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CAUTION:
This Technical Information Paper may require the use, disposal, or both of chemicals which may present serious health hazards to humans. Procedures for the handling of such substances are set forth on Material Safety Data Sheets which must be developed by all manufacturers and importers of potentially hazardous chemicals and maintained by all distributors of potentially hazardous chemicals. Prior to the use of this technical information paper the user should determine whether any of the chemicals to be used or disposed of are potentially hazardous and, if so, should follow strictly the procedures specified by the manufacturer as well as local, state, provincial, and federal authorities for safe use and disposal of these chemicals.

AC Motor Bearing Failure Due to Electrical Discharge

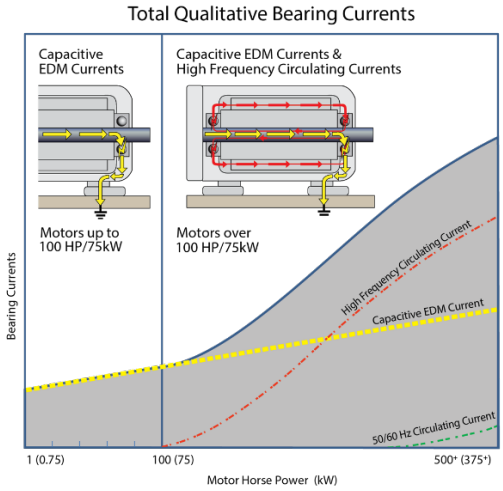
1. Scope

This document was created by a TAPPI Task Group to provide information and guidelines for application of Shaft Grounding Ring to protect motor bearings from electrical fluting damage in AC induction motors operated on variable frequency drives (VFD). Motors range in size from 1 HP to over a 1000 HP.

There are two sources of bearing currents which need to be addressed:

1. Capacitive EDM Current (from VFD): Capacitive induced voltage from the pulse width switching waveform produced by the variable frequency drive (VFD) are present in a motor operated on drives.

2. High Frequency Circulating Current (from VFD): High frequency circulating currents (HFCC) may flow due to a high-frequency flux produced by common-mode currents. AC Motors over 100 HP.



Information in this document helps a mill identify, test for, and prevent electrical bearing failures in inverter driven equipment whether by VFD driven AC motors or DC motors. This document provides information on shaft grounding rings, insulated bearings, correct installation per industry best practice, shaft voltage testing, and shaft maintenance requirements.

2. Safety precautions

Care should be exercised when working with any rotating equipment like motors and any electrical equipment to ensure they are properly guarded and lockout/tagout procedures are followed. Precautions are required to avoid unsafe situations where a worker could be struck or be trapped by the rotating equipment caught in a pinch point or injured by other equipment. Personal protective equipment should be worn, and safety rules obeyed when working in or around rotating equipment. Mill hazard and safety requirements must be reviewed before any work is performed and followed at all times.

This TIP may require the use of chemicals that may present a health hazard to workers. Procedures for handling such substances are set forth in Material Safety Data Sheets (MSDS) for those chemicals. Prior to the use of this technical information paper, the user should determine whether any of the chemicals to be used or disposed are potentially hazardous, and if so, strictly follow the procedures specified by both the manufacturer as well as the local, state and federal authorities to insure safe use and disposal of these materials.

3. System Design and description

Background

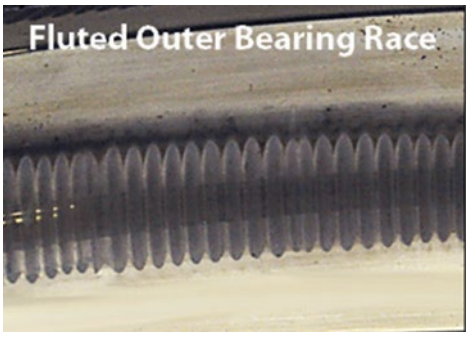
Variable frequency drives (VFDs) operating AC induction motors create damaging shaft voltages and bearing currents from both capacitive induced voltages from stator to rotor (EDM currents) and from high frequency circulating currents from the magnetic flux imbalances in the motor. These destructive currents will discharge through the motor's bearings causing electrical pitting and fluting, a washboard-like damage in the bearing race and decrease lubrication life of the bearing.

Note that this bearing damage can occur both in the motor and in its attached equipment such as gearboxes, encoders, break motors etc. and rotating operation makes them prone to mechanical failure and system downtime.

Bearing failures

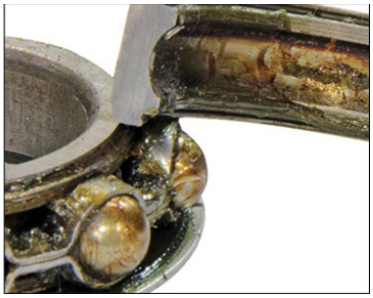
Capacitively induced shaft voltages are common in AC motors when the motors are operated by pulse width modulation (PWM) drives also known as variable frequency drives, adjustable speed drives etc. VFDs control the motors with insulated gate bipolar transistors (IGBT) which switch on and off extremely rapidly to control the speed of the motor. What is important to know is that the positive and negative pulses create a high peak to peak voltage in the motor's stator windings and which then are capacitively coupled to the motor's rotor.

