POWER-QUALITY DISTURBANCES AND THEIR EFFECT ON VSD PERFORMANCE

Understanding the Electrical and Operational Limits of VSDs in Industrial Applications

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INTRODUCTION: THE HIDDEN COST OF VOLTAGE SAGS

Voltage sags are the most common power-quality disturbance affecting industrial and commercial facilities worldwide. Despite their brief duration, these events can lead to significant financial losses due to equipment malfunctions, process interruptions, and unplanned downtime.

In recent decades, there has been a significant proliferation of variable speed drive (VSD) installations in modern industry. The adoption of the technology to improve production efficiency and lower costs has seen the most industrial production employing VSD technology on their site. To operate effectively and continuously, a VSD requires a high level of power supply quality due to the sensitivity of the electronics in their construction.

It is very common that voltage sags are mistakenly perceived as full power interruptions. That erroneous view is further exacerbated as many VSD's will trip, which halts the load or process they are supplying, and in doing so, create the impression that there has been a complete outage or loss of voltage. However, complete outages are rare in modern power systems. The real culprit behind most production stoppages is often a momentary voltage drop—one that sensitive equipment cannot tolerate.

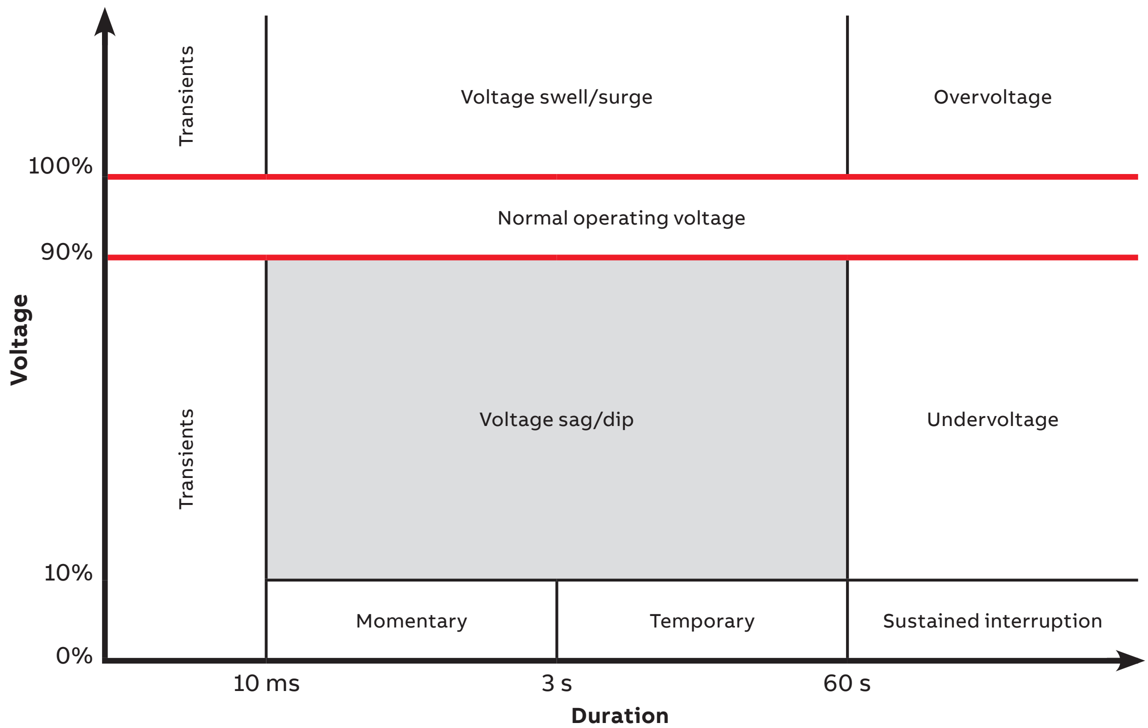
As industries increasingly demand higher levels of availability and operational continuity, identifying the true causes of downtime becomes essential. This has led to a growing emphasis on cost-effective power protection strategies that address the root cause: voltage sags.

DEFINITION AND CHARACTERISTICS OF VOLTAGE SAGS

Voltage sags are defined by IEEE as events where the line-to-line or line-to-neutral/ground RMS voltage falls to between 90% and 10% of nominal voltage for a duration varying somewhere between half a cycle and 60 seconds (Figure 1). Where the voltage drops below 10%, it is considered an interruption.

