U. S. Department of Labor
Mine Safety and Health Administration
Office of Technical Support
Approval and Certification Center
Electrical Safety Division

Investigative Report

On

Variable Frequency Drives

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Abstract

An investigation was conducted to determine whether present day ground fault relaying systems located in outby power centers would detect grounded phase conditions occurring between a variable frequency drive (VFD) and a driven motor. Results of the investigation show that ground fault conditions occurring at one-sixth speed and below (i.e. less than 10 hertz) are not detected by standard 60-hertz ground fault detection systems presently utilized in underground mine power centers. An additional finding of the investigation is that the design of some VFDs produces as much as 480-milliamperes of grounding conductor current between the VFD and the driven motor.

To insure the safe use of variable frequency drives in underground mines the following is recommended:

1. Variable frequency drives should not be permitted in underground mines if the drive introduces more than 125-milliamperes of current onto the grounding conductor,
2. At all speeds throughout the drive operating range variable frequency drive circuits should be
   A. limited to a maximum 500-milliamperes of ground fault current,
   B. provided with ground fault protection set to trip at not more than 40% of the maximum available ground fault current or 125-milliamperes whichever is less, and
   C. provided with circuit interrupters that totally clear a ground fault condition on the circuit in less than 125-milliseconds,
3. Variable frequency drives should not be permitted to re-start when a ground fault condition exists on the circuit,
4. Regardless of phase voltage, circuits supplying power to variable frequency drive circuits should be provided with MSHA accepted ground wire monitors which insure that the frames of the motor and structure are limited to not more than 40-volts external to the neutral grounding resistor during ground fault conditions (e.g. a MAPS installation based on a continuity ground wire monitor), and
5. In addition to the above, all other MSHA regulations, policies, and procedures should be applied to variable frequency drive installations without regard to the system voltage or drive operating speed.

Purpose

The purpose of this investigation was to determine whether present day ground fault relaying systems located in out-by power centers would detect ground fault conditions occurring between a variable frequency drive and the driven motor.

Introduction

Title 30 Code of Federal Regulations (30CFR), Section 75.800 and 75.900 requires that three phase circuits in underground mines be protected with circuit breakers equipped with devices to provide protection against under-voltage, grounded phase, short circuit, and overcurrent. The circuit breaker must trip when any of these conditions occurs. The MSHA Program Policy Manual also states, "A high-voltage circuit extending underground shall be protected against the harmful effects of a grounded phase in the under-ground circuit and in any surface circuit supplied from the same set of transformer windings. Consequently, if one set of transformer windings supplies resistance-grounded power to both underground and surface loads, the circuit(s) extending to the surface loads must also be provided with grounded-phase protection. Fuses may be used to provide grounded-phase protection only for small control transformers installed in the same substation as the transformers that supply the resistance-grounded circuit. In all other cases, circuit breakers equipped with grounded-phase protective devices must be used to provide the required grounded-phase protection. Grounded-phase relays should be adjusted to operate on as low a value of current or voltage as practical. In order to provide safe, reliable relaying, settings should not exceed 50 percent of the maximum fault current for current relaying or 50 percent of the phase-to-neutral voltage for potential relaying.

The Coal Mine Safety and Health Electrical Supervisor's discussed a situation reported to Mr. Larry Cook, CMS&H District 4 Electrical Supervisor, by Mr. James Goble of Mining Controls, Incorporated during their quarterly meeting on June 23, 2001. The situation concerned the ability of ground fault relaying systems presently installed in underground power centers to correctly detect and trip in response to a ground fault condition occurring between a variable frequency drive and the driven motor. The Supervisors requested that A&CC investigate the situation.

Discussion

The investigation was initiated by examining the National Mine Safety and Health Academy's mine fan at the Mine Simulation Laboratory. The VFD controlling that fan is a Toshiba Tosvert-130G2/2+, Model 4110 to 420K. The fan is a three-phase 480-volt Model 66MPAV2R manufactured by Fan Systems Inc. The fan circuit ground fault relay is a standard off-the-shelf Pemco Corporation Model 21060, adjustable 2 to 4 amperes and set at 3 ½ amperes. It is designed to operate on 60-hertz power systems. Ground faults applied between the VFD and driven motor revealed three things:

1. The ground fault relay installed in the power center would trip in response to all ground faults at operating speeds above 10 hertz or one-sixth speed.
2. At operating speeds below 10 hertz, the ground fault relay would not trip.
3. Regardless of operating speed, the drive shut itself down each time a ground fault was applied and it could not be restarted until the fault was removed.