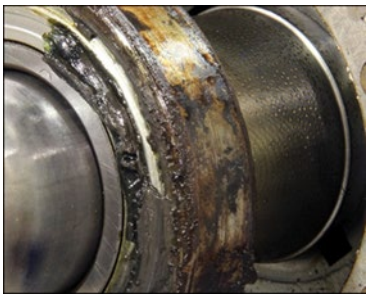
If shaft voltage is high enough, usually 10 to 40-volt peaks (per NEMA MG1 Part 31.4.4.3, the voltage will discharge through the motor's bearings creating millions of pits in the motor's bearings through electrical discharge machining (EDM) effect. This continuous EDM damage in the bearings leads to frosting and fluting and premature bearing failure.



Lubrication failure

During the arcing inside the bearing, extremely high temperatures are present which melt the hardened steel of the bearing and burn the grease. During a motor's operation on a drive billions of pits are blasted into the bearing race and with every arc the lubrication is continuously burned. Lubrication is also contaminated by metal particles from the steel and lubrication life is shortened dramatically.





Bearing failures of this type are frequent when not properly mitigated and consequences can include unscheduled down time, expensive repairs, lost production and in extremely rare cases worker injury and damage to attached equipment such as gear boxes, encoders and break motors. Mills should employ bearing current mitigation per industry best practices and preventive maintenance practices to keep the motor's shaft conductive.

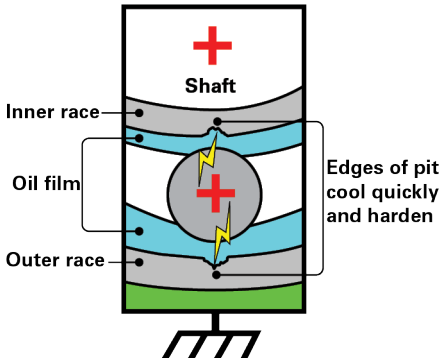
Materials

Motor bearings are designed to last for a specific L-10 life, a calculation to determine, with 90% reliability, how many hours a bearing will last under a given load and speed. Bearings are either steel race and rotating element or may have insulation on the outside or inside of the bearing ace, or they may have ceramic rolling elements and steel races. The rolling elements are held in a cage to separate them.

Steel bearings are the most common bearings in electric motors and attached equipment. They have steel rolling elements, race and usually metal cages and are lubricated with grease (commonly Polyrex EM). When the equipment is rotating a thin oil film forms between the rolling element and raceway. This oil film is normally a dielectric but because it is only microns thick a shaft voltage can overcome its dielectric properties.

Electrical Arcing in steel bearings

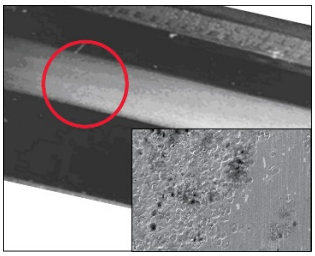
Steel bearings have a nominal electrical breakdown threshold of 10 to 40-volt peaks (per NEMA MG1 Part 31.4.4.3) where the electrical shaft voltage potential will overcome the dielectric of the oil film and arc through the bearing creating an EDM pit. Since the VFD has a carrier frequency setting of 2000 to 16000 pulses per second, there are millions of pitting opportunities every hour of operation of the motor/drive system.



Bearing inspection

ANSI/EASA Standard AR100-2015, Section 2, Mechanical Repair: 2.2 Bearings states that "Bearings should be inspected for failure modes such as spalling, contamination, fretting, fluting, and scoring." Signs of electrical arcing in the bearings are:

1) Burnt lubrication/grease
2) Pitting of the bearing race (a grey line along the bearing ball track)
3) Fluting damage (washboard like pattern) in the bearing race – inner or outer – sometimes heavier in the load zone
4) Discolored dull or gray rolling elements (balls) or fluting lines on the cylindrical elements


Inspection steps

a) Cut the bearings: **Follow established safety precautions and use personal protective equipment including eye protection, hearing protection, face shield, gloves and protective clothing.**

b) Inspect lubrication, inner race, outer race and ball for damage and signs of arcing.

4. Repair/replace and specification guidelines

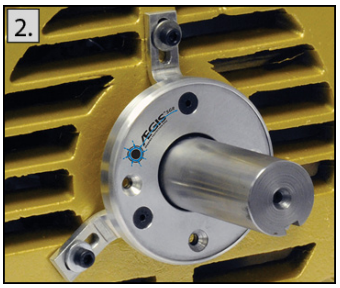
Whenever a motor is selected to operate on VFDs the motor's bearings are susceptible to electrical damage. The following best practices apply to:

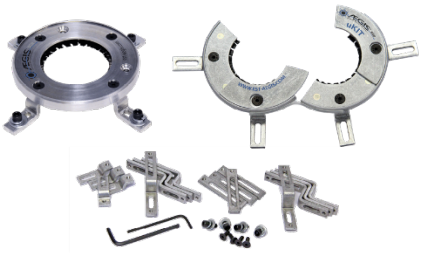
1) New motors
2) Replacement motors
3) Repaired motors