The duration of a sag begins whenever the voltage drops below 90% of the nominal amount and stops when all three voltages return to being over 90%. The magnitude is defined as the lowest value of any of the three phases reached within this period[1].

Figure 1
Definitions of voltage sags, swells, and transients (IEEE 1159: 2009)



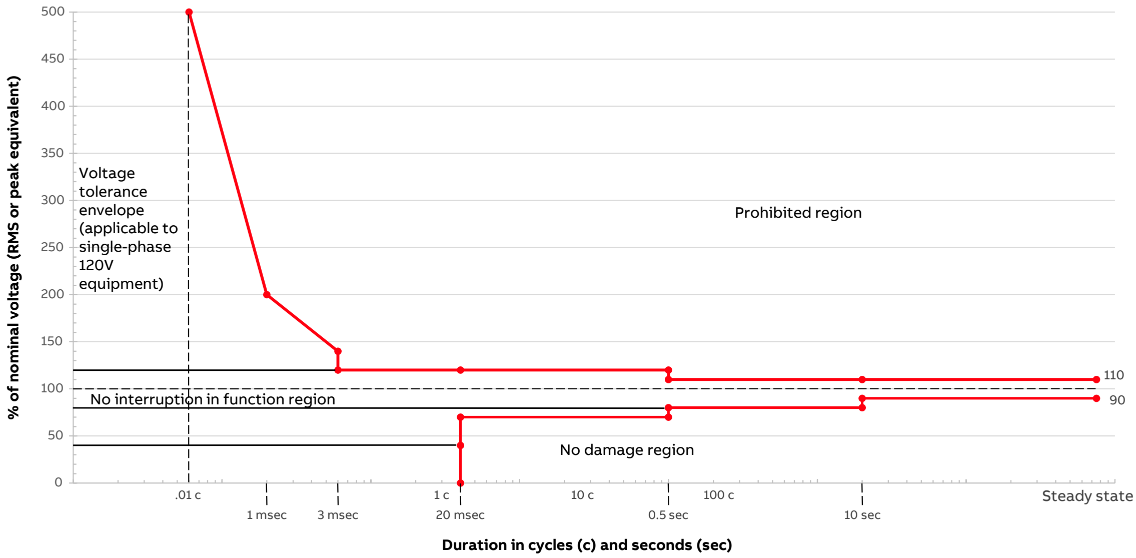
Depending on the depth and duration of the voltage sags, combined with the sensitivity of the equipment, a voltage sag can be misinterpreted as a complete outage of power.

Operations sensitive to voltage sags are typically continuous process operations, multi-stage batch operations, and data processing. Whether or not a voltage sag causes a problem will depend on the depth and duration of the sag and on the ride-through capability of the equipment.

Modern electronic equipment is sensitive to voltage sags, including variable speed drive (VSD) controls, motor starter contactors, robotics, programmable logic controllers, power supplies, and control relays. Much of this equipment is used in applications that are critical to an overall process, which can lead to extremely expensive downtime when voltage sags occur.

Power acceptability curves have been developed by different industries to provide a standard in specifications regarding what voltage duration and magnitude equipment must be able to ride through them. Two well-known power acceptability curves are SEMI F47 for the semiconductor industry and ITIC for computer equipment (Figure 2).

