Are Bearing Currents Causing Your Motor Failures?

"We just lost another motor! Why are all of our motors failing?" Does this sound familiar? If you're at a loss to explain why your motors seem to experience premature failure one after another, take a step back and look at the big picture. Are all of the motors that have failed being controlled by variable frequency drives? If so, you may be experiencing the detrimental effects of shaft voltage resulting in bearing current.

What are they, why do they cause premature motor bearing failure, and how can you protect against them? To answer these questions, we first need to understand how variable frequency drives (VFDs, ADSs, or inverters) operate.

VFD Operation

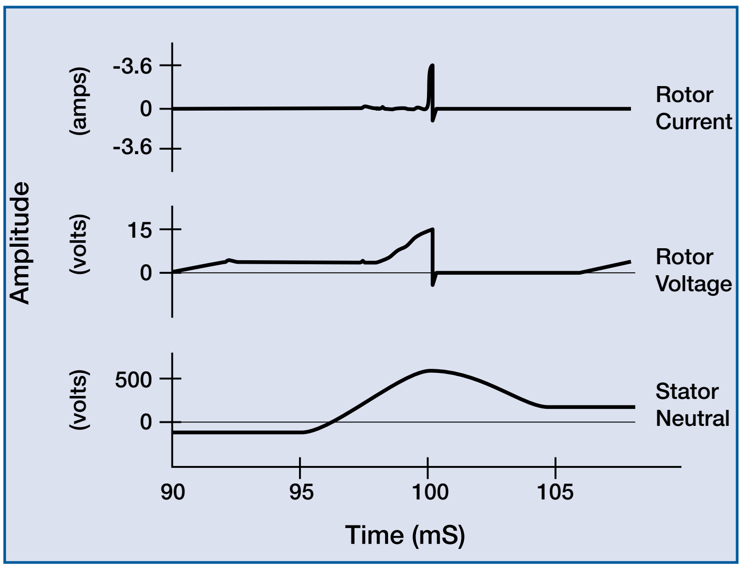
VFDs regulate the speed of a motor by converting sinusoidal line AC voltage to DC voltage, then back to a pulse width modulated (PWM) AC voltage of variable frequency. The switching frequency of these pulses ranges from 1 kHz up to 20 kHz and is referred to as the "carrier frequency." The ratio of change of the $\Delta V/\Delta T$ creates a parasitic capacitance between the motor stator and the rotor, which induces a voltage on the rotor shaft. If this voltage, referred to as "common mode voltage" or "shaft voltage," builds up to a sufficient level, it can discharge to ground through the bearings. Current that finds its way to ground through the motor bearings in this manner is called "bearing current."

Let's examine how this condition develops, and what physically happens to the bearing as a result.

Bearing Damage

It should be noted that one of the major causes of bearing current results from voltage pulse overshoot created by the fast-switching IGBT (insulated gate bipolar transistor) in the VFD. We will discuss this phenomenon in the context of this publication. Other sources of shaft voltage include non-symmetry of the motor's magnetic circuit, supply unbalances, transient conditions, and others. Any of these conditions can occur independently or simultaneously to create bearing currents.

Shaft voltage accumulates on the rotor until



Example of voltage - current relationship

it exceeds the dielectric capacity of the motor bearing lubricant, then the voltage discharges in a short pulse to ground through the bearing. After discharge, the voltage again accumulates on the shaft and the cycle repeats itself.

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This random and frequent discharging has an electric discharge machining (EDM) effect, causing pitting of the bearing's rolling elements and raceways. Initially, these discharges create a "frosted" or "sandblasted" effect, and usually the first symptom of bearing current damage is the audible noise created by the rolling elements riding over these pits in the bearing race. Over time, this deterioration causes a groove pattern in the bearing race called "fluting" which is a sign that the bearing

Bearing Fluting

has sustained severe damage. Eventually, the deterioration will lead to complete bearing failure.

Problem Prediction

VFD-induced shaft voltage can exist in every VFD-driven motor application. It is not specific to the air movement industry, nor is it specific to any particular manufacturer's motors, drives or equipment. However, shaft voltage only becomes a problem when it leads to bearing current and consequential damage to the motor bearings. How can you determine if your motor bearings are at risk? The truth is that the phenomenon of shaft voltages and bearing currents is well understood and well documented, but it is also somewhat rare and unpredictable.