The following best practices should be followed for all motors and during bearing inspection. Implement the following best practices in the VFD/motor system to protect motor bearings and those of attached equipment. Best practices apply to low voltage and medium voltage motors: For complete manufacturer's recommendations refer to the AEGIS® Bearing Protection Handbook (current edition) fond on www.est-agis.com/handbook

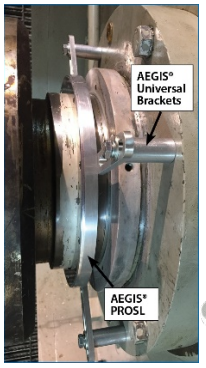
The following products are needed to implement repairs or specified for new motors:

1) **Shaft Grounding Ring**: Must be designed with circumferential conductive micro fibers completely surrounding the motor's shaft such as AEGIS® Shaft Grounding Rings
    a. Shaft Grounding ring with 2 rows of fiber for Low voltage motors up to 500 HP (375 kW) (such as AEGIS® SGR)
    b.





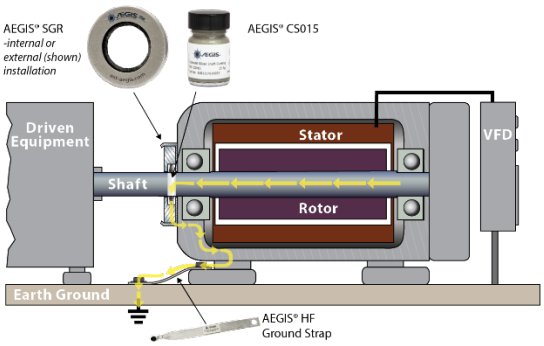
    c. Shaft Grounding ring with 6 rows of fiber for Medium Voltage motors and Low Voltage over 500 HP (375 kW) (Such as AEGIS® PRO series)



2) **Insulated bearings/bearing insulation**: Used to stop circulating currents
    a. Ceramic coated bearing (ball or cylindrical)
    b. Ceramic Ball (Hybrid bering) ball bearing only
    c. Bearing insulation installed in the bearing journal with ceramic coating or other insulation.
3) **Colloidal Silver shaft coating** such as AEGIS® part number CS015 for coating the motor's shaft surface to minimize corrosion and enhance conductivity
4) **High Frequency Grounding Strap** for high frequency bonding such as AEGIS® HFGS – a flat braided bonding strap with motor bolt hole on one end and terminal connection at the other end

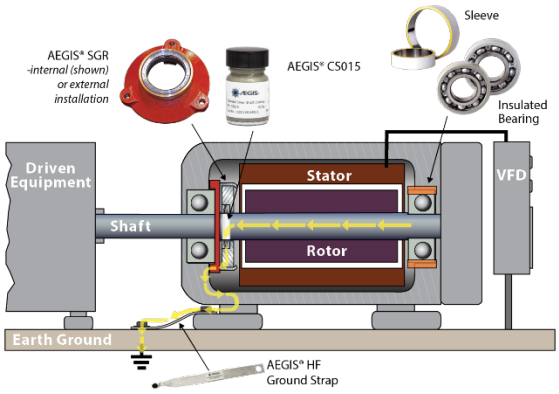
Low Voltage Motors up to and including 100 HP (75 kW)

1) Install one 2-row AEGIS® SGR shaft grounding ring on either the drive end or the non-drive end of the motor to discharge capacitive induced shaft voltage.
    a. **Install inside motor (preferred)** because of the extreme environment of the steel mill. AEGIS® SGR may be installed either internally or externally.
    b. Use AEGIS® Colloidal Silver Shaft Coating (PN# CS015) on motor shaft where fibers touch.
2) Install one AEGIS® HFGS high frequency bonding strap from motor foot to facility ground
3) **Follow all safety precautions. GHS SDS available for download at www.est-aegis.com**



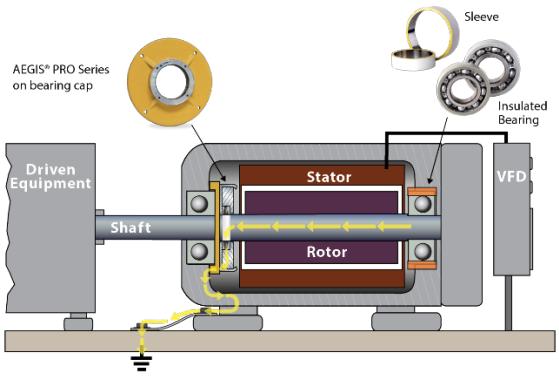
Low Voltage Motors over 100 HP (75kW) to 500 HP (375 kW)

1) Non-Drive end: Bearing housing must be isolated with insulated sleeve or coating or use insulated ceramic or hybrid bearing to disrupt circulating currents.
    a. Insulation is always installed on the opposite side of the shaft grounding ring, usually the NDE of the motor.
2) Drive end: Install one 2-row fiber AEGIS® Shaft Grounding Ring.
    a. **Install inside motor (preferred)** because of the extreme environment of the steel mill. AEGIS® Ring can be installed internally on the back of the bearing cap or externally on the motor end bracket.
    b. Use AEGIS® Colloidal Silver Shaft Coating (PN# CS015) on motor shaft where fibers touch.
3) Install one AEGIS® HFGS high frequency bonding strap from motor foot to facility ground
4) **Follow all safety precautions. GHS SDS available for download at www.est-aegis.com**