Figure 2
ITIC (CBEMA) curve for electrical equipment operation



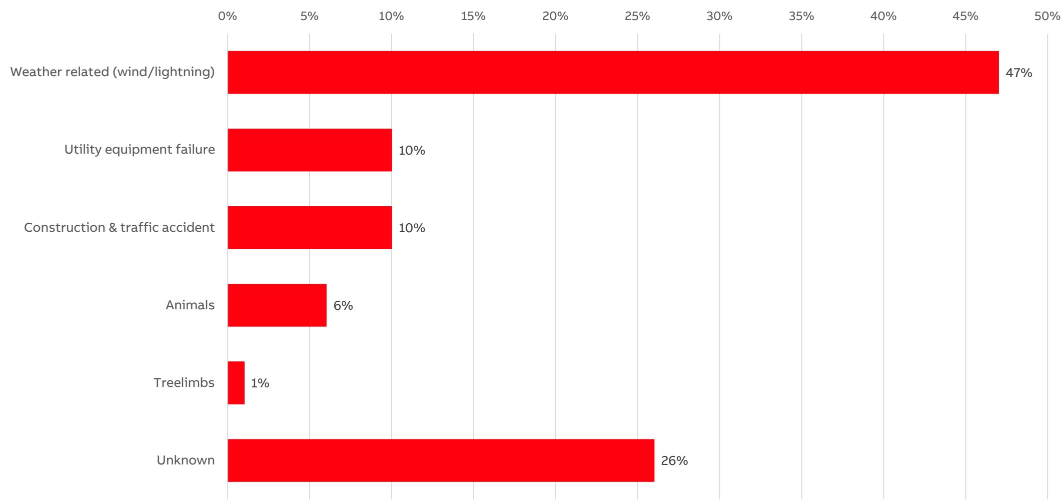
CAUSES AND CLASSIFICATIONS OF VOLTAGE SAGS

Voltage sags occur due to short duration increases in current for two main reasons: faults in the power system (external faults) and the starting of large loads (internal faults).

Starting a large load, such as an induction motor, can result in starting current 5-8 times higher than the nominal running current, causing a sag in the nearby network. Compared to the voltage sags caused by network faults, these sags are shallower and have a longer duration, ranging from one to tens of seconds.

Most voltage sag events in the power system are caused by external influences with the majority being weather-related events, particularly lightning strikes (Figure 3). In many countries, storm and monsoon seasons result in numerous voltage sags due to conductors blowing into each other or tree branches falling onto power lines.

Figure 3
Causes of voltage sags



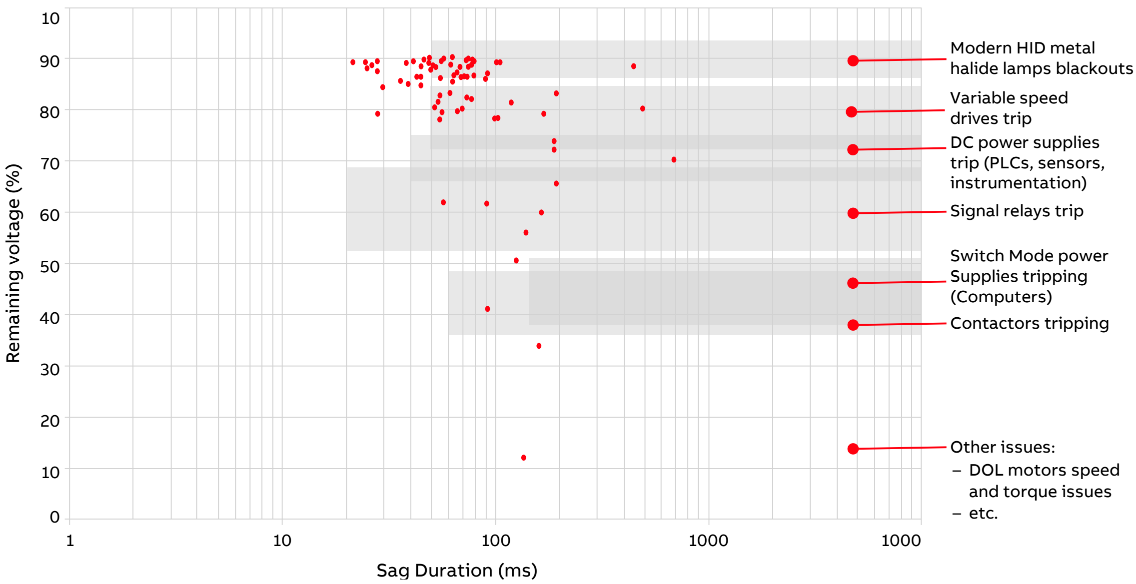
In colder locations, the accumulation of snow and ice can cause single-phase flashovers. Human error, such as instances of vehicles running into local power lines or construction work accidentally hitting underground cables, is also a common cause. Nesting birds or animals that climb can also interfere with pole-mounted equipment[4].

EQUIPMENT SENSITIVITY

Equipment can be sensitive to either the magnitude, the magnitude and duration, or other voltage characteristics such as phase imbalance and phase-angle spurts .

Typically, most electronic equipment is sensitive to both the magnitude and the duration of the sag.

Figure 4
Typical distribution of voltage sags and equipment affected.



Network sag events occur in all utility networks and reveal a similar picture when plotted on a scatter graph (Figure 4).

The light grey rectangles illustrate various equipment's sensitivity and response to different magnitudes and durations of sag events.

