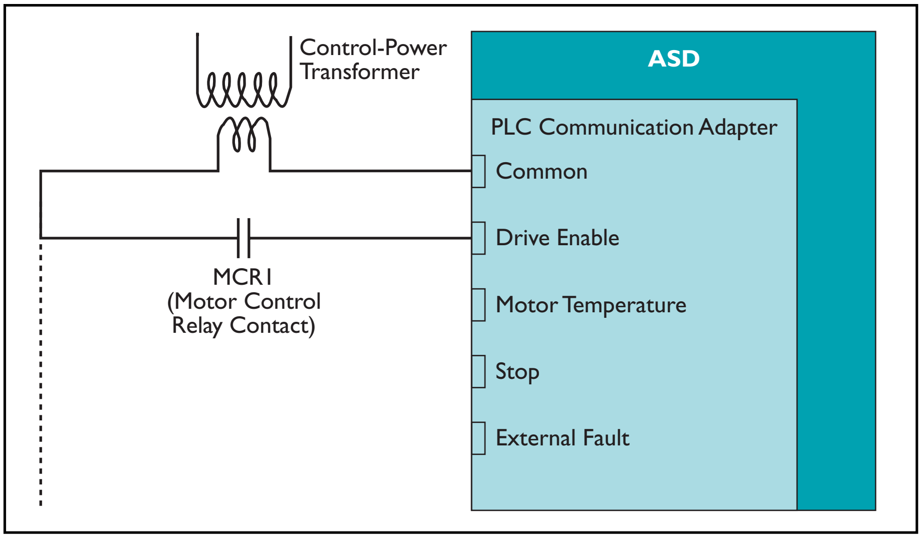


Figure 9. Typical connection of an ASD to PLC control signals

instead of the DC bus, as shown in Figure 11. 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 11 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.

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.

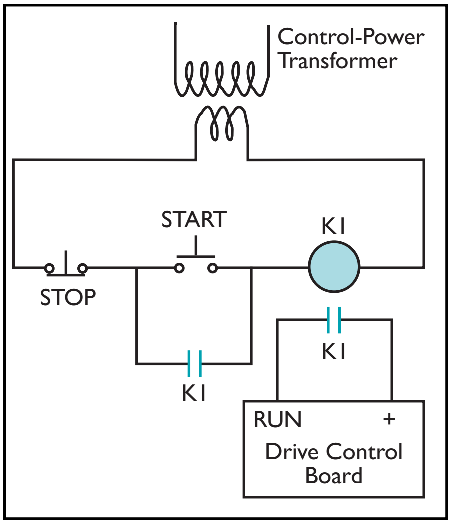


Figure 10. Simplified start/stop circuit for an ASD

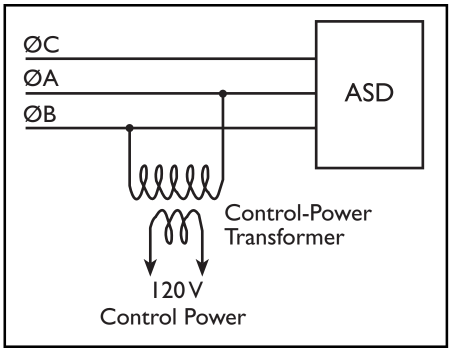


Figure 11. Source of control power in early ASD designs

In modern ASDs, which derive control power from the DC bus, ride-through for the control circuits may be several seconds. The amount of ride-through depends

Effects of Voltage Sags on the DC Bus

ASDs are delta-connected loads. That is, they use phase-to-phase instead of phase-to-neutral voltages. In Figure A, all phase-to-phase voltages are normal. The voltage across the DC bus follows the input voltage while the DC capacitors are charging, then decreases until the next phase-to-phase voltage exceeds the level of the DC bus. This charging and discharging of the DC-bus capacitors creates 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 percent 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 B (below) shows how a single

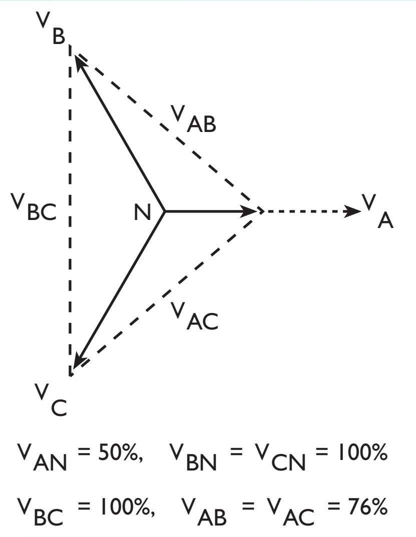


Figure B. Effect of line-to-neutral sag (V_{AN}) on phase-to-phase voltages (V_{AB} and V_{AC})

line-to-neutral voltage sag to 50 percent of nominal can become a sag to 76 percent of nominal on two phase-to-phase voltages, while the third phase-to-phase voltage remains normal.

