

The Effects of Phase Shift on Low-Voltage Tolerance of Industrial Process Devices

Background The low-voltage tolerance of common industrial process devices is usually determined by applying momentary voltage interruptions and sags of various magnitudes and durations and recording whether the device dropped out. However, other characteristics of applied voltage sags may need to be varied to yield more useful information about the low-voltage tolerance of process devices. PQTN Brief Number 44 indicates that the point on the sine wave at which the sag occurs can affect the low-voltage tolerance of a process device. Another characteristic of voltage sags is the shift in voltage phase angle at the beginning and end of a sag event. Figure 1 shows a positive and negative phase shift. A positive phase shift occurs when the voltage crosses through the zero point before it would during normal voltage conditions, and a negative phase shift occurs when the voltage crosses through the zero point after it would during normal voltage conditions.

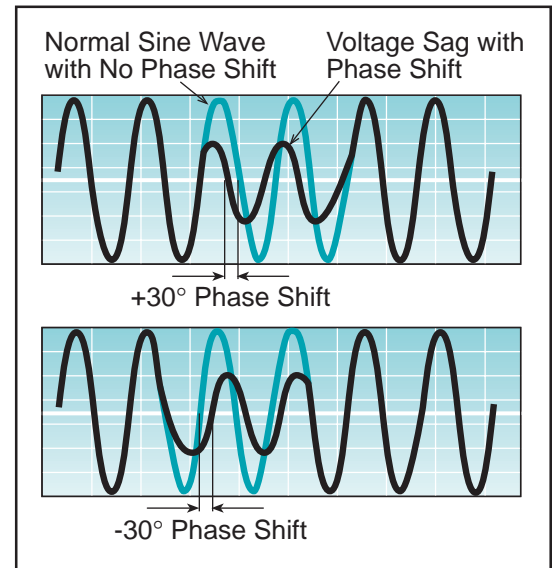


Figure 1. Positive and Negative Phase Shifts During a Voltage Sag

Phase shifts typically result from an interaction between fault current and impedance in the electrical distribution system (see the Tutorial inside). This Brief looks at how phase shifts occurring during voltage sags can affect the resulting low-voltage tolerance of the same process devices tested for PQTN Brief Number 44.

Objective The objective of the tests performed at the EPRI Power Electronics Applications Center (PEAC) Power Quality Test Facility was to determine the effect of phase shifts—occurring during voltage sags—on the low-voltage tolerance of common relays, motor starters, contactors, and power supplies.

Test Setup The low-voltage tolerances of four general-purpose relays, five motor starters, seven contactors, and five DC power supplies were characterized. Table 1 lists the description of each device. To characterize the devices, a computer, waveform

Table 1. Tested Process Devices and Their Ratings

Name	Volts	Size	Description
CR1	120	10 A	DPDT Relay
CR2	120	10 A	DPDT Relay
CR3	24	10 A	DPDT Relay
CR4	24	5 A	DPDT Relay
MS1	120	2 HP @ 230 V	3-Pole Motor Starter
MS2	120	3 HP @ 230 V	3-Pole Motor Starter
MS3	120	3 HP @ 230 V	3-Pole Motor Starter
MS4	120	1.5 HP @ 230 V	3-Pole Motor Starter
MS5	120	30 HP @ 230 V	3-Pole Motor Starter
MC1	120	10 A	4-Pole Contactor
MC2	120	10 A	4-Pole Contactor
MC3	120	3 HP @ 230 V	3-Pole Contactor
MC4	24	7.5 HP @ 230 V	3-Pole Contactor
MC5	24	10 HP @ 230 V	3-Pole Contactor
MC6	24	7.5 HP @ 230 V	3-Pole Contactor
MC7	24	40 HP @ 230 V	3-Pole Contactor
PS1	120	60 W	PLC Power Supply
PS2	120	140 W	Instrument Power Supply
PS3	120	200 W	Computer Power Supply
PS4	120	500 W	Multi-Output Power Supply
PS5	120	40 W	Unregulated Power Supply