LIMITATIONS OF SIMPLIFIED SAG CHARACTERIZATION

Voltage sags are visualized using a two-dimensional plot of voltage magnitude vs. duration. While this is a common reporting method, it oversimplifies the event by ignoring:

- Phase imbalance (differences in voltage between phases)
- Phase angle shifts (Figure 5)
- Waveform distortion (non-sinusoidal behavior during a sag)

These factors can significantly influence how a VSD responds to a sag[1].

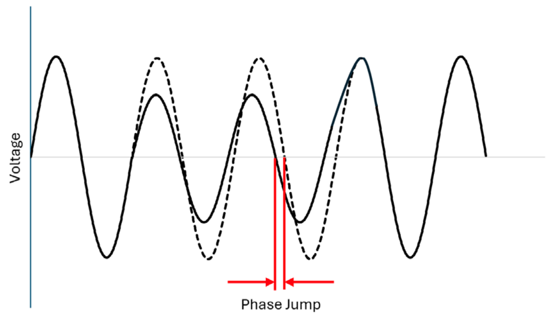


Figure 5 The effect of a voltage sag on the phase angle of supply voltage

For example, a single-line-to-ground power-quality event that takes place with 55% remaining voltage in the utility (Figure 6), which is then propagated through a Dyn11 distribution transformer to the consumer, will affect all three voltages and phase angles with the following transformations:

- Two line-to-line voltage magnitudes are slightly impacted (L1-L2 and L2-L3)
- The third line-to-line voltage is significantly impacted (L3-L1)
- All three phase angles are impacted

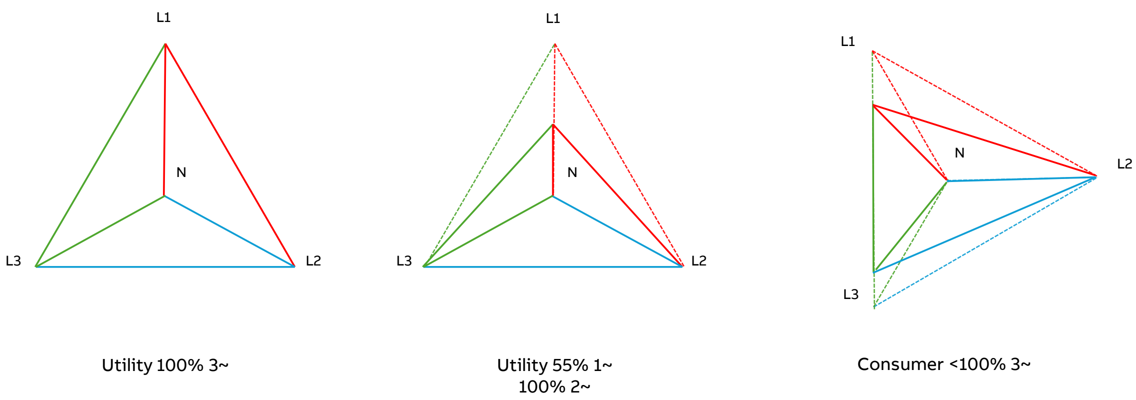


Figure 6 Transformation of utility single-line-to-ground power-quality event to consumer via distribution transformer

VOLTAGE SAGS AND VARIABLE SPEED DRIVES (VSD)

The sensitivity of VSD's to voltage sag events stems from the power-electronic components within them, which are highly responsive to even minor voltage fluctuations. As industrial processes become more complex and VSD deployment increases, understanding their behavior during sags is critical.

