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Shaft Grounding—A Solution to Motor Bearing Currents

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ABSTRACT

Variable Frequency Drives induce shaft voltages onto the shaft of the driven motor because of the extremely high speed switching of the insulated gate bipolar transistors which produce the pulse width modulation used to control AC motors in heating, ventilation, air conditioning and refrigeration systems. This voltage induced on the shaft becomes great enough to overcome the dielectric of the oil film in the bearing causing bearing discharges known as electrical discharge machining effect. Unless mitigation for these shaft voltages is employed in the motor, the motor's bearings may become damaged from the electrical bearing currents which cause pitting and excessive bearing noise, fluting and finally motor failure. The cause of this problem and commonly applied mitigation methods are discussed as well as a new and highly effective conductive micro fiber shaft grounding ring technology which resolves these problems.

OVERVIEW OF VFD INDUCED BEARING CURRENTS

One of the fastest growing applications of pulse width modulation (PWM) variable frequency drive (VFD) inverters is in commercial and industrial heating, ventilation, air conditioning and refrigeration (HVAC/R) equipment. VFD's allow system designers to realize substantial energy savings and motor control capability provided by PWM drives. As the use of VFD's to control motors in air handlers, heaters, fans, blowers, pumps, air conditioning units, chillers and clean rooms has increased over the years, there has also been an increase in motor failure from bearing currents as the VFD's induce voltage onto the shaft of the driven motor which ultimately may cause pitting, fluting and finally bearing and motor failure.

This cause of motor failure has become an increasingly important reliability issue and the prevention of bearing failure in VFD driven motors an important design consideration to ensure motor reliability and to reduce operating costs. Technical articles and actual testing results show the severity of bearing damage that may occur in motors when drives are used – often in a relatively short period of time.

From its first minute of operation, a VFD induced destructive voltage is present on the motor shaft until an alternate discharge path, usually the motor's bearings, is found to discharge the voltage to ground. Inside the bearing, once voltage is sufficient to exceed the breakdown potential of the oil film layer, bearing currents cause an electrical discharge machining (EDM) effect which pits the bearing race and rolling elements. This destructive phenomenon continues until the motor bearings become so severely pitted that fluting such as that shown in Figure 1 occurs. This causes excessive vibration and noise in the motor, which may be audibly transmitted through the HVAC system ductwork. Finally motor failure occurs, sometimes in as little as only a few months.

CAUSES OF BEARING CURRENTS IN MOTORS DRIVEN BY VARIABLE FREQUENCY DRIVES

The root cause of bearing current discharges that damage motor bearings is the high speed switching from pulse width modulation (PWM) drives that use insulated gate bipolar transistors (IGBTs). Switching events may occur at a rate of over 12,000 Hz. The generated voltage pulses induce an AC voltage onto the motor shaft via parasitic capacitive coupling between the rotor shaft and the stator windings. This may even occur in a properly grounded and suitable electrically shielded motor [6]. Because the IGBT's fast rise time of only 50 ns or less, this

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capacitive coupling may cause the peak motor shaft voltage to reach as high as 60 volts, or higher in some cases, unless a discharge path exists. Typically, when the voltage reaches 20-30 volts or more, the oil film in the bearing breaks down and a discharge takes place. These discharge events occur continuously while the motor is operating, causing the electrical bearing damage to increase over time. This process is also known as electrical discharge machining (EDM) effect. This extremely fast bearing discharge, measured at around 40 ns, instantaneously heats and melts the surface of the bearing race and causes a small pit at the discharge point. Over time, the size of such pits can increase. It has been reported that the stray capacitive currents can generate shaft voltages in the following three different ways [8]:

1. High motor frame voltage due to common mode current return path circuit inductance. A well-grounded motor frame can minimize the motor frame voltage by employing auxiliary high frequency bonding connections for ground potential equalization.
2. High frequency axial shaft voltage induced by a circumferential magnetic flux around the motor shaft. This type of circulating currents can be interrupted with insulated sleeves or ceramic bearings. For motors less than 11 kW, it has been shown that no circulating bearing current flow occurs [9].
3. Coupling of Common Mode Voltage via bearing capacitance between the shaft and the motor frame and capacitance between the stator and rotor. This mechanism is considered as the most predominant factor in bearing failures when the motor frame is adequately grounded [4]. Bearing currents caused by stator-to-rotor capacitive coupling must be diverted from the motor shaft by providing a least resistance path to ground other than the bearings themselves. Ceramic bearings or insulated sleeves around the bearing stator break the electrical current path through the bearings, but in many cases cannot protect the bearings of connected equipment.