As shown in Figure C, 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 C was calculated for a five-horsepower ASD at full load with 370-μF 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 D shows a symmetrical three-phase voltage sag to 50 percent 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 percent 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."

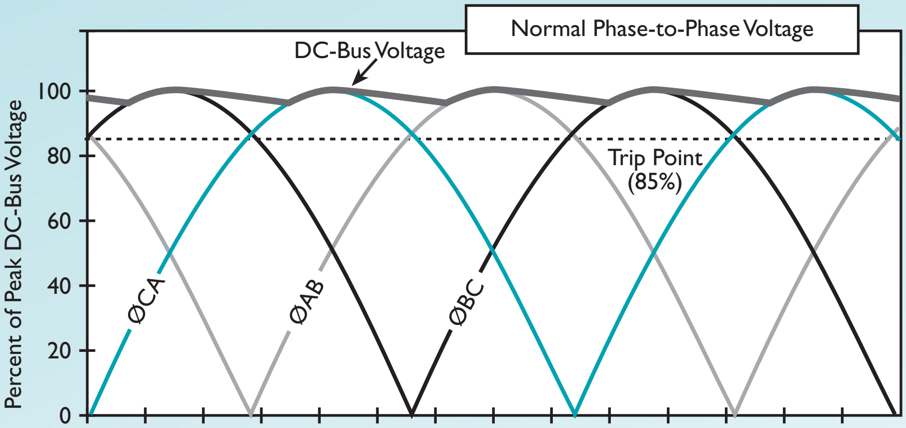


Figure A. DC bus during normal phase-to-phase voltage

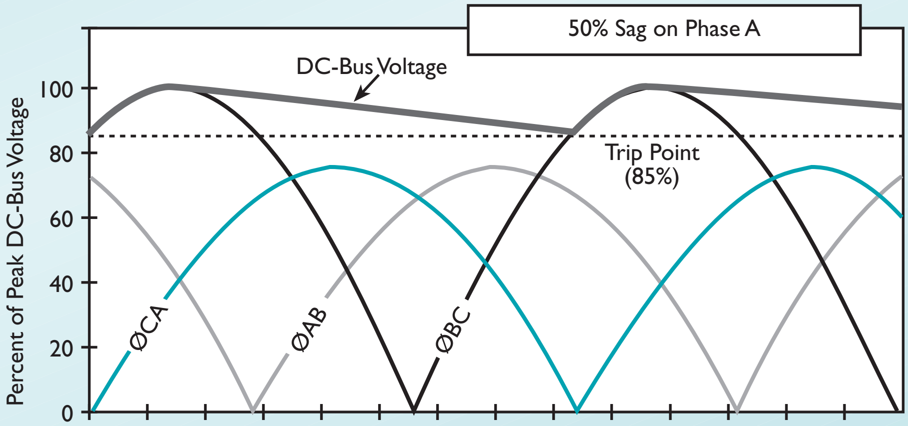


Figure C. DC bus during a 50-percent voltage sag on Phase A

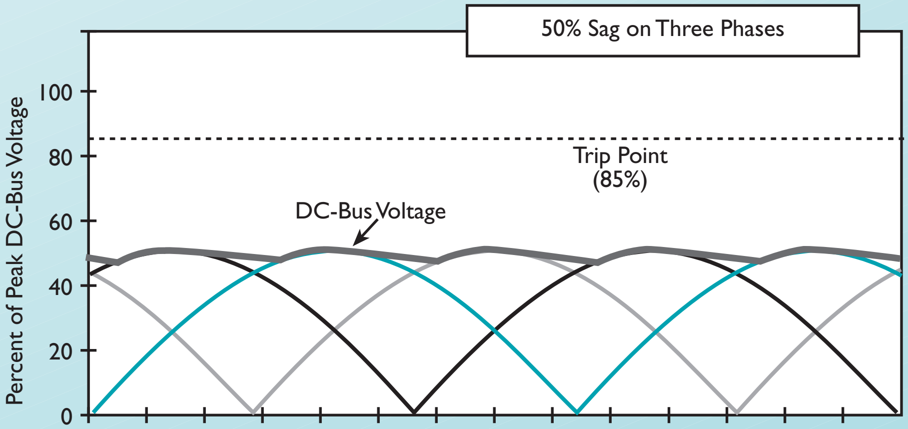


Figure D. DC bus during a 50-percent symmetrical voltage sag on all three phases upon the size of the DC-bus capacitors in the drive and the level of motor load. Also, modern control circuits are powered by switch-mode power supplies, which provide better ride-through for control circuits than linear 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 if the undervoltage trip point is 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 12 shows the inrush current at the end of a three-phase voltage sag to 50 percent of nominal.