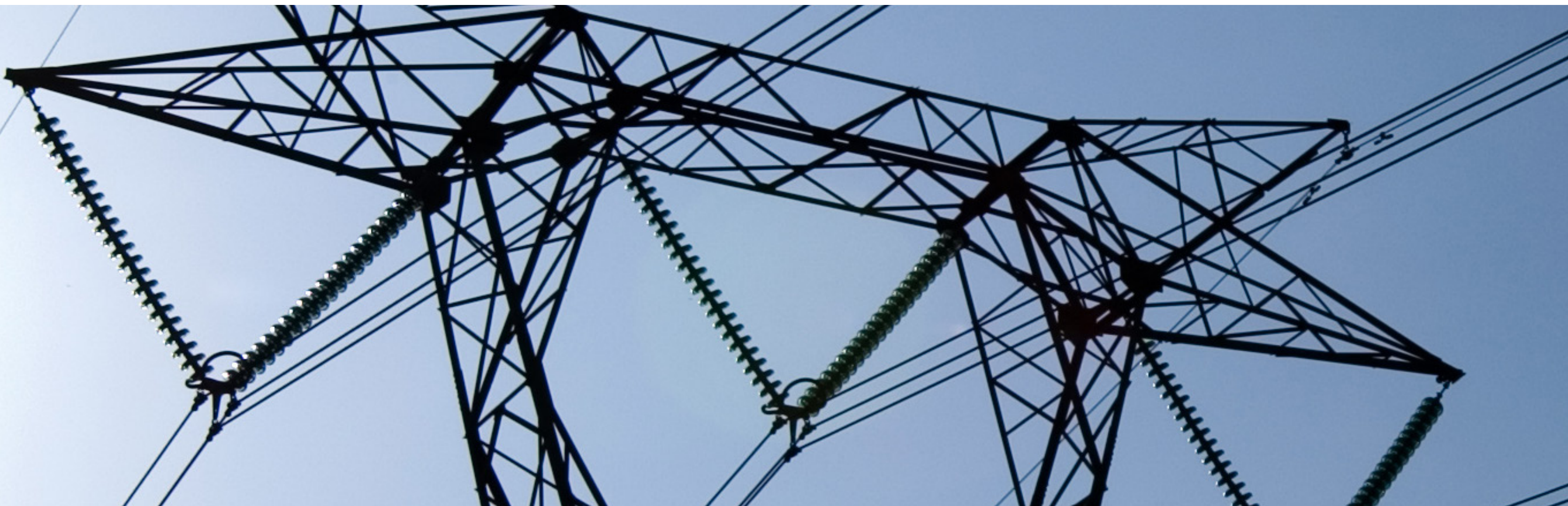
There are four primary reasons a VSD may trip during a voltage sag[1]:

1. **Protective Tripping:** The drive controller detects abnormal operating conditions and trips to protect internal components.
2. **DC Bus Undervoltage:** A drop in AC input voltage reduces the DC bus voltage, triggering an undervoltage trip.
3. **Overcurrent Events:** Increased input current during the sag—or high inrush current when the sag ends—can cause overcurrent trips or blow fuses to protect the power electronics.
4. **Process Sensitivity:** The driven process may not tolerate speed or torque variations caused by the sag, thus prompting a shutdown.

SENSITIVITY AND RIDE-THROUGH CHALLENGES

VSDs are particularly vulnerable due to their reliance on DC bus capacitors for ride-through capability. As equipment becomes more compact and power-dense, the energy storage capacity of these capacitors decreases, reducing the VSD's ability to ride through even short sags.

Unlike other power-quality issues such as harmonics or voltage imbalance, the effects of voltage sags are instantaneous and can be catastrophic for continuous or critical processes.

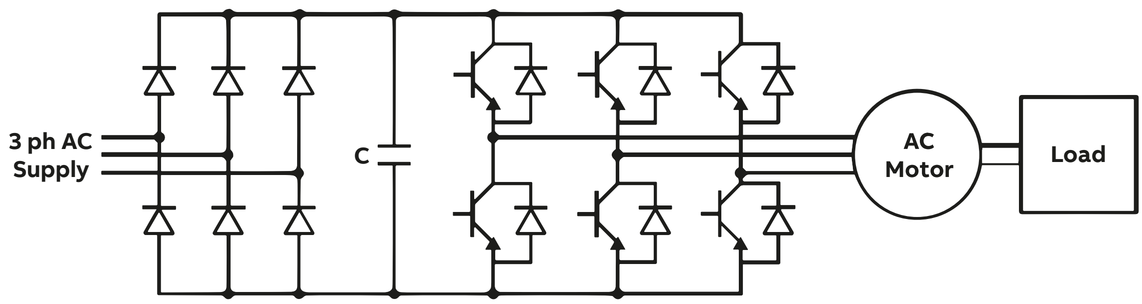


VSD TOPOLOGY AND RESPONSE

Most VSDs in the low-to-medium power range use a Voltage Source Inverter (VSI) topology (Figure 7). This is the most common and cost-effective architecture for controlling AC motors in industrial and commercial applications. This type of VSD is compact and cost effective. They have high-efficiency good dynamic response, are easily scalable from a few kW up to hundreds of kW and support regenerative braking (with additional circuitry).

