Increased Reports of Bearing Damage in AC Motors Operating from Modern PWM VFD's

Repair shops and motor manufacturers are seeing an increased number of instances where bearings and connected equipment are being damaged by electrical current flow. The failure rate is thought to be small, relative to the total number of motors sold, but the frequency of failures is growing as more users install modern type PWM VFD's. Since there are numerous industry papers available that discuss the details of problems caused by PWM VFD's, this paper will focus on a more general discussion of the causes, analysis and possible solutions.

History

Bearings' being damaged by electrical current is not a new failure mode, but the risk factors for past failures were limited to large motors operating on sine wave power, unique motor designs that required a non-symmetrical magnetic circuit or an unbalanced supply voltage. Manufacturers and users understood the possible causes of this failure mode and had specifications in place that defined when proper precautions were justified to avoid field failures. Since the source of more recent bearing failures is related to PWM waveforms and specific site installation factors, these customary precautions are no longer effective in consistently preventing damage caused by current flowing through the bearing(s).

PWM Power Has No Defined Limits:

One important fact that contributes to the difficulty in predicting a potential VFD related bearing current condition is the lack of an industry standard for acceptable PWM waveform profiles. Unlike sine wave power, that has well defined parameters used in evaluating and predicting circuit response, a modern PWM type power source has unknown profiles that can vary without any visual indicators. Each brand of VFD, each power rating inside a brand and each operating load point can have different PWM waveform profiles that can impact the proper operation of an entire system. The use of dynamic pulse adjustment and the lack of standardization for PWM power are major factors that make analyzing and predicting PWM related bearing failures extremely difficult. Unlike older PWM VFD's, the high frequency waveform components and common mode voltage conditions caused by modern VFD's must be addressed by the system integrator and system designer.

VFD Technical Guidelines In Print:

VFD manufacturers have some concept of the possible impact that PWM waveforms can have on an installed system and normally provide important guidelines in their printed manuals. Information on how output filter options may be desirable, how special motor wiring considerations should be followed and the importance of proper motor grounding methods are all normally covered in their printed material. Unfortunately, locating this information will normally require careful study of a huge manual and seldom gets pointed out in detail prior to a sale. Many VFD manufacturers have a list of installation recommendations that they will provide upon request to help minimize PWM related problems, but the burden of asking is left with the system designer or user. Due to the purchasing process, not all specifying engineers and users are aware that PWM installation related issues (including bearing currents and common mode voltage) are possible and fail to include the VFD manufacturer's recommendations as part of their specification. Output filter options designed for a specific brand of PWM VFD, recommendations for special PWM cable from the VFD to the motor, recommendations for proper conduit installation between the motor and VFD and the recommendation of adding an insulated bearing and shaft grounding device to the motor are typical examples of what may be included on the recommendation list.

VFD System Specification:

The VFD manufacturer should be contacted early in the specifying process so proper motor, cabling and VFD options can be specified to help minimize or eliminate potential causes of field related PWM waveform problems. One VFD manufacturer has now introduced a new 3-level PWM switching topology to address the source of the bearing current problem and avoid the need to add external components to treat the symptoms. Other drive manufacturers promote correcting the problem at the source adds too much cost to the VFD and feel this approach is less desirable than users adding external component costs on a case-by-case basis. This approach of "treating the symptom" requires the specifying engineer or user to assess their installation and determine if it is better to correct the problem with a filter at the VFD or try to control the symptoms with add-ons throughout the rest of the system. In many instances, the cost associated with an unscheduled shutdown and system repair can greatly exceed the combined costs of the VFD output filter(s) and external system add-ons (special output cable, insulated bearing and shaft grounding system).