The National Electrical Manufacturers Association (NEMA) Publication MG 1 Section IV "Performance Standards Applying to All Machines," Part 31 "Definite-Purpose Inverter-Fed Polyphase Motors" is the industry-accepted standard for defining what we call a VFD compatible motor. This standard addresses, in part, the motor's capability with respect to temperature, torque, insulation, and operating limitations (excess current, line voltage, across-the-line starting, etc). It also addresses "shaft voltages that can result in the flow of destructive currents through motor bearings," but concludes with the following statement:

"At this time, there has been no conclusive study that has served to quantify the relationship of peak voltage from inverter operation to bearing life or failure. There is also no standard method for measuring this voltage. Because of this, the potential for problems cannot consistently be determined in advance of motor installation."

Because of the phenomenon's rarity and unpredictability, most manufacturers do not include warnings or recommendations in their literature or operation & maintenance manuals.

Contributing Factors

Amidst the unpredictable cases of bearing current damage, industry experts have identified some things that exacerbate the occurrence and promote damaging effects:

High carrier frequency
The higher the carrier frequency, the higher the rate of the current discharge pulses, or the more rapid the damage caused by EDM will occur. At higher carrier frequencies the VFD will generally run quieter, however, it becomes more destructive on the motor insulation and bearings.

Most experts recommend that the carrier frequency be adjusted as low as possible without creating unacceptable audible noise levels, and to avoid frequencies above 6 kHz altogether. Accordingly, it is generally a good idea to specify and install a VFD that has an adjustable carrier frequency by relatively small increments (i.e. by 1 kHz increments) to allow for fine-tuning to the lowest acceptable level.

Constant speed operation
Some industry experts believe that constant speed operation increases the risk of bearing current damage. Interestingly, the first well-known cases of bearing current damage were in clean room applications, in which VFDs controlled fan motors are used to maintain a constant airflow. However, there have been many cases of bearing current damage reported in air handling and other industry applications in which the equipment is not operating at a constant speed. While motor bearings operating

at a constant speed are indeed more susceptible to DM damage, motors that are in variable speed duties are certainly not immune.

Inadequate grounding
One of the largest potential causes of motor bearing damage due to bearing currents is inadequate grounding, especially at high operating frequencies. The challenge is to provide a low impedance ground path for the voltage to flow to earth ground without passing through the motor bearings or other components. Proper grounding is especially critical on the motor frame, between the motor and the VFD, and from the VFD to earth.

Problem Identification

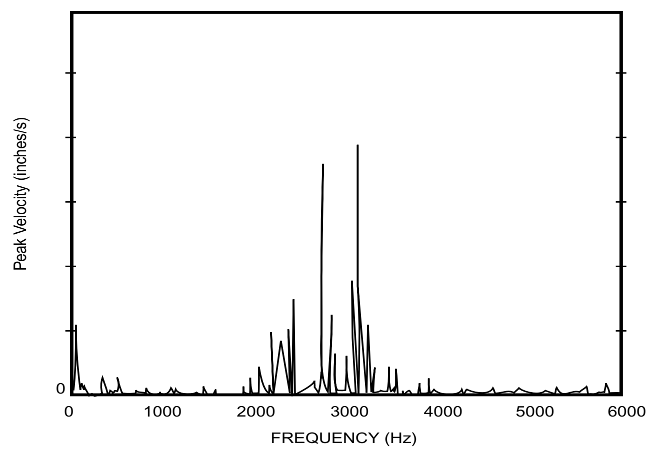
As stated earlier, the first symptom of bearing current damage is often the audible bearing noise. Unfortunately, by the time the bearing noise is apparent, EDM damage has already occurred and deterioration has developed to the point that complete bearing failure is probably not far behind.

Currently, there are two common non-destructive methods used in the industry to detect bearing currents and bearing current damage: vibration analysis, and shaft-to-ground voltage & current analysis. While both can be implemented to either confirm or deny bearing current suspicions, owners are better served by incorporating these methods to establish a baseline and monitor trends. This can provide early detection of possible problems. It can also verify whether or not any installed protection methods are effective.

It is important to understand that both of these test methods require very specialized equipment and experienced people to operate the equipment and analyze the data.

Vibration analysis
Vibration analysis can be useful in confirming the existence of bearing fluting damage caused by EDM. The high frequency, high resolution spectrum of a bearing in the early stages of fluting damage will exhibit a "mound" of energy in the 2-4 kHz frequency range. As EDM damage continues and bearing degradation progresses, the fault energy spikes will migrate into regular bearing fault frequencies. Continuous monitoring of the vibration levels starting shortly after initial installation and start-up can provide important indications of increasing or changing energy spikes.