VFD INDUCED BEARING CURRENT IDENTIFICATION TECHNIQUES

Serious electrical bearing damage may exist whenever high frequency drives are used to control electric motors. The severity of the bearing damage will vary depending on the grounding of the drive and the motor and the mitigation techniques used in the system. These stray capacitive currents find their way through the path of least resistance, usually the bearings. It is however impractical to measure the actual bearing currents in motors in real world operational environments because of the physical design of motors and lack of access to the bearing current discharge path. A much more practical approach is to measure shaft voltages by applying an oscilloscope probe to the motor shaft. The ground lead of the probe is connected to the motor frame. The other lead of the probe is connected to the center of the rotating shaft via a heavy gage copper wire. The length of the copper wire should be as short as possible to minimize the effect of radiated signals from the inverter power lines. The voltage signals from an oscilloscope can be obtained with different time scales to understand the bearing discharges. The shape of the voltage on the oscilloscope shows the more gradual voltage rise times of the capacitively induced voltages and the sharp discharge times associated with bearing discharges. Figure 2 shows a typical motor shaft voltage measured at 1800 rpm.

Note that bearing voltage discharges occur at the sharp voltage drops of the voltage waveform in Figure 2. This indicates a corresponding current flow (EDM current) in the bearing. If a high frequency oscilloscope is not available, a common digital voltmeter may be used to check for the presence of the bearing currents. Although the use of the voltmeter is neither accurate nor scientific, the voltage value change has some relationship between the shaft voltage and the result-

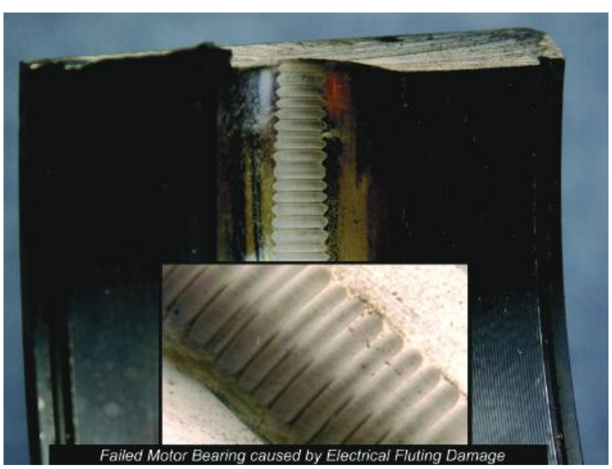

Figure 1 *Fluted bearing from VFD induced electrical bearing current discharges.*

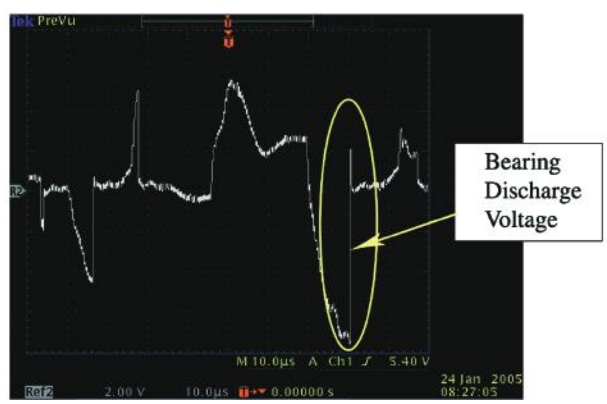

Figure 2 *A typical Shaft Voltage measured on a one horsepower motor, 460V, 3 phase, 1800 rpm with no protection. The measurement was taken after running one year continuously.*

ing bearing currents and will indicate the presence of bearing currents.

STRATEGIES FOR MITIGATING VFD INDUCED SHAFT VOLTAGES IN MOTORS

Numerous papers have been published by both motor manufacturers and drive manufacturers about this subject in the last several years to understand the causes of bearing currents in PWM driven electric motors and to find a solution to eliminate the electrical bearing damage [1-4]. Many solutions have been proposed, however, no technique to date is either practical or effective in solving the bearing current problem in the long term. Some solutions are narrow in scope or application and most are costly. Many are not technically feasible.