The test results indicate that some present day ground fault relaying systems lack the sensitivity to detect a low-level ground fault between a VFD and the driven motor. One explanation could be that the frequency response of the ground fault current transformer (CT). Tests show that today's ground fault systems provide their most effective performance at or near their designed 60-hertz frequency. The systems can be redesigned, however, to have greater sensitivity over a broader frequency range. This would improve the ability of the ground fault system to detect faults that occur between the VFD and the driven motor.

While researching the ground fault situation, it was found that the design of some VFDs produces ground current flowing in the grounding conductor between the VFD and the driven motor. Alan Martin of the Pennsylvania Bureau Of Deep Mine Safety reported that SMC Electrical Products had measured as much as 480-milliamperes on their 2300-volt drive. Because of the potential hazards of grounding conductor current, an effort was made to determine the extent of the current. It was decided that physical measurements would be conducted on as many drives as were available and that the amount of current flow would be measured at operating speeds of 6, 10, 15, 20, 25, 30, 40, 50 and 60 hertz. The measurements were made by recording the voltage developed across a 10-ampere 100-millivolt shunt installed in the grounding conductor. The recordings were made with a Tektronics Model THS730A portable storage digital oscilloscope.

After re-examining the Academy's VFD, a group of five questions was developed to provide critical information about a drive's performance. The questions were:

1. Is the drive protected by adequate circuit breakers provided with under-voltage, grounded phase, short circuit and overload protection, see 75.800? Is the drive resistance grounded, see 75.802?
2. What is the maximum current, i.e. the frequency, wave shape and amplitude, induced in the grounding conductor while operating at speeds of 6, 10, 15, 20, 25, 30, 40, 50, and 60 hertz at full load and no-load?
3. What is the maximum current, i.e. the frequency, wave shape and amplitude, induced in the grounding conductor while the drive is ramping up to speeds of 6, 10, 15, 20, 25, 30, 40, 50, and 60 hertz at full load and no-load?
4. What is the maximum current, i.e. the frequency, wave shape and amplitude, produced in the grounding conductor when the drive is ground faulted at operating at speeds of 6, 10, 15, 20, 25, 30, 40, 50, and 60 hertz at full load and no-load?
5. How does the drive react when the drive circuit has an existing ground fault and the drive is restarted or reset?

This investigator believes that ramping up to approximately 6 hertz is a vulnerable time for a VFD installed on a belt-drive, because it is this time when personnel are most likely to be on and around the belt-drive structure to conduct belt-splicing procedures. Following introductory phone calls, the questions were provided to:

Andy Barrett at Line Power Manufacturing Corporation,
Jim Goble at Mining Controls Incorporated,
Victor Kitts at Pemco Corporation,
Jon Beaver at SMC Electrical Products (SMC),
Randy Osburn of State Electric Supply Company,
Jim Burton of Rockwell Automation and
Bill Kephardt at Robicon Incorporated.

Jim Goble at Mining Controls Incorporated (MCI), Jon Beaver at SMC, and Bill Kephardt at Robicon Incorporated responded with information on the questions.

Following the introductory calls, Question No. 1 was omitted from the list because the units can be installed with or without these features. Jim Goble at MCI reported that MCI does not manufacture a variable frequency drive. Appointments were established to visit with SMC and Robicon to examine their drives.

