Diffusing current trouble

Shown here is a ring (attached with a mounting adapter) that channels current away from motor bearings.

Variable frequency drives can cause voltage buildup on motor shafts. Several methods — one fairly new — can channel it away.

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The use of variable-frequency drives (VFDs) to control ac motors has increased dramatically in recent years: on power generators, gas turbines, wind turbine generators, ac traction and break motors, cleanroom and HVAC systems, and other industrial and commercial applications. In addition to their low operating cost and high performance, they save energy. So the new challenge now facing system engineers is how to minimize damage to ac motors from shaft current.

A normal ac power supply is symmetrical, so that its three-phase vectors sum to zero. But variable frequency drives turn that into dc current, and then chop it into power at rates to 20 kHz. At those high frequencies, constant, perfect phase balance is impossible — and the phase vectors sum to a nonzero voltage. So from its first minute of operation, a VFD induces voltages that build up on the motor shaft until they find discharge paths to the grounded frame. In most cases, the motor bearings present the path of least resistance. Once voltage is sufficient to overcome the resistance of the oil film layer in the bearing, shaft current flows through it, causing electrical discharge machining (EDM) pits and fusion craters in race walls and ball bearings. This happens literally millions of times per minute, and continues until the bearings become so severely pitted that fluting, excessive noise, and failure occur.

Electrical bearing damage

New bearing race walls are smooth. As the motor runs, a track eventually forms where the bearing ball contacts the wall. With no electrical discharge damage, this type of mechanical wear would be the only cause of degradation.

Due to the high-speed switching frequencies of PWM inverters, variable frequency drives induce shaft current in ac motors. As mentioned, the switching frequencies of insulated-gate bipolar transistors used in these drives produce voltages on the motor shaft during normal operation — voltages that can reach 70 $V_{p\,to\,p}$ or more.

Once these voltages reach a level sufficient to overcome the dielectric properties of bearing grease, they discharge along the path of least resistance — typically the motor bearings — to the motor housing. (Bearings are designed to operate with a very thin layer of oil between the rotating ball and the bearing race.)

Induced shaft currents

Due in large part to an increased focus on energy savings, the use of pulse-width-modulated (PWM) variable-frequency drives to control ac motors has grown dramatically. However, without some form of mitigation, shaft currents travel to ground through bearings, causing pitting, fusion craters, fluting, excessive bearing noise, and eventually, total bearing (and subsequent motor) failure. This is not a small problem. Consider:

- Most motor bearings are designed to last for 100,000 hours, yet motors controlled by VFDs can fail within one month — 720 hours. In fact, on one HVAC system in particular, every single VFD-controlled vane axial fan motor (ranging from 30 to 60 hp) of a large building project failed within a year — two within six months. Repair costs totaled more than $110,000.
- Large pulp and paper companies concur that VFD-controlled ac motors used in their plants typically fail due to bearing damage within six months.
- The largest motor manufacturer in the U.S. has cited eliminating drive-related motor failures as its number-one engineering challenge.
- Today, there are almost a dozen blogs on the Internet focused on discussing VFD-induced shaft currents, sharing information and experiences, and suggesting solutions.
- Motor failures caused by VFD-induced shaft currents result in hundreds of thousands of hours of unplanned downtime, in the U.S. alone, each year. In addition, these failures affect the performance and mean time between failure (MTBF) of the original equipment manufacturing (OEM) systems in which they are used.
- With recent motor-price increases (approximately 16% over last year) due to rising copper prices, this problem is increasingly costly.

During nearly every VFD cycle, induced shaft voltage discharges from the motor shaft to the frame via the bearings, leaving a small fusion crater in the bearing race. Then new fusion craters form over old ones. The discharges can be so frequent that the entire bearing race can quickly become covered with pits, taking on a frosted look. As damage continues, the frosting increases, eventually leading to noisy bearings and failure. A phenomenon known as fluting may occur as well, producing washboard-like ridges across the frosted bearing race.

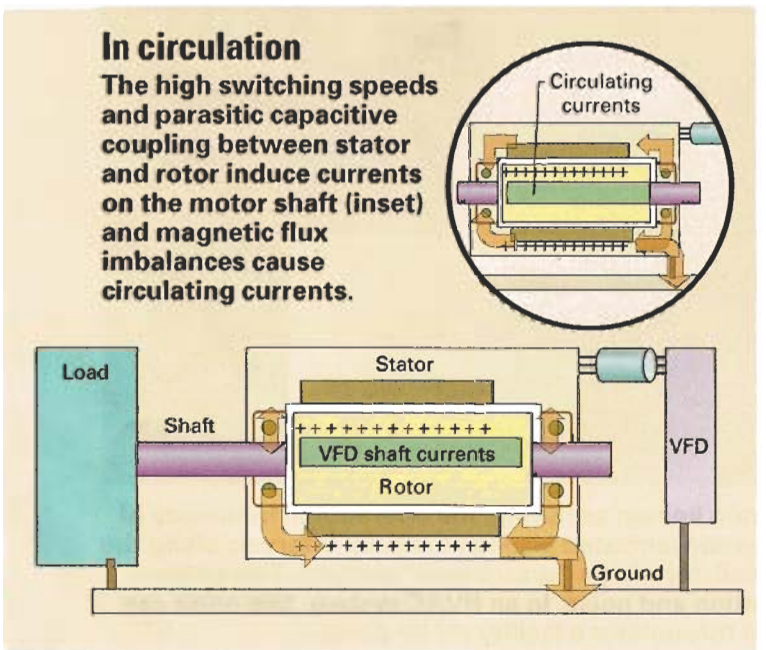
Failure rates vary widely depending on many factors, but evidence suggests that a significant portion of failures occur only 3 to 12 months after system startup. Because many of today's ac motors have sealed bearings to keep out dirt and other contaminants, electrical damage has become the most common cause of bearing failure in ac motors with VFDs. If half of all ac motor failures are due to bearing failure, almost 80% of these are caused by electrical damage to bearings.