Low Voltage Motors over 500 HP (75kW) to 500 HP (375 kW) or Medium Voltage Motor

1) Non-Drive end: Bearing housing must be isolated with insulated sleeve or coating or use insulated ceramic or hybrid bearing to disrupt circulating currents.
2) Drive end: Install one 6-row fiber AEGIS® PRO Series Shaft Grounding Ring.
   a. **Install inside motor (preferred)** because of the extreme environment of the steel mill. AEGIS® Ring can be installed internally on the back of the bearing cap or externally on the motor end bracket.
   b. **AEGIS PRO SLR may be used for external installations** – incorporates O-ring barriers to minimize ingress of materials into the conductive micro fibers.
   c. Use AEGIS® Colloidal Silver Shaft Coating (PN# CS015) on motor shaft where fibers touch.
3) Install one AEGIS® HFGS high frequency bonding strap from motor foot to facility ground
4) **Follow all safety precautions. GHS SDS available for download at www.est-aegis.com**

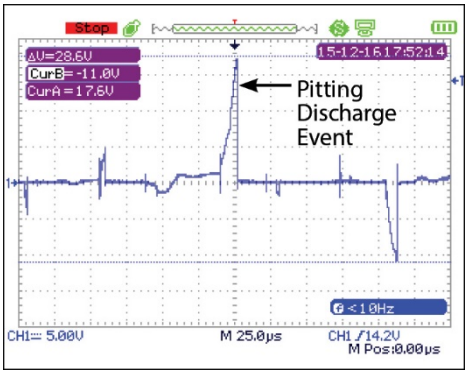


5. Shaft Voltage Testing

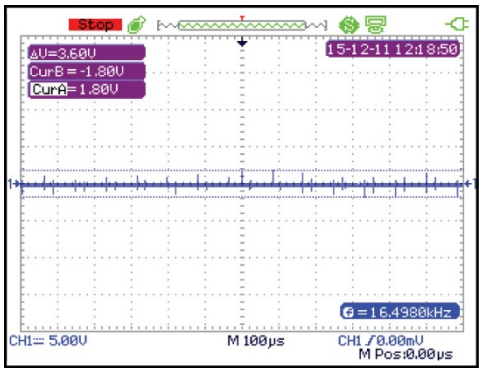
Use a digital portable oscilloscope for shaft voltage testing on the motor while it is operating. Motor with no shaft grounding rings installed may have high shaft voltages and bearing discharges which can be measured on the shaft of the motor while it is running.

Preferred testing equipment: AEGIS-OSC-9100MB-W2: The AEGIS® Shaft Voltage Tester™ kit includes everything you need to start testing motor shaft voltages. At its core is a 2 channel, 100 MHz digital oscilloscope with a 5.7" screen and easy screen capture.

1) High amplitude EDM discharge pattern: Typically, EDM discharges can occur from 20 to 80 volts peak to peak (10 to 40 volts peak) depending on the motor, the type of bearing, the age of the bearing, and other factors. The waveform image shows an increase in voltage on the shaft and then a sharp vertical line indicating a voltage discharge. This can occur thousands of times in a second, based on the carrier frequency of the drive. The sharp vertical discharge at the trailing edge of the voltage is an ultra-high frequency dv/dt with a typical "discharge frequency" of 1 to 125 MHz (based on testing results in many applications).



2) Peak to Peak voltage with AEGIS® ring installed: With the AEGIS® ring installed, a bare steel shaft will typically show shaft voltages of 2 to 10 volts peak to peak (1 to 5 volts peak) depending on the power of the motor, ground noise, the conductivity of the shaft and other factors. The voltage readings may be decreased further with the application of AEGIS® Colloidal Silver Shaft Coating which allows for higher shaft surface conductivity and a more efficient electron transfer to the conductive micro fiber tips. The waveform image shows the low peak to peak waveform of a motor with the AEGIS® SGR ring installed and discharging the shaft voltages