Voltage analysis
Measuring the actual voltage and current present on the shaft can be helpful in determining the likelihood of damage from EDM. However, since all motors have some level of voltage, one must determine at what levels is cause for alarm. Unfortunately, there is no magic number that tells whether or not a motor is "safe" from EDM damage. For one thing, there are many variables that can



Example of vibration spectrum showing "Bearing Fluting"

affect the measured data, i.e., bearing lubrication, measurement equipment & method, running speed, etc. Additionally, this method of predicting EDM damage is not an exact science. Different experts have different opinions of "safe" levels depending on their individual experiences. Many experts, however, agree that trending this data can be most helpful in identifying deviations that can indicate the beginning of a problem, the worsening of an existing problem, or the failure of an EDM protection method.

Methods of Protection

Now that we understand how bearing currents are generated and what they can do to your motor bearings, as well as a couple of ways to determine whether or not there may be a problem, you're probably wondering how you can protect your motors.

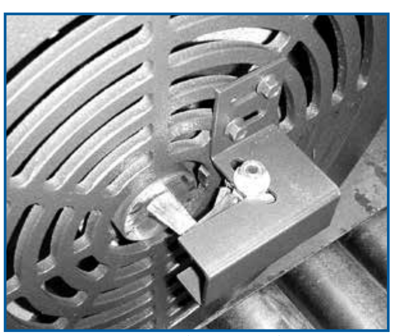
Protecting motor bearings from an unpredictable occurrence of bearing currents is not an exact science, but rather a process of risk assessment and cost analysis. There are certain measures you can take in order to reduce the risks — but not without additional cost. Since the occurrences are unpredictable, one has to weigh the cost of protection against the costs in the event that the problem was to arise.

For example, installing a shaft grounding assembly in each of 15 direct-coupled fans with 100-HP motors would be much cheaper than replacing those 15 motors three months after start-up. On the other hand, replacing 15 smaller 3-HP motors would be much less expensive, so waiving the extra cost of shaft grounding assemblies might be an acceptable risk.

If protection is warranted, the following recommendations are a few of the most frequent that have been used successfully in various industries and applications.

Shielded cable
High frequency grounding can be significantly improved by installing shielded cable with an extremely low impedance path between the VFD and the motor. One popular such cable type is continuous corrugated aluminum sheath cable. There are some new third party grounding kits that are just now becoming available to install as part of the whole system. Early testing and patent applications of such kits claim to eliminate common mode voltage from the system altogether.

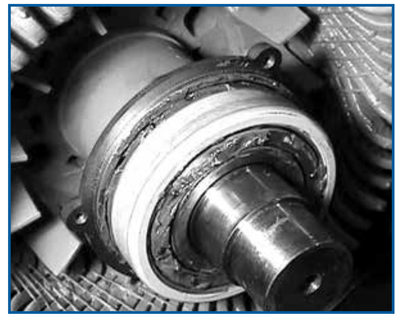
Shaft grounding
Grounding the shaft by installing a grounding device provides an alternate low-impedance path from the motor shaft to the motor case. This effectively channels the current away from the bearings. It significantly reduces shaft voltage, and therefore bearing current, by not allowing voltage to build up on the rotor.



Grounding Brush

One of the more popular shaft grounding devices is a grounding brush. Grounding brushes can be custom fit to virtually any motor shaft, and can also be retrofit to existing installations. They do, however, require replacement every few years depending on the shaft rotating speed, brush tension, and motor duty.

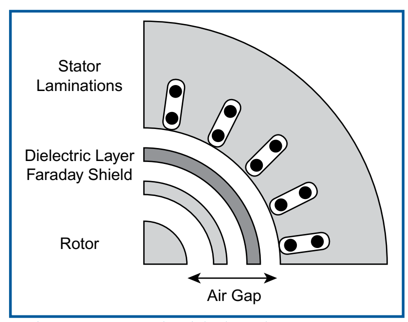
Insulated bearings
Insulated bearings eliminate the path to ground through the bearing for current to flow. But, installing insulated bearings does not eliminate the shaft voltage, which will still find the lowest impedance path to ground. This can potentially cause a problem if the path happens to be through the driven load or through some other component.



Insulated Bearing

In order to direct the shaft voltage to ground through an acceptable path, one could install a shaft-grounding device in addition to the insulated bearings. Obviously this combination is better than one or the other independently, but at a much higher cost. Again, careful risk and cost analysis can help determine the extent of protection most appropriate for your situation. Insulated bearings tend to be rather expensive, and usually have substantial lead–times from suppliers.