ASD manufacturers recommend ultra-fast-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.

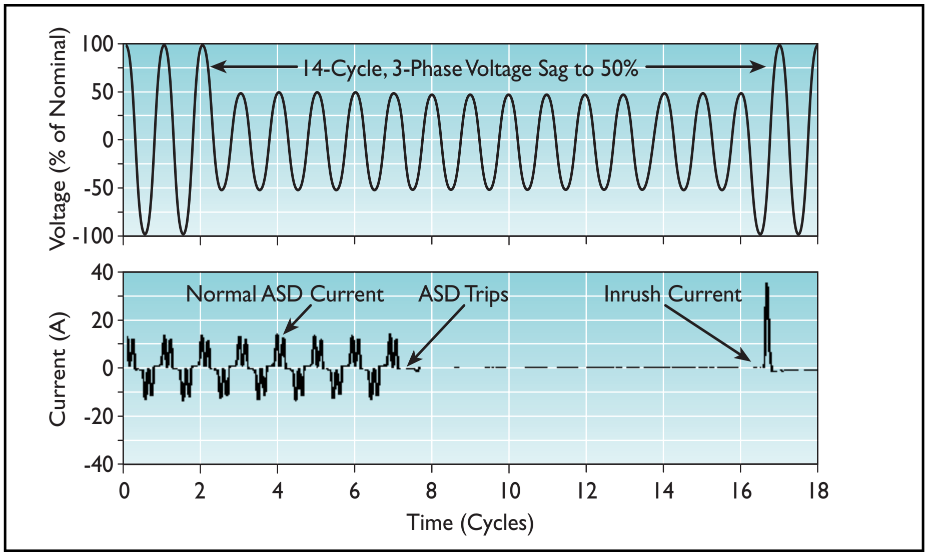


Figure 12. Inrush current after a three-phase symmetrical voltage sag to 50 percent of nominal

Improving 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, when using line-side contactors is necessary, single-phase power conditioners and support devices can 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 are derived from the line side instead of the DC bus, then the control power should

Protection Against Inrush Current

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 on page 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.

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 need to safely 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.

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 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."

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. Figures 13 and 14 show motor speed during the shutdown and restart of two different ASDs (Model A and Model B) for a constant-torque load.

In both the cases, motor speed slowed during the shutdown. However, the speed change of the motor connected to Model A (Figure 13) was minimal, whereas the

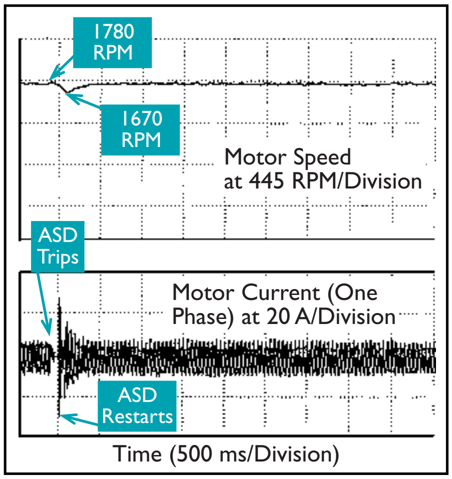


Figure 13. Motor speed and current during a five-cycle voltage sag (Model A, "flying restart" enabled)

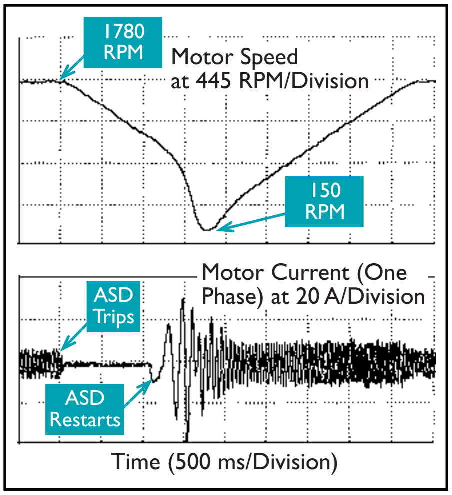


Figure 14. Motor speed and current during a five-cycle voltage sag (Model B, "flying restart" enabled)

speed change of the motor connected to Model B (Figure 14) was significant. The restart algorithm accounts for the different changes in motor speed during voltage sags with the same duration and magnitude. ASD users should consult with the ASD manufacturer to determine restart characteristics before purchasing an ASD.