As demonstrated above, electrical damage to the bearings of VFD controlled motors can build over time. In these cases the bearings eventually deteriorate to the point of failure. To prevent such damage in the first place, the induced shaft current must be kept from discharging through the bearings by insulation and/or providing and an alternate path to ground:

1. Insulation: Insulating motor bearings may be accomplished by either adding an insulating material to the bearing race or bearing journal such as an insulating sleeve or ceramic coating or using ceramic ball bearings. This solution tends to shift the problem elsewhere as shaft current looks for another path to ground. Sometimes when ceramic coatings are used, because of the capacitive effect of the ceramic insulation, high-frequency VFD-induced currents actually pass through the insulating layer and may cause electrical bearing discharges and eventually failure. Also, when an insulation method of the motor bearing is used, directly coupled attached equipment, such as a pump or encoder may provides a path to ground. Then, the other equipment often winds up with bearing damage of its own. Finally, insulation and other bearing-isolation strategies may be costly to implement, may result in special motor modification, and may be only partially effective.

2. Alternate discharge paths: When properly implemented, a conductive link is established between the rotor and stator, usually in the form of a brush. These strategies are preferable to insulation because they provide an alternate discharge path for the shaft voltages and prevent bearing currents. Techniques range in cost and sometimes can only be applied selectively, depending on motor size or application. The ideal solution would provide a very-low-resistance path from shaft to frame, would be low-cost, and could be broadly applied across all VFD/AC motor applications, affording the greatest degree of bearing protection and maximum return on investment.

There are a number of technologies now available to protect AC motor bearings from damage due to shaft currents, few meet all the criteria of effectiveness, low cost, and application versatility:

1. **Faraday shield:** A conductive shield between the rotor and stator inside the motor would prevent the VFD current from being induced onto the shaft by effectively blocking it with a capacitive barrier. However, this solution is extremely difficult to implement, very expensive, and has been generally abandoned as a practical solution.
2. **Insulated bearings:** Insulating material, usually a nonconductive resin or ceramic layer, isolates the bearings and prevents shaft current from discharging through them to the frame. This forces current to seek another path to ground, such as through an attached pump or tachometer or even the load. Due to the high cost of insulating the bearing journals, this solution is generally limited to larger-sized NEMA and IEC motors. Sometimes, high-frequency VFD-induced currents may be capacitively coupled through the insulating layer and cause bearing damage inside the bearing anyway. Another drawback is the potential for contaminated insulation, which can, over time, establish a current path around the insulation, allowing current flow through the bearings.
3. **Ceramic bearings:** The use of nonconductive ceramic balls prevents the discharge of shaft current through the bearing. As with other isolation measures, shaft current will seek an alternate path to ground possibly through equipment connected to the motor. Such Bearings are very costly and, in most cases, motors with ceramic bearings must be special ordered and so have long lead times. In addition, because ceramic bearings and steel bearings differ in compressive strength, ceramic bearings must be resized in most cases to handle mechanical static and dynamic loadings.
4. **Conductive grease:** In theory, because this grease contains conductive particles, it should provide a continuous path through the bearing and so bleed off shaft voltages gradually through the bearing without causing a damaging discharge. Unfortunately, the conductive particles in these lubricants may increase mechanical wear into the bearing, rendering the lubricants ineffective and often causing premature failures. This method has been widely abandoned as a viable solution to bearing currents.
5. **Grounding brush:** A metal brush contacting the motor shaft is a more practical and economical way to provide a low-impedance path to ground, especially for larger frame motors. However, these brushes pose several problems of their own: a. They are subject to wear because of the mechanical contact with the shaft. b. They collect contaminants on their metal bristles, which may reduce their effectiveness. c. They are subject to oxidation buildup, which decreases their grounding effectiveness. d. They require maintenance on a regular basis, increasing their lifetime cost. Most grounding brushes are installed externally to the motor and require extra space and special mechanical design considerations for the

brush mounting. Contact grounding brushes are also subject to severe wear and contamination if installed externally. They also generate high heat at high speeds. It is not suitable to use contact grounding brushes for applications requiring more than 1800 rpm. Their effectiveness may be reduced significantly over a short period of time due to vibration of the brush mounting spring and oxidation of the shaft surface. As a result, such brushes require frequent maintenance. In most applications, the contact brush may often be serviced when the bearings are replaced due to failure. In case of high frequency circulating currents in larger frame motors, it is also important to note that a single contact grounding brush may worsen the bearing current discharge at the bearing location opposite of the grounding brush. This situation forces the use of two grounding brushes on the motor; one on the drive-end and one on the non-drive end. Alternately, one grounding brush may be applied on the drive end when one insulated bearing with a grounding brush on the drive-end.