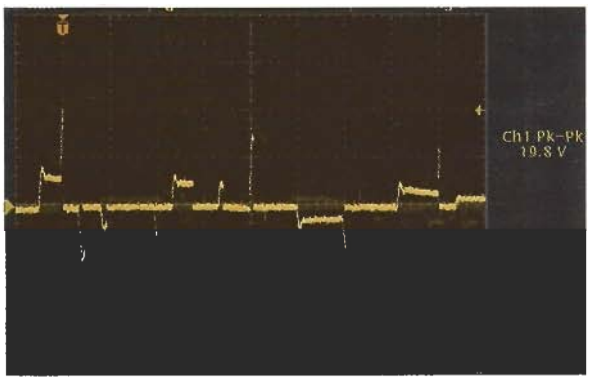
Mitigating shaft damage

To prevent electrical damage in the first place, induced shaft currents can be diverted from the bearings by insulation, or given an alternate path to ground. Insulating motor bearings is effective, but tends to shift the problem elsewhere, as shaft current looks for another path to ground. If attached equipment, such as a pump,

In circulation

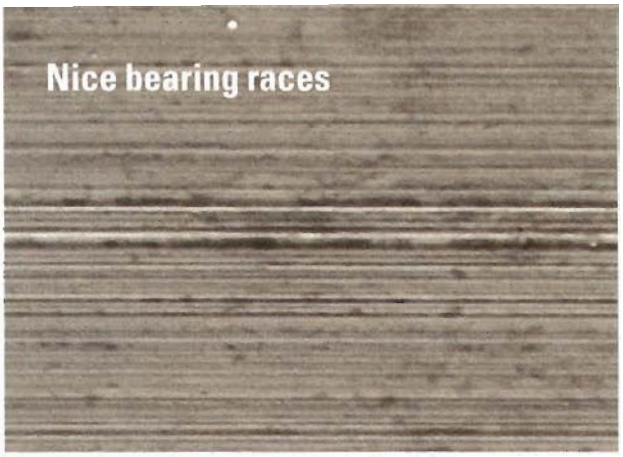
The high switching speeds and parasitic capacitive coupling between stator and rotor induce currents on the motor shaft (inset) and magnetic flux imbalances cause circulating currents.



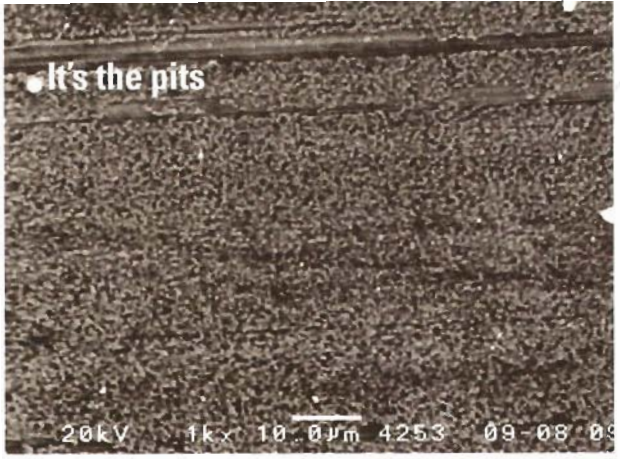


Caution: High voltages

The switching frequencies of insulated-gate bipolar transistors (IGBTs) used in VFDs produce voltages on the motor shaft during normal operation through electromagnetic induction. These voltages, which can register 70 $V_{p\text{-}to\text{-}p}$ are easily measured by touching an oscilloscope probe to the shaft while the motor is running.



A scanning electron microscope image shows how new bearing race walls are smooth. As the motor runs, a track eventually forms where the bearing ball contacts the wall. With no electrical discharge damage, this type of mechanical wear would be the only cause of degradation.



A frosted bearing race shows damage after 5,400 hours of continuous use in a VFD/ac motor system. Fusion craters increase in number and size as each cycle of induced voltage discharges from the shaft through the bearings to the frame and ground, and soon the entire race is covered with millions of pits.