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 controls 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 15, ideal torque-speed characteristic curves describe how the steady-state load torque changes over the load's speed range, and power-speed characteristic curves describe how the steady-state load power changes over the load's speed range.

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 15. 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 15, 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 in Figure 15, the torque increases as the speed increases. The power required by variable-torque loads varies as a cubic function of speed in

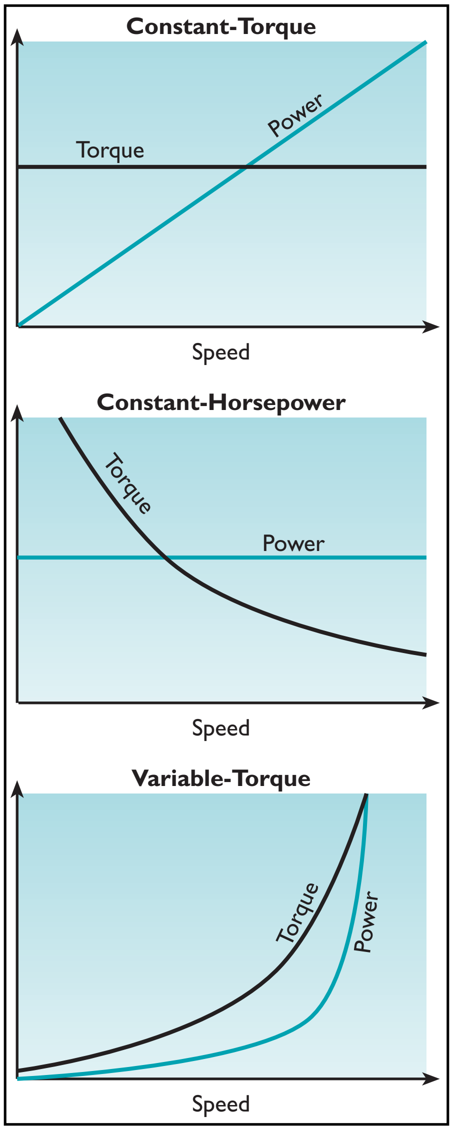


Figure 15. Torque-speed and power-speed characteristic curves for three load categories

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 16 and 17 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.

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 18.

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

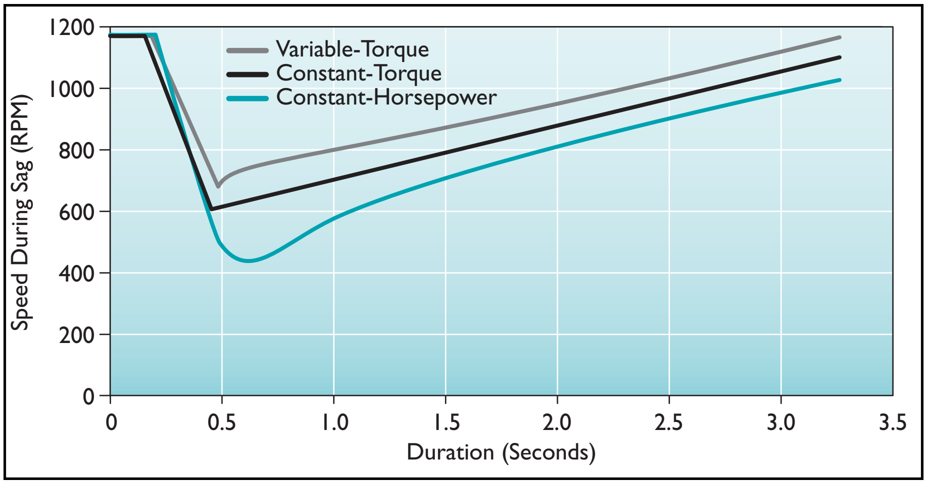


Figure 16. Typical effect of load type on motor speed during a 20-cycle, three-phase voltage sag ("flying restart" enabled)