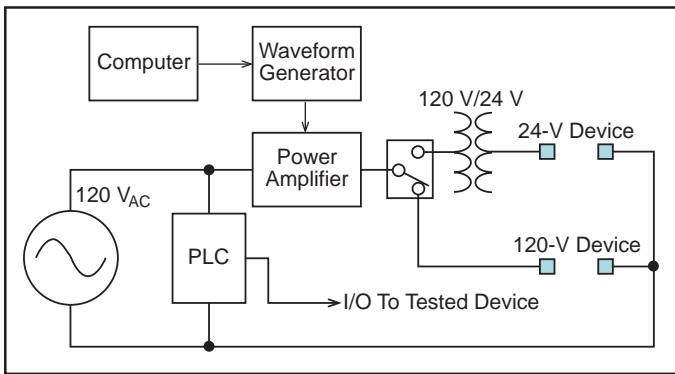


Figure 2. Test Setup

generator, and power amplifier were connected in the test setup as shown in Figure 2. Nominal voltage was applied to the tested device, either 120 or 24 AC volts. Voltage to devices rated at 24 volts was stepped down from 120 volts using a 1-kVA step-down transformer. During each trial, a voltage-sag waveform stored in the memory of the computer was selected. Then, the sag was induced by a waveform generator and power amplifier. Voltage sags had one of seven phase-shifts measured at the zero crossing: -60, -40, -20, 0, +20, +40, or +60 electrical degrees. The duration of all induced sags was six cycles, a common duration of voltage sags occurring at process facilities. During each phase-shift setting, the depth of the applied voltage sags was reduced from 95 percent of nominal in five-percent steps until the tested device dropped out. Device dropouts were detected by a programmable logic controller (PLC).

TEST RESULTS

Table 2 shows the test results and the range of low-voltage tolerance (the difference between maximum and minimum values) for each tested device. In ten of the 13 cases where phase shift affected the tolerance of the device, the most extreme phase shifts (-60 or +60 degrees) had the greatest effect on low-voltage tolerance. While none of the power supplies were affected by the phase shifts, the tolerance of all of the relays was greatly affected, especially for ± 60 -degree phase shifts. The low-voltage tolerance of the motor starters and contactors was slightly affected, with no more than a ten-percent range for any one device. Figure 3 shows the composite low-voltage tolerances of the devices.

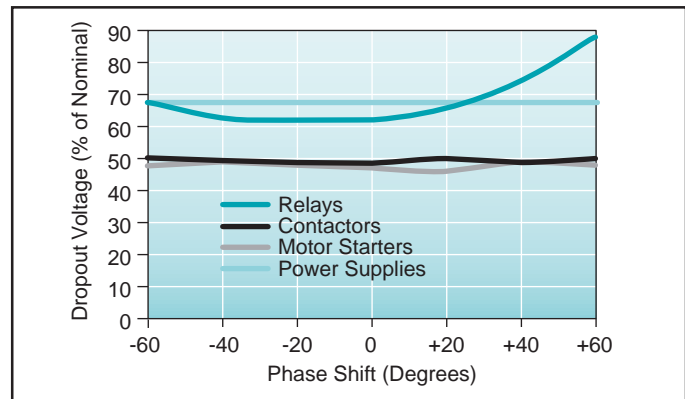


Figure 3. Composite Low-Voltage Tolerances for the Relays, Motor Starters, Contactors, and Power Supplies at Different Phase Shifts

DISCUSSION

Clearly, the general-purpose relays were most affected by the phase shifts. However, even for these sensitive control devices, only the large phase shifts (+40, +60, and -60 degrees) had a significant effect on low-voltage tolerance. The average range in low-voltage tolerance for the relays was 25 percent of nominal across all phase shifts. For the motor starters and contactors, the average range was only five percent. The power supplies were not affected at all by the phase shifts. Only three devices (MS2, MC6, and MC7) had a better low-voltage tolerance during a phase shift.

SIGNIFICANCE

PQTN Brief Number 44, the companion to this Brief, concludes that the point on the sine wave at which a voltage sag is initiated does affect the low-voltage tolerance of some common process control devices. According to the test results reported here, the effect of phase shift on process control devices ranges from modest to insignificant. In any event, relays tend to be very sensitive to voltage sags regardless of the phase shift. Because control relays are integral components of industrial processes, designing them to be more robust will result in improved tolerance of entire processes and therefore should be a priority for manufacturers.

During tests to determine the low-voltage tolerance of industrial process devices, controlling only magnitude and duration will certainly provide important information for manufacturers and end users. If point-on-wave

Table 2. Magnitude (Percent of Nominal Voltage) at Which the Device Dropped Out During a Six-Cycle Voltage Sag (Seven Different Phase Shifts)

Phase Shift	Device																				
	CR1	CR2	CR3	CR4	MS1	MS2	MS3	MS4	MS5	MC1	MC2	MC3	MC4	MC5	MC6	MC7	PS1	PS2	PS3	PS4	PS5
-60	90%	70%	55%	55%	55%	45%	35%	50%	55%	35%	40%	50%	55%	55%	60%	55%	75%	65%	50%	60%	90%
-40	70%	70%	55%	55%	55%	50%	35%	50%	55%	35%	40%	50%	55%	55%	60%	50%	75%	65%	50%	60%	90%
-20	70%	70%	55%	55%	55%	45%	35%	50%	55%	35%	40%	50%	55%	55%	55%	55%	75%	65%	50%	60%	90%
0	70%	70%	55%	55%	55%	45%	30%	50%	55%	35%	40%	50%	50%	55%	55%	55%	75%	65%	50%	60%	90%
20	70%	75%	60%	60%	55%	40%	30%	50%	55%	35%	45%	50%	55%	55%	55%	55%	75%	65%	50%	60%	90%
40	80%	80%	70%	70%	60%	45%	35%	50%	55%	35%	45%	50%	55%	55%	50%	50%	75%	65%	50%	60%	90%
60	90%	95%	90%	75%	55%	45%	30%	50%	60%	35%	40%	50%	50%	60%	55%	60%	75%	65%	50%	60%	90%
Range	20%	25%	35%	20%	5%	10%	5%	0%	5%	0%	5%	0%	5%	5%	10%	10%	0%	0%	0%	0%	0%