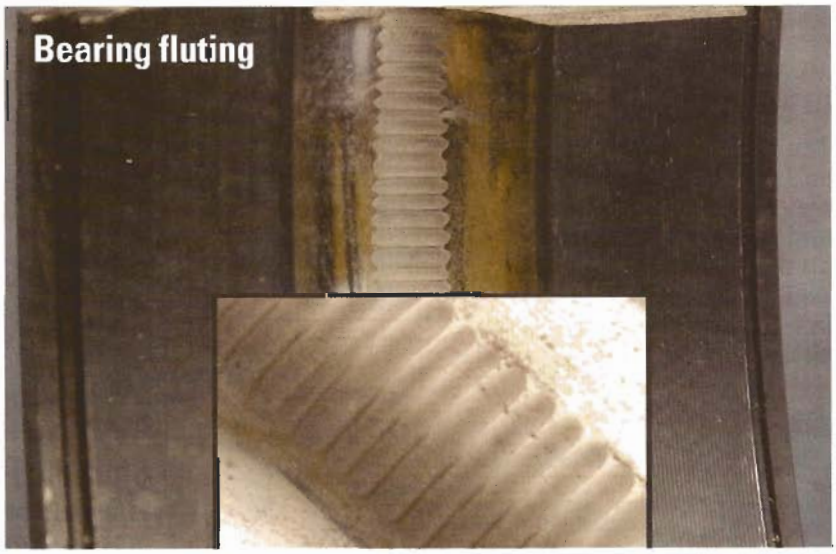
provides this path, the other equipment often winds up with bearing damage of its own. Sometimes, because of the capacitive effect of ceramic insulation, high-frequency VFD-induced currents actually pass through the insulating layer and still cause bearing failure. Alternate discharge paths are preferable to insulation, because they neutralize shaft current.

❶ **Faraday shields** prevent the VFD current from being induced onto the shaft by effectively blocking it with a capacitive barrier between the stator and rotor. This solution is extremely difficult to implement, very expensive, and has been generally abandoned as a practical solution.

❷ **Insulated bearings** include a nonconductive resin or ceramic layer to isolate the bearings and prevent shaft current from discharging through them on its way to the frame. This forces current to seek another path to ground — through an attached tachometer or load, for example. Due to the high cost of insulating the bearing journals, this solution is generally limited to larger-sized NEMA motors. Sometimes, high-frequency VFD-induced currents actually pass through the insulating layer and cause bearing damage anyway. Another drawback is the potential for contaminated insulation, which can, over time, establish a current path through the bearings.

❸ **Ceramic bearings** are nonconductive ceramic balls to prevent the discharge of shaft current through bearings. As with other isolation measures, shaft current seeks an alternate path to ground. This technology is very costly, and in most cases, motors with ceramic bearings must be special ordered and 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.

❹ **Conductive grease** contains conductive particles to provide a lower-impedance path through the bearing, and bleed off shaft current without the damaging discharge. Unfortunately, the conductive particles in these lubricants increase mechanical wear to the bearing, render-



In a phenomenon known as fluting, the operational frequency of the VFD causes concentrated pitting at regular intervals along the bearing race wall, forming a "washboard" pattern. This pattern results in vibration and noise. In an HVAC system, this noise can be transmitted throughout a facility via air ducts.

ing the lubricants ineffective and often causing premature failures. In fact, this method has been widely abandoned as a viable solution to bearing currents.

❺ Metal **grounding brushes** contact the motor shaft to provide a more practical and economical low-impedance path to ground, especially for larger NEMA-frame motors. These brushes:

- Are subject to wear because of the mechanical contact with the shaft.
- Collect contaminants on their metal bristles, which destroys their effectiveness.
- Are subject to oxidation buildup, which decreases their grounding effectiveness.
- Require regular maintenance.

Brushes are spring loaded, and made of phosphor, bronze, or carbon.

❻ **Shaft grounding rings** consist of a ring of engineered conductive microfibers that redirect shaft current through a low-impedance path from shaft to frame. The synthetic, nonmetallic rings don't rely on friction for connection; instead, they're fit over either end of the motor shaft and lock in place with simple screw-on mounting brackets. (A split-ring design allows installation around the shaft without disassembling attached equipment.) Then ionization boosts the electron-transfer rate to promote discharge of high-frequency currents. The microfiber design makes for hundreds of thousands of discharge points, so the ring channels shaft currents around motor bearings to protect them from electrical damage.

Conductive microfiber shaft grounding rings are scalable to NEMA-frame and larger motors, and designed for motors with shafts from about 0.3 to 6.0 in., including IEC frames and high-horsepower ac and dc motors. No machining is required, and the rings can be installed in minutes — even in the field. Once installed, the rings require no maintenance — and with no parts to wear out, the rings last as long as bearings.

Anything that can cause corrosion of other motor parts — salt water, for example — can also cause corrosion of the ring casing. But an ac motor coupled with a VFD costs between $2,400 and $100,000 or more, and may be part of a manufacturing process that generates revenues from $10,000 to $1,000,000 or more per hour. The cost of installing a grounding ring in a VFD-powered system is usually less than 1% of equipment cost.

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