The rectifier stage uses diodes (uncontrolled) or thyristors (controlled) to convert the AC supply to DC. The DC stage smooths and stores DC power using capacitors and sometimes inductors. The inverter stage uses insulated gate bipolar transistors (IGBT) or metal-oxide-semiconductor field-effect transistors (MOSFET) to generate variable frequency and voltage AC.

Figure 7
Topology of three-stage VSD



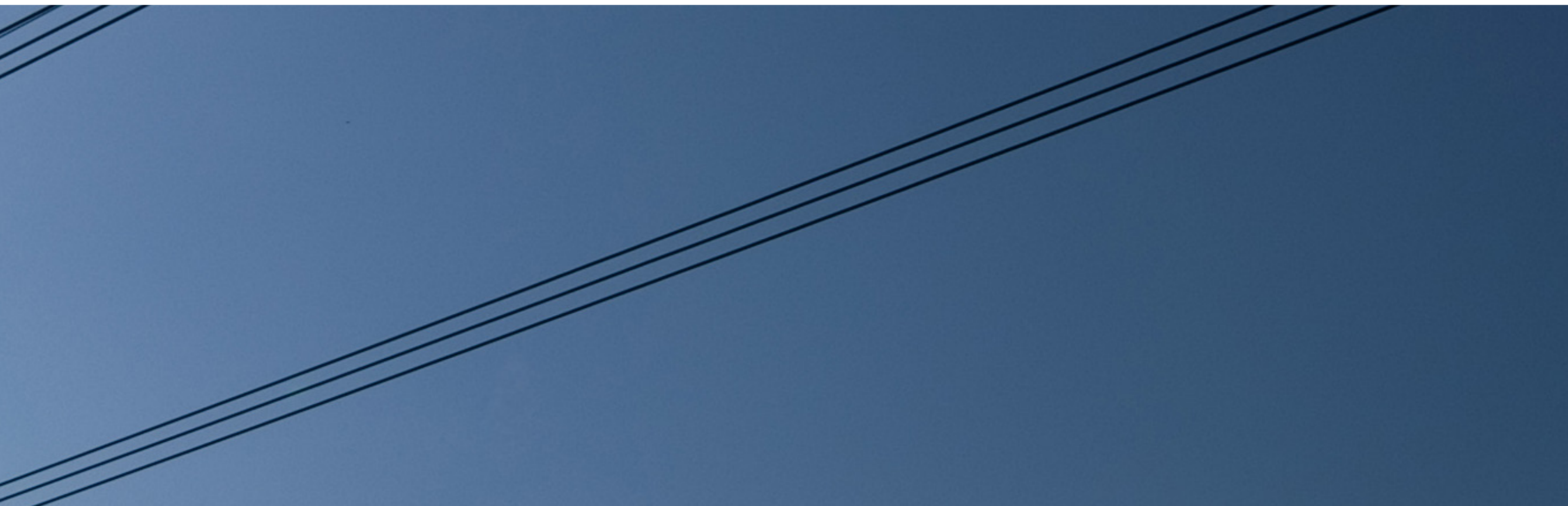
In VSDs with an uncontrolled rectifier, AC voltage variations directly affect the DC link. A balanced three-phase sag reduces the DC link voltage, often triggering an undervoltage trip. When the AC supply returns to normal, the DC bus capacitors may draw a large inrush current, potentially exceeding the rectifier diodes' capacity and causing an overcurrent trip.

These VSD's can fault within one second — or even within a single cycle — during a voltage sag. Even brief interruptions can halt motor operation, leading to production losses and delays.

To protect the hardware:

- Undervoltage trip settings should typically be set between 70% and 85% of the nominal DC voltage.
- AC overcurrent trip settings are usually between 200% and 250% of the rated motor current.

In unbalanced sags, increased ripple in the DC bus voltage can also lead to tripping—especially when the sag magnitude is below 80% and the duration exceeds 12 cycles.



RESTART BEHAVIOR AND RISKS

After a voltage sag-induced trip, Variable Speed Drives (VSDs) can often be configured to automatically restart once nominal voltage levels are restored. However, enabling this feature requires careful consideration of the mechanical process dynamics, particularly whether the connected load can safely tolerate transient variations in motor speed and torque during reacceleration. This is especially critical in applications involving high-inertia loads or sensitive downstream equipment.