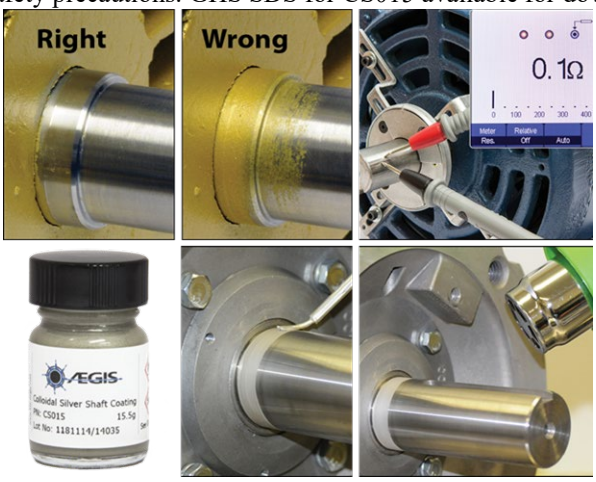


6. Shaft maintenance recommendations

Shaft Preparation for Internal and External Installation

1) The shaft grounding ring MUST NOT RIDE OVER A KEYWAY.
   a. Adjust or select mounting spacers to avoid the keyway of the motor
   b. Ensure you order the correct shaft grounding ring to match the motor shaft diameter where the ring fibers will touch.
   c. If the ring will be located over a keyway the keyway must be filled in with an epoxy filler and smoothed to the shaft diameter with no shaft edges exposed.
2) Motor shaft must be conductive: Shaft must be clean and free of any coatings, paint, or other nonconductive material (clean to bare metal).
   a. Depending on the condition of the shaft, it may require using emery cloth or Scotch-Brite™.
   b. If the shaft is visibly clean, a non-petroleum-based solvent may be used to remove any residue.
   c. If possible, check the conductivity of the shaft using an ohm meter.
3) Ohms test: Place the positive and negative meter leads on the shaft at a place where the microfibers will contact the shaft. Each motor will have a different reading but in general you should have a maximum reading of less than 2 ohms. If the reading is higher, clean the shaft again and retest.
4) Colloidal Silver Shaft Coating (CS015) is recommended for all applications. The silver enhances the conductivity of the shaft and lessens the amount of corrosion that can impede the grounding path.
   a. Shaft must be clean and free of any coatings, paint, or other nonconductive material.
   b. The shaft must be clean to bare metal.

c. If possible, gently warm the shaft when the AEGIS® CS015 will be applied. This helps the CS015 cure faster. Allow CS015 to come to room temperature prior to opening.
d. Apply a thin, uniform coat of the AEGIS® Colloidal Silver Shaft Coating to the area where the AEGIS® microfibers will be in contact with the motor shaft.
e. Apply all around the shaft.
f. Wait for the first coat to dry to a tack free surface.
g. Drying can be accelerated with the use of gentle heat from a heat gun, but don't exceed 200°F (93°C) while curing.
h. Apply a 2nd thin, uniform coat of CS015.
i. Allow CS015 to dry to a tack free surface before installing the AEGIS® Ring.
j. The coating will cure at room temperature in 16-20 hours or in about 60 minutes at 200°F (93°C).
k. Follow all safety precautions. GHS SDS for CS015 available for download at www.est-aegis.com



Periodic Shaft maintenance

Shaft maintenance for VFD fed AC induction motors is not needed when the ring is properly installed inside the motor. In some applications and when the shaft grounding ring is externally installed a periodic maintenance may be performed to ensure high conductivity and shaft grounding ring performance. The following indicates a need for maintenance on external shaft grounding ring installations.

1) Shaft voltage testing after shaft grounding ring installation shows an increasing voltage approaching 20 volts peak to peak. An increasing peak to peak shaft voltage reading indicates that there may be non-conductive or resistive shaft corrosion under the ring's micro fibers.
2) Bearing discharge events are present in the shaft voltage readings.
3) The ring is in a severe environment where contamination can cause heavy buildup of contamination on the motor's shaft.
4) If testing indicates that the motor shaft must be cleaned:
    a. Remove the shaft grounding ring by loosening any brackets and sliding it along the motor's shaft to expose the area under the conductive micro fibers.
    b. Follow the shaft maintenance procedures described above.
    c. Re-install the shaft grounding ring.

Keywords

Electrical Bearing Damage, Paper Machine, Variable Frequency Drive, Adjustable Speed Drive, Shaft Grounding Ring, Bearing Protection, Shaft Voltage Testing, Baring Fluting Damage, AC Induction Motor

Additional information

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Electro Static Technology / ITW

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Bearing Protection Best Practices

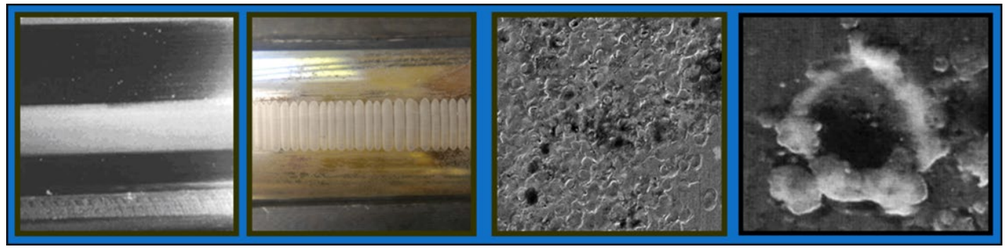





AEGIS® 2-Year Warranty Against Bearing Fluting Damage on All AEGIS® Ring Installations

What the experts say…

- **Industry Applications, 1998, Vol. 32, No. 6:** "Pulse width modulation (PWM) inverters have recently been found to be a major cause of motor bearing failure in inverter-drive systems." ***Shaotang Chen, Member IEEE et. al.***
- **IEEE 2004, IAS 2004, 0-7803-8486-5/04**: "The surfaces of the bearing races of bearings with operation time greater than 500 h are melted several times at the whole surface due to small craters…..", ***A. Muetze, A.Binder, Vogel, J.Hering***,
- **March 2005 Journal of Electrostatics** "Statistical model of electrostatic discharge hazard in bearings of induction motor fed by inverter" ***by Adam Kempski et. al.*** "Electrical Discharge Machining (EDM) bearing currents have been found as the main cause of premature bearing damages in Pulse Width Modulation (PWM) inverter fed drives."