Why Specifying "Inverter Duty" Doesn't Automatically Address Bearing Problems:

Currently, the National Electrical Manufacturers Association (NEMA) provides guidelines that can be incorporated into motors intended for use as inverter-fed motors. NEMA MG1 part 30 and part 31 lists performance levels that can be expected to be acceptable for different levels of motor designs when used on adjustable-voltage and adjustable-frequency controls. As can be seen from the NEMA MG1 standard, the products are not specifically identified as "Inverter Duty" motors. The term "Inverter Duty" motor has no standard definition or specification in the industry because each VFD application and installation can have many different variables. Current VFD designs and installation factors have reached a threshold where an increasing number of installations can not achieve acceptable levels of reliability without the addition of optional protective features. The complexities of potential field problems make analytical evaluations of the system difficult and time consuming. In some instances, the required solution(s) for improved system reliability will exceed what can be addressed in a motor design. Added system components like common mode filters, dv/dt output filters, PWM cabling systems, continuous metal conduit, insulated bearings and shaft grounding devices may be required for achieving high levels of system reliability. Since the majority of users appear to feel the risk of field problems is not sufficient to justify the added cost to all of their VFD installations, the optional protective features required to address potential bearing problems must be specified in the RFQ by the user or system designer. Users and system design engineers will have to continue to evaluate the cost of optional components and specify the level of protection that is financially justified until the market evolves to include bearing protection features as a standard for PWM VFDs and motor systems.

Recognized Sources for Bearing Current Damage:

The three known potential sources for shaft voltage levels that can cause current to flow through an AC motor bearing(s) or connected equipment are:

1) Static charge build-up caused by the connected load (EDM currents)

2) Unbalanced voltages applied to the motor terminals or internal motor characteristics causing magnetic dissymmetry (circulating currents)

3) PWM VFD's creating common mode voltage, EDM and/ or circulating currents

The appropriate solution(s) in preventing bearing damage differ depending on the source of the voltage. It is important to identify the most probable cause(s) to avoid introducing new problems.

- Static charge build-up is normally associated with unique types of equipment that are connected to the motor shaft (large fans in dry air, large belts and large rolls of paper). When rotated in the right atmospheric conditions, these loads create a static electric charge that can flow through the motor shaft and bearing(s) seeking a path to ground. Since the motor frame is normally well grounded, it can represent the most desirable discharge path. By comparing the characteristics of the connected load under review to the types mentioned above, the probability of a static charge being the voltage source of a field problem can be determined. The use of an isolating type motor coupling to break the circuit path from the load to the motor shaft can help protect the motor. The static charge will still build on the connected equipment and seek a discharge path which may require some form of safety action to warn or protect workers. A shaft grounding device, that provides a desirable discharge path to ground, appears to be a solution used in some installations to minimize this problem.

- Magnetic dissymmetry inside a motor has been normally associated with large hp units operated from sine wave type power sources or unique winding designs that require this unbalanced condition to meet a particular performance requirement. The path of the bearing current flow caused by this voltage is normally internal to the motor. Since certain motor design characteristics and manufacturing variations can result in this condition, the motor manufacturer will normally have identified this risk and included an insulated bearing in the original product design. It is unusual to experience this condition in modern AC motor designs unless some external factor is contributing to the problem. On rare occasions, a rotor may become damaged or an air gap problem may develop due to a high inertia connected load or frequent starts or stops. These conditions will normally have additional symptoms that will require a repair shop to evaluate and repair.

In many instances, the source of circulating currents in a motor will be from external factors related to the installation. Finding and correcting the external condition(s) or adding an insulated bearing in the motor is the responsibility of the system design or specifying engineer. A "circulating current" condition allows current to flow in a circuit loop between the rotor, stator and both motor bearings. In most instances where this failure mode is encountered in the field, the cause can be traced back to external voltage transients or unbalanced voltages being delivered to the motor terminals. These conditions can be a power source issue or a voltage drop issue caused by a poor connection. The simplest solution to prevent circulating currents, if the integrity of the rotor and air gap are sound, is to break the circuit path by insulating one of the motor bearings (normally the opposite drive end bearing) and using an isolated shaft coupling to connected equipment. PWM VFDs can contribute to circulating currents, also.