Voltage sags lasting longer than 100 milliseconds are particularly problematic. During such events, the DC bus voltage within the VSD can drop significantly due to insufficient input power from the rectifier stage. If the sag persists and the DC bus voltage falls below the undervoltage threshold, the inverter section may cease operation or enter a fault state. This can lead to a complete shutdown of the drive, and in some cases, improper commutation or gate drive failures, potentially damaging the IGBTs or other power semiconductors.

If the VSD remains disconnected for several seconds—either due to a protective trip or manual intervention—the DC bus capacitors will discharge to a low voltage state. Upon re-energization, these capacitors must be recharged rapidly to restore the DC link voltage. This results in a high inrush charging current, which flows through the input rectifier diodes or thyristors. The magnitude of this current is influenced by several factors, including the capacitance value, the residual voltage on the DC bus, the source impedance, and the presence (or absence) of soft-charging mechanisms such as precharge resistors or inrush current limiters.

If not properly managed, this surge current can exceed the peak current ratings of the rectifier components, leading to thermal overstress, diode failure, or even catastrophic damage to the front-end converter. Additionally, repeated high-current events can degrade capacitor life and compromise the long-term reliability of the drive system

FINANCIAL IMPACT OF VOLTAGE SAGS

Voltage sags are among the most disruptive and costly power quality disturbances in industrial environments. They are responsible for approximately 90% of the total financial losses attributed to poor power quality across European industries. According to a comprehensive study by the European Copper Institute[2], poor power quality—including voltage sags, harmonics, and transients—results in annual losses exceeding €150 billion within the EU industrial sector[6]. Similarly, research conducted by the Electric Power Research Institute (EPRI) in the United States estimates that the U.S. economy suffers up to $180 billion in annual losses due to power quality issues, with voltage sags being the predominant contributor[3].

The financial consequences of voltage sags vary by industry but are consistently severe due to their impact on sensitive electronic equipment, automation systems, and production continuity[8] :

- Semiconductor Manufacturing: In this highly sensitive sector, even a brief voltage sag can cause photolithography tools, ion implanters, or etching systems to shut down or malfunction. A single sag event lasting just a few hundred milliseconds can result in scrapped wafers, production delays, and equipment recalibration, leading to losses that can exceed $250,000 per incident.
- Food & Beverage Processing: Automated bottling, packaging, and refrigeration systems are vulnerable to voltage sags, especially during high-speed operations. A sag-induced trip in a bottling line can halt production for hours, spoil temperature-sensitive goods, and require manual intervention to restart. In large facilities, this can translate to tens of thousands of euros in lost product and downtime per event.
- Plastics and Injection Molding: Voltage sags can interrupt the precise timing required for mold heating, injection, and cooling cycles. If a sag causes a drive or PLC to trip mid-cycle, the result is often molded part defects, equipment jams, or tooling damage. For high-volume operations, this can mean losses of €10,000–€50,000 per hour of downtime, not including the cost of wasted raw materials.

These examples underscore the critical need for voltage sag mitigation strategies such as ride-through capabilities in VSDs, uninterruptible power supplies (UPS), and power conditioning equipment. Investing in power quality solutions not only protects sensitive equipment but also ensures operational continuity and long-term cost savings.

MITIGATION STRATEGIES

Sustaining good power quality requires collaboration between the utility, the plant, and the equipment manufacturers. Utilities can achieve a certain level of reliability, but eliminating voltage sags and interruptions entirely is impossible. Reducing sags on the power system can be costly, as sags affect customers over a wide area.

Utilities can increase reliability by reducing fault occurrence through measures such as tree trimming, animal guards, arresters, and circuit patrols. The duration of an event can be reduced by having safety equipment trip faster, using smaller fuses, instantaneous trips, and transmission relays. The severity of sags can be reduced by raising the nominal voltage or installing larger station transformers[5].

Improving the ride-through capability of installed equipment such as by adding requirements (for example, power acceptability curves to the specified Distributed Generation apparatus) helps make the plant more resistant to variations in the power supply[7].

However, utilities will never be able to completely remove voltage sags from the grid. Therefore, industries with high availability requirements still require modern power protection and conditioning solutions.

