Written by MT Staff
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Often, in the wake of unexpected shutdowns due to costly equipment failures, superficial investigations result in plant engineers assigning fault to mechanical components. In many cases, however, thorough engineering analysis can delve deeper to reveal the causes for malfunctions and prescribe long-term, cost-effective solutions. Such was the case recently at an automotive assembly plant.

Premature failures of pulse-width modified (PWM) variable frequency drives (VFDs) serving supply and exhaust fan motors caused costly interruptions to the plant's automated paint process. When the company started to investigate these intermittent drive shutdowns in the paint house, 70 VFDs ranging in capacity from 30-400 hp were in service at multiple 2000 kVA low-voltage substations.

Throughout the preceding year, the plant had reported multiple shutdowns of the paint house VFDs with each event costing approximately $300,000 in downtime and lost production. In each incident, maintenance technicians had performed field diagnostic procedures to determine what initiated the shutdowns.

The technicians reported finding one or two blown fuses at the affected drive. They also tested and condemned one or more gate turn-off thyristors (GTOs) on the voltage-source inverters. The condemned GTOs and fuses were replaced and the drives were successfully restarted without further incident. Each event involved a different VFD and none of the drives had experienced more than one shutdown event. With plant maintenance technicians blaming the shutdowns on component failures within the PWM drives, they removed the manufacturer from the plant's acceptable bidders' list.

Harmonic problems identified

Subsequent engineering analysis, however, proved that the shutdowns were due to accelerated aging and premature failure of PWM drive fuses. The fuse failures were linked to high voltage distortion levels on low-voltage busses that resulted in erratic drive operation.

A Square D Engineering Services team, led by Blane Leuschner, P.E., identified harmonic problems through onsite measurements and harmonic modeling using the Alternative Transients Program (ATP). ATP is a shareware program developed in Canada and similar to one developed by the Electric Power Research Institute. Using ATP, the team resolved the

problem by combining additional line impedance with the application of harmonic canceling techniques.

A Square D Powerlogic monitoring system comprising approximately 500 devices was already in place at the plant. That system was supplemented by temporary measurements with portable test equipment. Permanent electronic meters were located at main breakers in the plant's 480 V system. In addition to measuring about 200 power system parameters, these meters were capable of capturing simultaneous waveform data on each phase of voltage and current, with sample-rate resolution high enough to detect suspected power quality problems. In addition, portable versions of the same meters were installed temporarily at the input terminals of several drives.

Onsite testing showed that harmonic distortion at the low-voltage bus increased with increasing numbers of VFDs in operation, as expected. "Measurements showed that voltage distortion at the main buses approached 10 percent when normal levels of drives were operated," Leuschner said. "While this level of distortion exceeds the 5 percent total harmonic distortion (THD) level usually applied to low-voltage buses, it is below the THD level at which VFD problems are usually encountered."

Further onsite testing showed that VFDs currents measured at the drives were erratic and did not resemble the expected 2-pulses-per-half-cycle signature characteristic of PWM drives. The erratic current signature was unusual for a PWM signature and signaled an anomaly.

"The anomaly was high frequency harmonics, typically around 960 Hz, in the line currents," Leuschner said. "Analysis of computer simulations showed that the noncharacteristic current harmonics resulted from low circuit inductance and high voltage distortion due to the operation of VFDs on each bus." The high voltage distortion resulted in severe flat topping of line-line voltage, which limited the ability of the dc bus capacitors to charge. Low circuit inductance compounded the problem by permitting a high-rate-of-change in the VFD line currents.

Harmonics modeling and analysis

In order to analyze the system mechanisms at work in producing the unusual current distortion, the engineering team created an ATP computer model of the VFDs and a low-voltage power system. The simulation included a complex PWM model consisting of about 1000 circuit elements. Actual measurements provided the basis by which the team verified the computer model in order to ensure accuracy of the simulations and effectiveness of the solution

alternatives.

"Initially, we based our engineering analysis on the reports by plant technicians that GTOs had failed during each shutdown event," Leuschner said. "The earlier conclusion reached by the plant was inconsistent with later onsite measurements and computer simulations. Those measurements and simulations didn't expose a power system event anywhere close to damage levels on the GTOs in the inverter section."

In addition, the drive engineers determined that drive design prevented GTO failure from drawing enough current to blow an ac fuse. The engineers asserted that the GTO location in the drive was not getting enough available fault current due to upstream circuit components such as diodes, dc bus, etc. None of the empirical evidence could explain why GTOs would fail unexpectedly.

Consequently, the team turned its attention to the GTOs themselves. They set out to determine how the GTOs had been damaged and if the damage was corroborated by laboratory testing under more controlled conditions than existed in the field under emergency circumstances. "We found out that none of the condemned GTOs had been re-tested under laboratory conditions," Leuschner said. "Neither were the GTOs subjected to forensic investigation that might have revealed their mode of failure."