- PWM Type VFD Waveforms have introduced a flurry of bearing failures due to electrical damage. Since the PWM power source has no standardized characteristics and the output waveform can be changed on the fly (based upon output frequency, load requirements and programmed parameter settings), the analysis of this condition is complex and difficult. In addition to the variations caused by the PWM power source, site specific conditions can compound and/ or cause bearing current damage. The ability to make system diagnostic measurements that directly indicate the cause of the failure is difficult if not impossible since the required measurement test points may be inside the motor. It is possible that more than one condition may be causing current to flow through the bearing(s) or connected equipment requiring extensive analysis and expense. One approach that simplifies the solution is to utilize the following components:

1) A VFD output filter designed to address common mode voltage and/ or high dv/dt levels

2) Proper grounding connection points, proper grounding cables and bonding straps for high frequency conditions and proper termination devices for high frequencies

3) Power cable and appropriate terminations between the motor and VFD that address the concerns caused by PWM waveforms

The VFD manufacturer or a VFD filter manufacturer can be contacted for assistance in understanding and selecting a common mode voltage and /or dv/dt output filter. Major wire manufacturers can be contacted to help specify a PWM type cable and proper installation techniques. Understanding issues with high frequency terminations and grounding points may require the services of a consultant with RF knowledge or some educational study. A search of the internet can identify several industry organizations with published technical papers that explain the concepts of high frequency grounding with PWM VFD's.

There are many technical papers available that provide different levels of detailed explanations of when, where and why bearing current damage may occur. A simple search of the internet will produce many papers on the topic written by VFD manufacturers, motor manufacturers, equipment OEM's, technical associations, bearing manufacturers and manufacturers of optional protective devices. Due to the complexity of PWM waveforms and the fact that the problems can be system generated, the reader should review as many of these published papers as necessary to achieve a suitable level of knowledge.

Summary:

Technical discussions of possible solutions regarding the recent increase in bearing failures related to current flow and PWM type power supplies seem to be split between two approaches. One approach is to implement solutions that address the VFD as the source of the problem and minimize the risk of problems occurring throughout the system. The second approach is to add one or more optional components in the system to try to direct or control the current path to protect the motor bearing(s) and connected equipment. Both technical discussions appear to agree on two major points:

1) The source of the voltage causing the current flow in the motor bearing(s) and system components is caused by the way a PWM VFD creates its 3 phase output voltage and frequency.

2) Characteristics of the PWM waveform impacting the installed system (relative to motor power cabling and high frequency grounding factors) can contribute to undesirable current flow through the motor bearing(s) or other connected components.

- Addressing the source of the problem requires altering the waveform characteristics to reduce or eliminate the common mode voltage component produced by the VFD. There are various methods available depending on the product expertise of the supplier:

1) One VFD manufacturer has commercialized a new product utilizing a 3-level PWM output topology to minimize the common mode voltage component delivered to the motor. An internet search on 3-Level Inverter Technology will produce many technical papers on this topic.

2) Adding output reactors/ filters designed to reduce common mode voltage is a solution proposed by one inverter filter manufacturer. An internet search on Common Mode Filter for PWM Bearing Current Failures will produce many technical papers on this subject.

3) Other VFD manufacturers offer several filter options that range from what is termed a "sine-wave" output filter inserted between the motor and VFD to a toroid filter that is placed around the leads running to the motor. An internet search on Toroid Filter for VFD Bearing Current Problems and Sine Wave Output Filter for VFD Common Mode Voltage will produce many technical papers on this topic.

4) A variety of sources stress using proper high frequency grounding components, installation techniques suited for high frequency and proper programming of the VFD switching frequency. An internet search on Bearing Currents in Modern AC Drives will produce many technical papers on these topics.

- Adding optional components to try to direct or control the impact common mode voltage and high frequency waveform components have on an installed system is a common practice. Depending on the level of analysis of the failure mode, this approach may or may not be effective and may cause a new symptom to appear elsewhere in the system. Adding optional components to the electrical system may seem sensible, but the possibility of the source of the problem finding a new path to ground or a circuit condition changing unexpectedly can lead to numerous unexpected failure modes. One example would be that adding a grounding device on the opposite drive end of a motor could initiate bearing current failures as it becomes the most desirable path for the majority of current flow to ground. Prior to the grounding device, the current level would be lower due to having multiple paths to ground. Circulating currents, caused by the PWM waveform, can also become a problem requiring an insulated bearing, too.