and phase shift can be controlled, then testing at zero degrees point-on-wave and +60 degrees phase shift will yield worst-case low-voltage tolerances. The extent to which phase shifts bear upon the performance of an industrial process cannot truly be determined because phase shifting during voltage sags at a typical industrial facility is not well documented. However, it is likely that the typical industrial facility will see few, if any, phases shifts as great as 60 degrees. Additional field research is needed to determine the real-world phase-shift characteristics of voltage sags. When voltage-sag data is collected from the field, it should routinely include information about point-on-wave and phase shift in addition to magnitude and duration.

Although control devices are essential to industrial processes, they are not the primary movers. The workhorse of most industrial processes is the induction motor, which may be the part of the process most adversely affected by phase shifts. To fully understand the effects of phase shift on industrial processes, control systems and motors need to be tested together. Results of such “system” testing will help power quality engineers establish the best practices for mitigating the effects of voltage sags on industrial processes.

ACKNOWLEDGMENTS

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TUTORIAL: Voltage Phase Shifts

A phase shift occurring during a voltage sag is a very complex phenomenon resulting from a fault in the power system. Figure A shows the ideal angular relationship between voltages in a three-phase system. During normal conditions, all three phases of the line-to-neutral voltage are equal in magnitude, and each phase is 120 degrees from the other two. All three phase angles sum to 360 degrees.

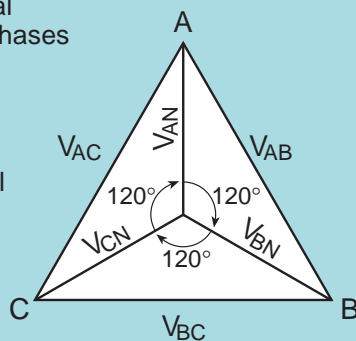


Figure A

Voltage phase shifts are caused by an interaction between load or fault current and the impedance of distribution lines. Figure B shows how a line-to-ground fault creates a voltage sag and phase shift. During a ground fault in the distribution system, one or more of the phases will be connected to ground through a fault impedance, shown as Z_f in the figure. The amount of current generated during a fault depends upon the fault impedance and whether the fault is line-to-

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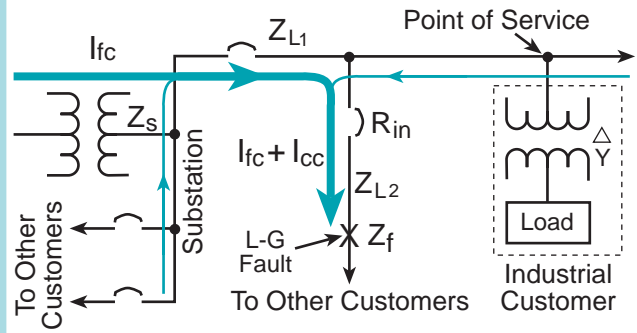


Figure B

ground, line-to-line, or three-phase. It also depends upon the available fault current in the system.

During the fault shown in Figure B, the voltage magnitude and phase relationship at the point of service will change based on the amount of fault current (I_{fc}), other load-contributing currents, and the impedances at the substation transformer secondary (source impedance Z_s), distribution lines (Z_{L1} , Z_{L2}), and fault (Z_f). The resulting sag at the point of service will persist until the in-line recloser R_{in} clears the fault. The angles between the three phases will then shift back to their original relationship.

What happens to the voltage phase between the point of service and the customer load depends upon two factors: 1) the connection of the service transformer (delta-wye, wye-wye, and so on) and 2) the connection of the load (single- or three-phase). In this example, the delta-wye connection will cause a further phase shift of 30 degrees. Figure C shows the voltage phase relationship on the secondary of the customer's service transformer for a line-to-ground fault at the primary side of the transformer (worst case). Although the phase angles sum to 360 degrees, the phase relationship between the three voltage phases is no longer equal. Any three-phase motor will likely experience voltage unbalance and torque transients.

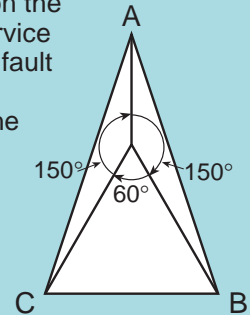


Figure C

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