He recommended that such additional testing be done. Why, the plant argued, would additional testing be performed, when the GTO/fuse replacements had apparently fixed the problem and returned the affected drive to service? The team replied that the replacements were only a stopgap measure and that, without testing to determine a long-term solution, degradation and premature fuse failure would continue.

Laboratory testing

The plant subsequently authorized more testing, which located only five failed GTOs. Tests were performed under laboratory conditions by the plant and by Square D to determine the mode of failure. Test results showed that none of the five GTOs was damaged, thus confirming Leuschner's analysis and proving that the GTOs had been condemned by mistake.

The engineering analysis then turned to the drive fuses. These fuses had indeed opened during

the shutdown events—there was no question about that conclusion. With the GTO failure theory freshly debunked, plant engineers and Square D investigators wondered if the drive fuses might have been damaged during prolonged operation under erratic harmonic currents.

"Our team searched published articles on the subject in search of a precedent, but found none," Leuschner said. "Yet, evidence suggested that the substantial high frequency content and dramatic fluctuation in peak current magnitude of the drive currents subjected the fuse elements to abnormal stresses and resulted in accelerated aging." That theory was supported when Square D measured other circuits in the plant and found that no fuse failures had occurred on a circuit where drive operation was stable. Investigators used two 400 hp drives already equipped with line reactors—which constituted the majority of the circuit load—to confirm stability.

Solution options

Following detailed computer simulations of the VFDs and power system, the team issued its prescription. The report indicated a combination of line reactors and phase-shifting isolation transformers would provide the most cost-effective solution to the problem.

Other typical solutions, such as harmonic filters and hybrid filters at the main 480 V buses, were considered and eventually discarded. "The harmonic filter option, a typical solution of choice in such a situation, encountered a common dilemma when harmonic filters are being considered for transformers with a high percentage of VFDs," Leuschner said. He explained that conventional shunt filters contain capacitance that increases displacement power factor on the applied bus. VFDs, however, typically operate at high displacement power factor, while producing high levels of harmonic current. Many VFDs on a bus means high levels of capacitance that can result in leading displacement power factor and overvoltage.

Further, ATP modeling revealed that harmonic filters would not resolve the erratic drive current phenomenon. Low system inductance was the major factor contributing to that erratic drive current, yet harmonic filters would appreciably change system inductance. Low inductance allowed the dc filter capacitors inside the VFD to charge erratically, resulting in the noncharacteristic ac current.

Simulation identified the optimum simulated-voltage and current distortion reduction and proved that the best technical solution was to increase system inductance seen by the VFDs. While line reactors alone could provide this inductance, the investigators also modeled delta-wye transformers to assess additional benefits. "We knew that even though harmonic current passes

through line reactors and wye-wye or delta-delta transformers without appreciable phase shifting, delta-wye transformers have a different effect," Leuschner said. "Fifth and seventh harmonic components, which comprise a significant portion of VFD currents, are phase shifted by 30 deg of the fundamental by delta-wye transformers."

The resulting phase-shift of these two dominant harmonic components comprises currents that are 180 deg out of phase with fifth and seventh harmonics from nonphase-shifted drives. The combination of line reactors and delta-wye transformers contributed to significant cancellation of the aggregate fifth and seventh harmonic current contribution of all the drives.

Of the 66 drives in the paint house not already equipped with inductive isolation—four 400 hp drives had line reactors—only seven were equipped with delta-wye isolation transformers, while 50 received line reactors. Delta-wye transformers were reserved for VFDs with ratings of 200 hp and above, while 100 and 125 hp drives were provided with open-style reactors in the existing drive enclosure. Inductive isolation was not required on drives under 100 hp. Fuses that had not failed and had been replaced were changed due to suspected deterioration.

Results and conclusions

During its Christmastime shutdown, the plant implemented the recommendations for line reactors and delta-wye transformers. All equipment was installed and operating within a month. Bad, erratic voltage and waveforms were corrected into clean sinusoidal voltage and double-hump current waveforms. Harmonic voltage distortion was reduced to less than 5 percent. Drive currents returned to their normal signature.

"Our recommendations also identified the need for improved training of plant maintenance technicians," Leuschner said. "Much of the early confusion about the cause of the shutdowns could have been avoided by more accurate assessment during in situ testing of the GTOs." While the GTOs are difficult to test in situ, the plant implemented procedures to improve this testing, and to require that any electronic devices suspected of damage would be subjected to laboratory testing.

No further fuse failures have occurred since the modifications were completed, and the drivers' manufacturer was returned to the plant's acceptable bidders' list. **MT**

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