6. **Shaft grounding ring (SGR):** Applied like a conventional grounding brush, this innovative new approach involves the use of a ring of specially engineered conductive micro fibers to redirect shaft current and provide a reliable, very low impedance path from shaft to the frame of the motor, bypassing the motor bearings entirely. The ring's patented technology uses the principles of ionization to boost the electron-transfer rate and promote extremely efficient discharge of the high-frequency shaft voltages induced by VFDs. With hundreds of thousands of discharge points, the SGR channels currents around the motor bearings and protects them from electrical damage. The SGR is a low-cost solution that can be applied to virtually any size AC motor in virtually any VFD application.

Grounding the motor shaft is commonly used method due to its simplicity and the relatively low cost of the electrical contact brushes. The idea of the grounding the motor shaft is to provide a lower impedance path to the motor frame than through the bearings. This lower impedance path may be established with the shaft grounding ring.

To improve the contact grounding brush performance in the shaft grounding ring, the brush wire material has been replaced with micro-diameter conductive fibers [22]. Figure 3 and Figure 4 show a conductive micro-fiber shaft grounding ring brush and a motor with the micro-fiber shaft grounding ring installed on the drive-end of the motor shaft, respectively. The micro-fibers surround the motor shaft completely to provide full contact with the shaft thereby minimizing the effect of the motor shaft eccentricity or vibration. Micro-fibers in the shaft grounding ring are not spring-loaded on the motor shaft while most contact grounding brushes are spring-loaded. The micro-fiber brushes are either press-fitted into the housing or mounted on the motor faceplate with two small screws.

This micro-fiber brush construction provides several advantages over the spring-loaded contact brushes. First, the wear rate of micro-fibers is very low, due to an insignificant force between the light weight micro-fibers and the shaft. As a result the heat generation of the fibers during operation is negligible, at even high rotating speeds. Tests at up to 14,000 rpm for 3000 hours have shown negligible wear indicating much longer life at the lower rotating speeds found in HVAC applications. Micro-fiber brushes are said to have no speed limitation [29]. Second, the current limits of micro-fibers are in general much higher than that of a conventional brushes or a solid carbon brush since micro-fibers can provide a large real contact area on a sliding surface, thereby greatly improving the efficiency of shaft voltage discharges. Third, the micro-fibers create a corona discharge at the tip of the fibers when the fibers are over a charged surface. Recent hard-disc manufacturer reports that currents can flow to a small diameter point without an intimate contact even though the surface voltage is

Figure 3 *Shaft grounding ring.*

Figure 4 *Shaft grounding ring installed on motor.*

less than 1 volt under a special circumstance [23]. Since the corona discharge is through the air molecules, the discharge can also take place in the media of water or dirty grease. This current transfer mechanism due to electrolysis or ionization of a surrounding medium allows the micro-fiber brush to be maintenance-free for the life of a motor, even when the shaft has oil or grease on it.

As with the application of conventional grounding brushes, motors susceptible to high frequency circulating currents, motors larger than 200 HP (150 kw), it may be necessary to install two micro-fiber brushes on both ends of the motor to solve both the circulating currents and capacitive coupled currents. Unlike insulating bearing methods, two micro-fiber brushes can divert the harmful bearing currents from the bearings safely to the motor frame and prevent shaft voltages from discharging through other connected equipment.

Figure 5 shows typical motor shaft voltage waveforms for both an unprotected motor and a motor installed with a micro-fiber brush. The waveforms were obtained after testing motors for one year continuously. As can be seen, the discharge voltage for the motor with the micro-fiber brush is much lower than for the motor without the brush. With the micro-fiber brush, most of the motor shaft current discharge takes place at the tips of micro fibers instead of taking place on the bearing surfaces. A test was carried out to verify the effect of the micro fibers shaft grounding ring, as shown in Figure 6. Figure 6 shows that there were no measurable bearing currents through bearings while there were shaft voltages of 7 volts peak when the micro-fiber brush was installed. The shaft currents were diverted to the micro- fiber brush instead of the bearing surface.