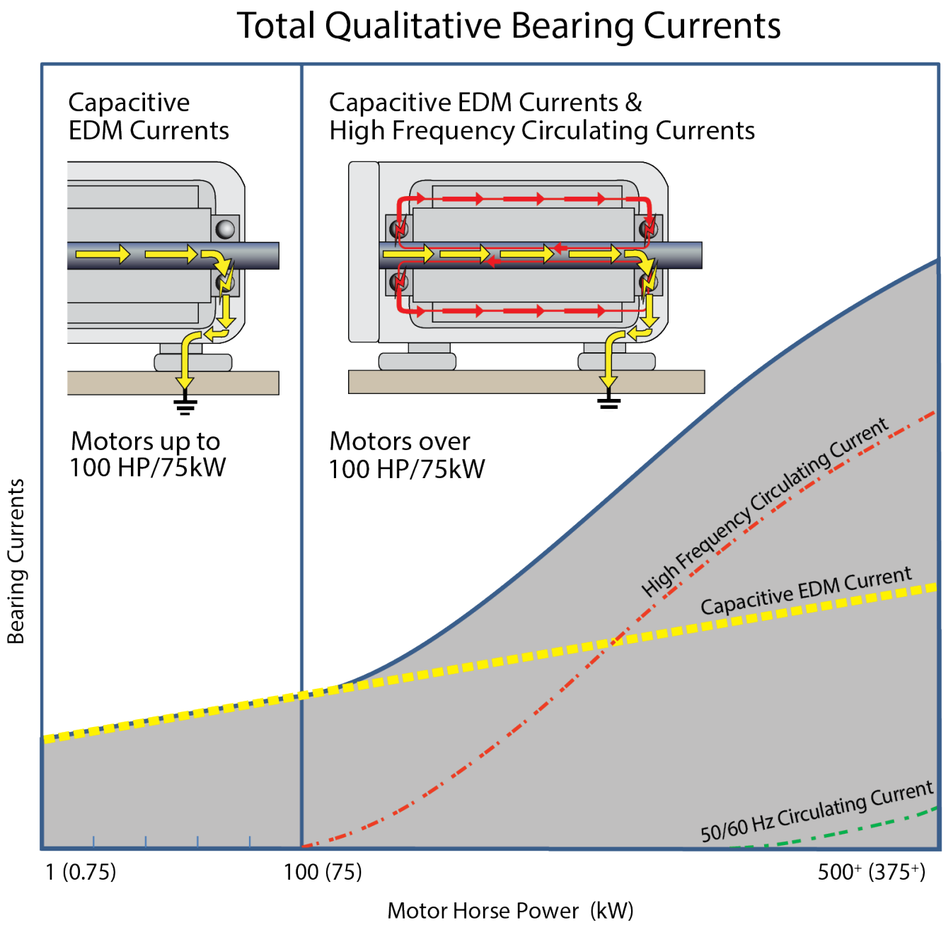


Bearing failures are costly…

Typical Motor Failure:	30 HP (22.5 kW)	300 HP (225 kW)	500 HP (375 kW)
Rigging/Removal and re-installation	$1,500	$12,000	$20,000
Motor Repair	$1,500	$8,400	$20,200
Production Downtime estimate	$5,000	$10,000	$100,000
Total cost of failed motor on production line	$8,000	$30,400	$140,200
Cost of AEGIS® installed on motor parts plus labor	$465 AEGIS® UKIT	$870 AEGIS® UKIT	$2,340 AEGIS® PROSL
Savings for preventing one motor failure	94%	97%	98%

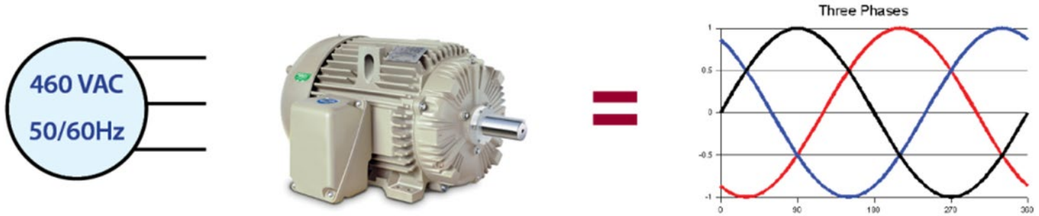
Sources of Bearing Currents

1. **Capacitive EDM Current (from VFD):** Capacitive induced voltage from the pulse width switching waveform produced by the variable frequency drive (VFD). **<u>All Motors</u>**
2. **High Frequency Circulating Current (from VFD):** High frequency circulating currents may flow due to a high-frequency flux produced by common-mode currents. Motors over 100 HP/75 kW