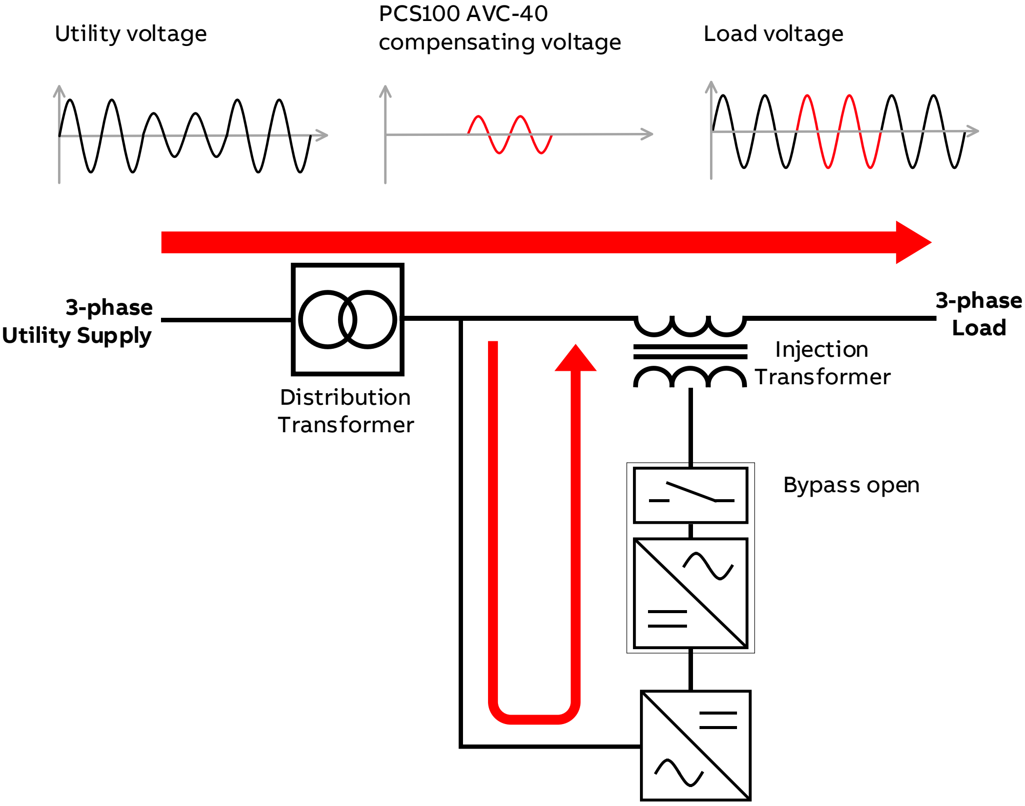
ABB POWER CONDITIONING SOLUTIONS

ABB's PCS100 AVC-40 is an active voltage conditioner designed to address the most common power-quality problems affecting industries worldwide.

The PCS100 AVC-40 is a unique solution that does not require bulky, hazardous, high-maintenance batteries to restore voltage. Since interruptions are rare in modern power systems, the PCS100 AVC-40 is a solution that meets the power protection needs of most industrial manufacturing plants; small footprint, simple installation, high efficiency, and a very low Total Cost of Ownership (TCO).

The PCS100 AVC-40 installed in the low-voltage supply (Figure 8) can eliminate most of the issues caused by voltage sags on the supply network. The magnitude of the voltage and their phase angles are corrected, which empowers them to provide full-quality voltage to ensure the proper functioning of equipment.

Figure 8
ABB PCS100 AVC-40 voltage sag correction operation



CONCLUSION

Voltage sags are among the most disruptive power-quality issues in industrial environments, often leading to costly downtime and equipment damage. While utilities can implement measures to reduce the frequency and severity of these events, complete elimination is not feasible. This makes it essential for facilities to adopt robust mitigation strategies.

Among the most vulnerable components in modern industrial systems are variable speed drives (VSDs). These devices, which are integral to motor control and energy efficiency, are highly sensitive to even brief voltage disturbances. Their reliance on DC bus capacitors for ride-through capability means that a sag lasting just a few cycles can cause a trip, halting critical processes.

As VSDs become more compact and power-dense, their tolerance for voltage sags diminishes, increasing the risk of operational interruptions. Therefore, any comprehensive power-quality strategy must prioritize VSD protection.

Solutions like ABB's PCS100 AVC-40 offer targeted voltage sag correction, which ensures stable voltage supply and safeguards sensitive equipment. By addressing the specific vulnerabilities of VSDs, facilities can significantly reduce downtime, protect assets, and maintain productivity in the face of inevitable grid disturbances.

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