It is important to understand that when modern PWM type VFD's are being utilized the dynamics of the power system change from having to consider low frequency conditions (50 or 60Hz) to having to handle both low and high frequency conditions (well into the mega-hertz range). System components and materials that are thought to be insulators in low frequency theory can now become conductors to the high frequency components produced by the VFD. The lack of understanding of high frequency behavior, in what has traditionally been a low frequency circuit, is a major contributor to many of the field problems involving PWM type VFD's.

1) Insulated bearings can be useful in sine wave and VFD installations where circulating currents are flowing and damaging the bearing(s) or connected equipment. Bearing manufacturers offer several products that achieve this effect. Equipment manufacturers may utilize a standard bearing and insulate the mounting area with a special material. Insulated bearings block the path that currents want to take to flow back to the source ground, but they do not eliminate the voltage from seeking other paths to ground. Current flow through the remaining paths to ground may increase. When insulating one or both bearings, the system designer or specifying engineer should determine whether to apply one or more of the following options to prevent or reduce shaft currents: sinewave filters, line reactors or mechanical devices, such as shaft grounding or an insulated half coupling.

2) Shaft grounding systems, when used as a stand alone option, provide an additional path for shaft voltage to flow back to the ground of the power source (VFD). The hope is this path will have lower impedance so the majority of current will flow through the grounding system instead of the other paths. A single shaft grounding system will not protect both bearings from circulating currents, but will tend to protect both bearings from EDM or static discharge. Proper selection of the shaft grounding material, maintaining a low impedance contact with the motor shaft, establishing a proper ground of the motor frame, the mounting location of a grounding device and the number of grounding devices are important variables in using this possible solution.

3) PWM type power cable is intended to minimize the common mode voltage by providing a better high frequency return path to the VFD power source. In addition, it can reduce cable capacitance to earth ground, help limit EMI and provide a longer cable insulation life. Proper installation is required to achieve the desired impact on the high frequency problems caused by PWM type waveforms.

4) Grounding practices and products better suited to high frequency applications are important. Flat cables for bonding equipment, multiple smaller diameter conductors to provide circuit ground, 360 degree terminations, aluminum jacketed power cables with shields and continuous metal conduit connection from VFD cabinet to the motor terminal box are just some installation considerations when PWM type power units are utilized.

5) Output filters inside the VFD cabinet were discussed for addressing the source of the problem, but they are still considered an optional external device. It is important to note that not all output filters perform as well in minimizing common mode voltages as others. Some of the more common VFD output filters utilized are intended to primarily address voltage spike issues and may not be sufficient to address bearing current problems. It is important to understand what filters are available and what function they are designed to address. In some severe installations, a dv/dt filter may need to be used in addition to a common mode filter. Voltage levels delivered to the motor terminals need to be checked since the VFD and the common mode filter can both drop the output voltage to unacceptable levels.

Conclusion:

The complexity associated with analyzing bearing current failures on PWM waveforms can be expensive and time consuming. Some motor and system features can be added to possibly correct field problems, but their effectiveness can not always be guaranteed and the possibility of field failures could still occur. The source of the problem has been identified as the characteristics of the modern VFD power source and the interaction of the high frequency waveform components with the power distribution paths between the VFD, motor, earth and VFD ground. The motor is frequently the first system component to display the effects of this PWM waveform damage, but other parts of the system can fail as the motor is "beefed up" to prevent problems. Optional devices added to the motor could become ineffective over time or due to improper grounding resulting in similar symptoms as when these devices are not utilized. Blindly applying external component solutions can be successful in some instances, but this approach can also introduce new failure modes in the motor or other system components.

Addressing waveform correction as part of the VFD specification and properly evaluating cabling issues can help address the field problems at their source. Adding key installation requirements at the time of equipment purchase can be desirable and cost effective when downtime and field problems are critical factors. It is imperative that the RFQ specification be technically complete so that the winning bid delivers products that perform as the system engineer intended upon commissioning. As PWM VFD's continue to evolve and expand in HP, technical issues will continue to surface requiring users and specifying engineers to improve their understanding and require the latest requirements for successful variable speed installations.

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