Faraday Shield
Placing grounded conductive material, such as copper foil tape or copper paint, in-between the rotor and the stator creates a Faraday Shield, resulting in an electrostatic shielded induction motor (ESIM). This method reduces the capacitively coupled currents crossing the motor air gap, minimizing the motor shaft voltage. One drawback to the Faraday shield is that the construction methods to obtain the desired benefits are very precise, which result in a higher cost motor.



Electrostatic Shielded Induction Motor (ESIM) with Faraday shield

Responsibility

Naturally, nobody wants to pay for repairs that follow damaging bearing currents if and when they do occur. And, spending extra money on protection methods for a problem that may or may not exist may be difficult to swallow in these days of tight budget considerations. Determining exactly where those responsibilities lie has been the topic of countless heated debates, many of which have resulted in costly litigation to settle the responsibility and cost issues.

After EDM damage occurs, some people contend that associated repairs fall within the jurisdiction of the motor warranty, while others claim that it's a warranty issue with the VFD manufacturer. To the contrary, it should not be considered as a warranty issue at all. A warranty claim implies a defect in material or workmanship. Bearing current damage can, and has, occurred in systems in which both the motors and drives were without defect.

During the early stages of a project, deciding if and how to implement protection methods is the ultimate responsibility of the owner. However, the system designers, engineers, equipment suppliers, and other players in the project are responsible for providing the owner with accurate and reliable information upon which an informed decision can be made.

Clearly, installing both the VFD and the motor from the same manufacturer narrows the number of parties involved, which would certainly make a responsibility debate easier; however, it does not necessarily prevent the situation from occurring in the first place. There are many factors outside the two individual components that can cause or promote bearing currents. For this reason, assigning ultimate accountability for a motor and VFD problem is difficult.

Recommendations

The best way to protect yourself and your equipment is to understand the causes and effects of EDM damage in order to make informed decisions during the specification, requisition and installation stages. While there is no magic recipe to follow, in this article we offer some guidelines that at the very least will bring these issues to light for discussion and consideration.

Recommendations and Guidelines

For…	Recommendation:	Notes:
Every VFD Application	Set carrier frequency <6kHz	The lower the carrier frequency the better
	Specify VFD model with carrier frequency adjustability increments no larger than 1kHz	Fine tune to the lowest acceptable level
	Shortest possible conductor lengths	Reduces reflected wave current
	Shielded cable with continuous low-impedance ground path from the VFD to the motor	Various third-party grounding systems are emerging in the market
< 25 HP motor	Shaft grounding device	Some protection - requires maintenance
25 HP & larger motor	Insulated motor bearings or ESIM	Higher level of protection
Long lead conductor	Inductive or RCL filter	Has to be individually tuned to the application
Difficult access to motor	Insulated motor bearings or ESIM	Higher level of protection - avoid high labor motor
Motor bearing failure despite protection	Voltage analysis to locate damaging current loops	Specialized equipment & personnel required
Noisy motor bearing operation	Vibration analysis to look for signs of EDM in motor bearings	Specialized equipment & personnel required
Failed motor bearing removed from motor	Inspect motor bearing races for signs of pitting or "fluting"	Qualified motor service technician required

Conclusion

In contemplating these and others' recommendations, it is important to carefully consider the entire system and all of the possible current paths. This is important both in trying to predict where problems would be most likely to occur, as well as identifying and correcting existing trouble areas.

Damaging bearing currents can occur in any VFD–controlled motor application, and will eventually cause catastrophic motor bearing failure. The motor bearings are damaged when accumulated shaft voltage discharges through the bearing causing an EDM effect. When and where bearing currents will become a problem is still unpredictable, although things such as high carrier frequency, constant speed operation and inadequate grounding can increase the risk and accelerate damage.

Suspicions of EDM damage can be verified by special vibration analysis techniques. Determining the likelihood of EDM damage in an existing application can be assisted by special voltage analysis to find possibly damaging current loops.

If bearing currents are a problem in your installation, or if the calculated risks are high enough, you can protect your equipment by using one of several methods, either independently or in combination. The most popular and successful methods include shaft grounding devices, insulated bearings, and Faraday shields.

Determining whether or not protection is warranted and determining the appropriate methods of protection is a shared responsibility based on cost analysis and risk assessment. Educating ourselves and each other about the cause, effect and protection of bearing currents is the best line of defense.

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