Line Voltage – Balanced Input Voltage Usually no problem for motors

Balanced voltage condition

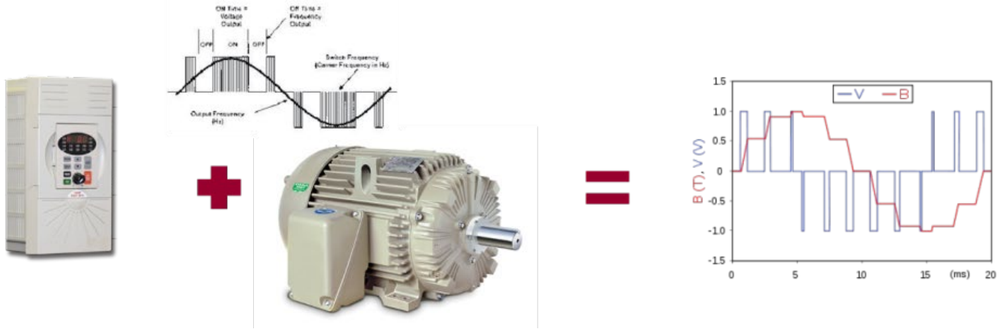


- Electric induction motors are designed for operation on 3 phase sine wave power - either 50 or 60 Hz.
- The input power is balanced in frequency, phase (120 degree phase shift) and in amplitude.
- Common mode voltage - the sum of the 3 phases always equal zero volts when properly balanced.

Note: Bearing protection generally not needed except for large frame motors.

Variable Frequency Drives PWM Voltage - A Problem for Bearings

Common mode voltage condition



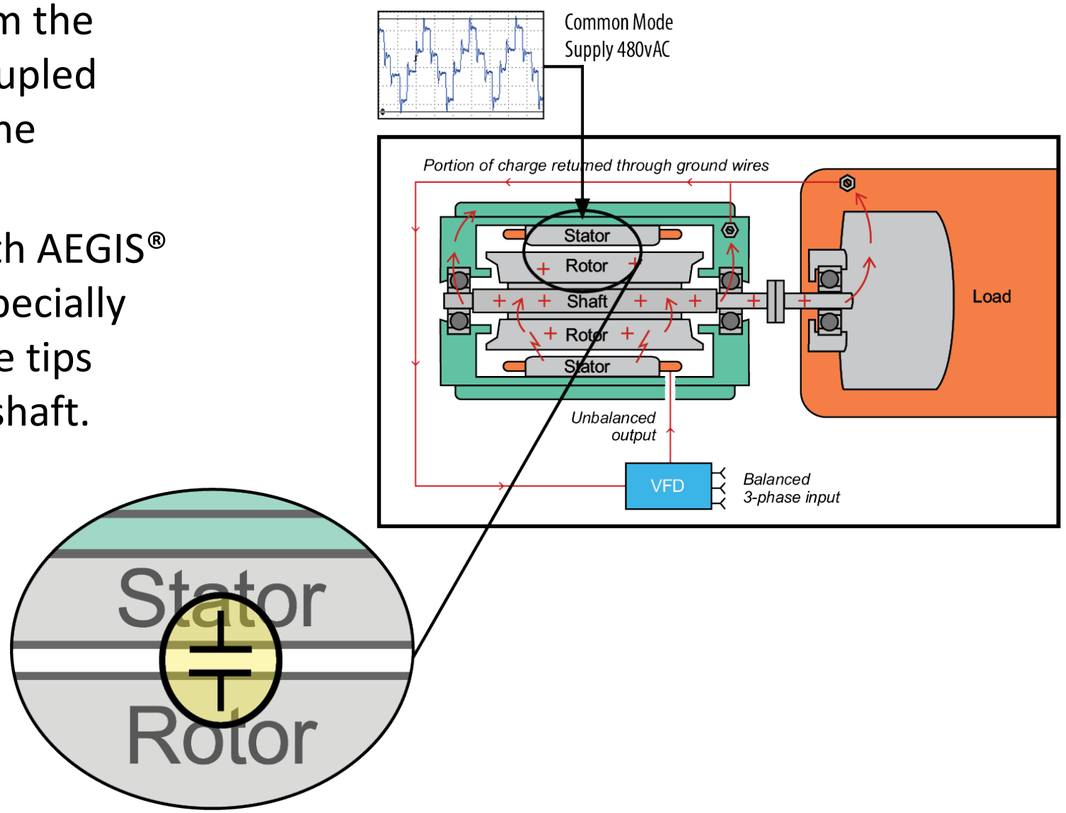
- When operated by VFD, the power to the motor is a series of positive and negative pulses instead of a smooth sine wave.
- The input voltage is never balanced because the voltage is either 0 volts, positive, or negative with rapid switching between pulses in all three phases.
- The common mode voltage is usually a “square wave” or “6 step” voltage wave form.

Bearing protection needed to mitigate electrical discharge machining (EDM) damage in bearings.