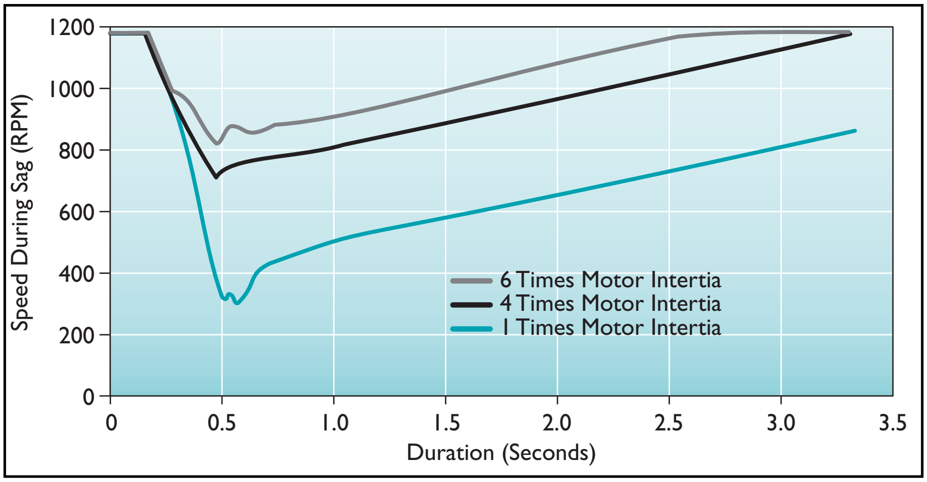


Figure 17. Typical effect of load inertia on motor speed during a 20-cycle, three-phase voltage sag ("flying restart" enabled)

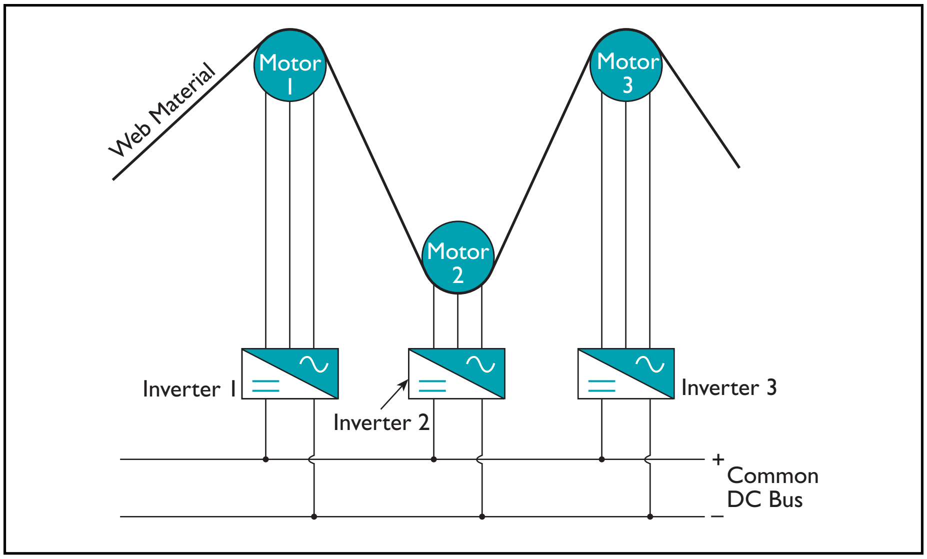


Figure 18. Coordinated-drive system with a common DC bus used to control a web process

shutdown of an ASD is to fortify its DC bus by either adding energy storage or installing a standby boost converter, which connect directly to the DC bus.

When a boost converter senses that the voltage across the DC bus is approaching the undervoltage trip point, it 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-percent remaining voltage during a voltage sag. Therefore, they cannot support the DC bus during deep three-phase voltage sags or momentary interruptions. For more information on boost converters, see *PQTN Brief No. 34: Performance of an ASD Ride-Through Device During Voltage Sags,* PB-106541, 1996.

The DC bus can also be fortified by adding an energy-storage module, such as super or standard capacitors. Table 1 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. For more information on ways to fortify a DC bus, see *ASD Ride-Through Technology Alternatives and Development,* TR-109903, 1997.

Table 1. Energy-storage devices for DC buses (from *ASD Ride-Through Technology Alternatives and Development,* TR-109903)

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

Summary

ASDs can improve the productivity and efficiency of motor-driven processes. However, 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 2 shows the various ASD ride-through options discussed in this PQ Commentary 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.

Table 2. 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

Key Terms: Industrial Process Control, Adjustable-Speed Drives, Voltage Sags and Momentary Interruptions

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EPRI • 3412 Hillview Avenue, Palo Alto, California 94304
PO Box 10412, Palo Alto, California 94303 USA
askepri@epri.com • www.epri.com