A long-term test was carried out to verify the effectiveness of micro-fiber brush. After running for one year, the vibration and sound levels were recorded with the motors with a micro-fiber brush. The one year endurance test revealed that the motors with a micro-fiber brush did not increase the levels of motor noise and vibration beyond the levels experience by a motor connected to sine-wave utility voltage. The micro-fiber brush does not eliminate the bearing current because of an occasional low impedance value between the bearing balls and bearing races, but it does provide significant reduction in the magnitude of bearing current and prevent the bearing from developing harmful fluting.

CONCLUSION

As the use of variable frequency drives (VFD) to control motors in air handlers, heaters, fans, blowers, pumps, air conditioning units, chillers and clean rooms has increased over the years, there has also been an increase in motor failures from bearing currents. These motor bearings are in danger of electrical discharge machining (EDM) effect and high frequency circulating bearing currents. The degree of the electrical damage in motors controlled by VFD is much greater than the degree that motors have ever experienced before. This potential electrical damage to the bearings must be mitigated to ensure long service life of a motor driven by the PWM VFD. The bearing current problem is considered as the most significant remaining reliability issue or inverter driven motors that needs to be solved to achieve vibration and noise control and eliminate premature motor failure. Bearing protection technologies and their respective advantages and disadvantages

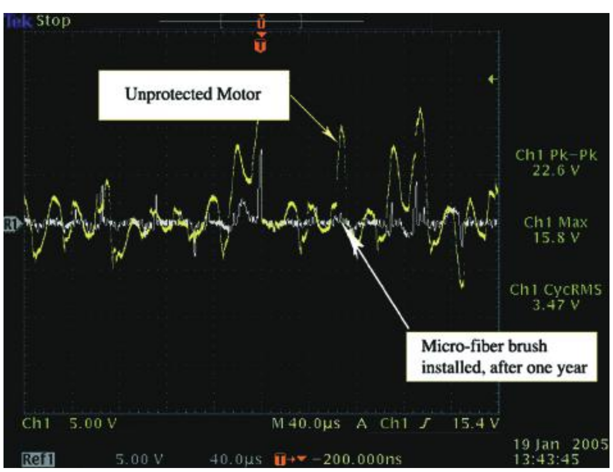

Figure 5 *Comparison of shaft voltages of unprotected motor and the motor protected with micro-fiber brush after one year of continuous testing. 1500 RPM, 1HP Motor, 8 kHz carrier frequency, 460 Volts, 3 phase, PWM inverter was used. Motor and inverter were grounded.*

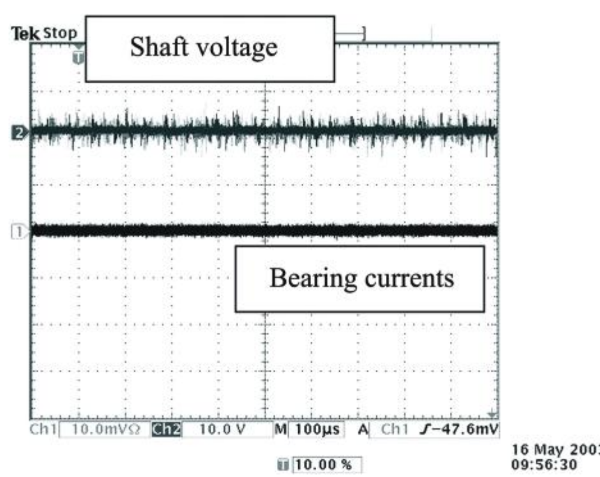

Figure 6 *Motor shaft voltage and bearing currents. Bearings were isolated to measure an accurate current flow. The micro-fiber brush was installed on the bearing cover. Test motor = 5HP motor, 460 V, 3 phase.*

should be considered to ensure the goals of reliability, long service life, and maintenance free operation are met when designing systems that use variable frequency drives to control AC induction motors.

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DISCUSSION

Christopher F. Benson, Student in Electrical Engineering, University of Utah, Salt Lake City, UT: Can the elimination of bearing currents or shaft currents improve the load balance?

H. William. Oh: I do not think that the load balance will change by elimination of bearing currents. However, the elimination of the bearing currents may reduce the EMI/RFI that may be generated by the current discharge in the bearing.