A 2300-volt, 500HP drive designed and manufactured by SMC in Barboursville, WV was examined on July 8, 2002. With respect to question No. 2 the SMC unit has an inherent value of about 18 milliamps produced in the grounding conductor while running at all speeds listed. The ground fault trip point is set at 25 milliamps for speeds below about 44%. Above 44% the unit shifts to a 50-milliamp setting. The drive satisfactorily tripped at speeds of 10% and above when a ground fault was applied. However, the unit would start and ramp up to 10% speed if reset with an existing ground fault on any phase. On July 31, 2003, Mr. Beaver reported, "We trip at 25mA across the whole operating range now. A maximum of 18mA of leakage current is measured at any speed and Microdrive will not re-start when a grounded phase condition exists on the circuit. Microdrive also has both current and voltage ground fault protection."

On June 6, 2002, a visit was made to Robicon and a 1000HP, 4160V, Perfect Harmony drive was examined. This visit was not completely successful, because a six-pulse VFD powering a dynamometer brake produced such a large amount of harmonic noise, that the measurements required to answer the questions could not be isolated. One important part of the test result was that the Perfect Harmony drive could be adjusted such that it could not be re-started if a ground fault existed on any phase. The fault had to be cleared before the drive could be re-started. A second visit was made to Robicon on March 12, 2003. During this visit, a separate test arrangement was used and the test data was successfully recorded. A draw back to the visit was that this particular Perfect Harmony drive would ramp up to approximately 6 hertz or 10% speed before recognizing that a ground fault had not been cleared.

A visit was made to Zero Ground in Wausau, Wisconsin on October 29, 2002 to examine some Beta Site installations. Zero Ground claimed to have VFD installations where the grounding conductor current produced by the VFD was reduced to nearly zero (i.e. zero in the seventh place). The Beta Sites visited were installed on 480-volt automatic milking machines, cattle herding machines, etc. on dairy farms. An examination of two Beta Sites verified Zero Ground's claim of reducing grounding conductor currents to nearly zero.

It is well known that many components used in mining produce some current that is circulated on the grounding conductor. For example, as good as trailing cable designs are current flow in the phase conductors produces some amount of current flow in the grounding conductor which is unavoidable. This current can be reduced, but it has not been demonstrated that it can be eliminated. Some components actually place current onto the grounding conductor for the purpose of insuring a certain degree of safety is achieved. The ground wire monitor is an example of this type of device.

A search conducted to identify currents which are potentially harmful or lethal (Bernstein, 1985) revealed a proposed safe current limit of 500-milliamperes for shocks less than 200-milliseconds in duration. Safe in this case means that the current will not cause ventricular fibrillation of the heart muscle. In addition, it was found that a shock of approximately 10-milliamperes prevents a person from "letting go" of an offending source (Dalziel and Lee, 1968). It was also found that for frequencies up to 1000 hertz there is little difference in the physiological effects of the current amplitude which produces electrical shocks (Bernstein, 1985).

Based on research conducted, it was determined that the technology is available to design, manufacture and install VFDs in underground mines that are safe and meet MSHA regulations, policies, and procedures. Ground fault relay systems have successfully demonstrated the ability to trip without nuisance at current levels as low as 7 to 10 milliamps. Drives have also demonstrated the ability to recognize existing ground faults, to shut down in response to a ground fault and not re-start until an existing ground fault is cleared or removed. Although present testing has been limited to 480-volt three-phase VFDs with Zero Ground, it has been demonstrated that VFDs can be installed such that the inherent grounding conductor current produced can be reduced to zero in the seventh place. Mr. Robert Hopkins of Zero Ground reported that in his opinion, he did not see why the technology used to reduce the grounding conductor current to zero on the 480-volt drives could not successfully be extended to drives operating at 4160-volts with nearly identical results.

This investigator believes that, based on the technology available, some grounding conductor current is unavoidable. I also believe that the grounding conductor current can and should be minimized to reduce exposure limits. Because grounding conductor currents produced by VFDs can be lethal, it is recommended that reasonable safeguards be utilized to further minimize the potential of personnel becoming a part of the VFD grounding circuit. Based on observations and test results of Zero Ground's 480-volt VFD installations, it has been demonstrated that the technology is available to reduce the grounding conductor current produced by a VFD to less than a few milliamperes.

Recommendations

To insure the safe use of variable frequency drives in underground mines the following is recommended:

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2. At all speeds throughout the drive operating range variable frequency drive circuits should be
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