Capacitive EDM Current

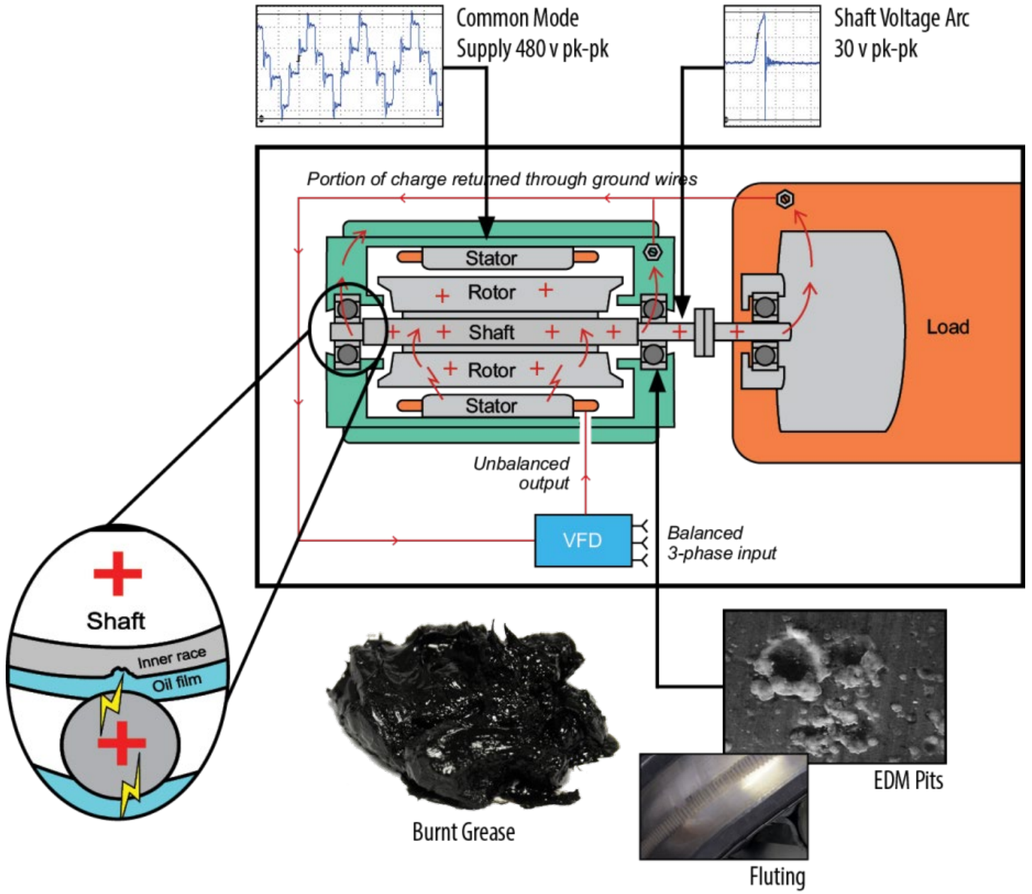
An Electric Motor works like a Capacitor

- The pulses to the motor from the VFD create a capacitively coupled common mode voltage on the motors shaft.
- Voltages are measurable with AEGIS® Shaft Voltage Tester™ and specially designed shaft voltage probe tips that can contact a spinning shaft.



Voltage Arcs through the Bearing

- Electrical discharge machining (EDM) creates thousands of pits
- Bearings degrade, resulting in increased friction and noise
- Eventually, the rolling elements can cause fluting damage to the bearing races
- Bearing lubrication/grease deteriorates/burnt
- Potential for costly unplanned downtime



Testing for Shaft Voltages

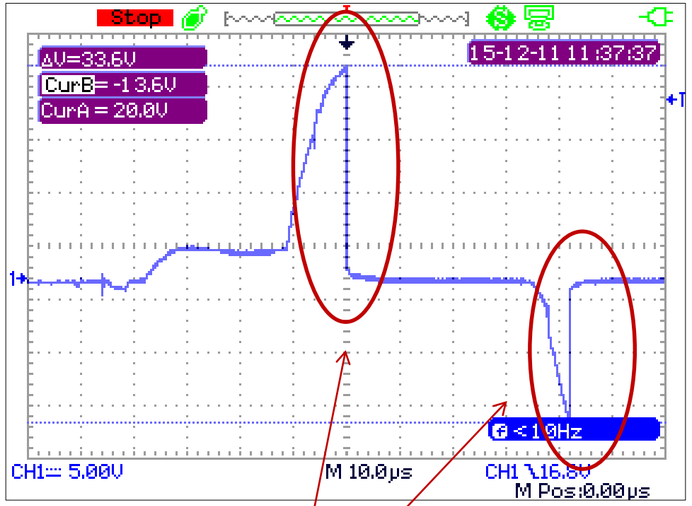
- AEGIS-OSC-9100 Shaft Voltage Tester™ Digital Oscilloscope with 100MHz bandwidth
- AEGIS® Shaft Voltage Probe™ Tips contact the spinning shaft.
- Magnetic base and Probe holder.

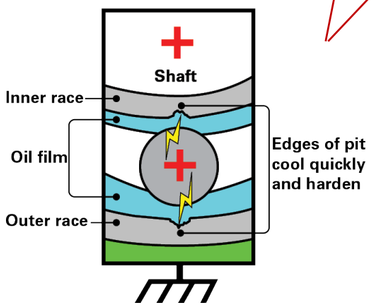
Electrical Discharge Machining (EDM) Wave Form

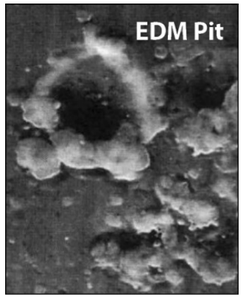
High Peak to Peak common mode voltage discharges

Typically 20 to 120 volts peak to peak. The sharp trailing edge is typical of an EDM pit created in the bearing race.

When the high speed oscilloscope is set up to capture the discharge wave form, one can see the common mode voltage increasing normally and then when the discharge threshold is reached, the high frequency discharge occurs as the current “arcs” through the bearing to ground.

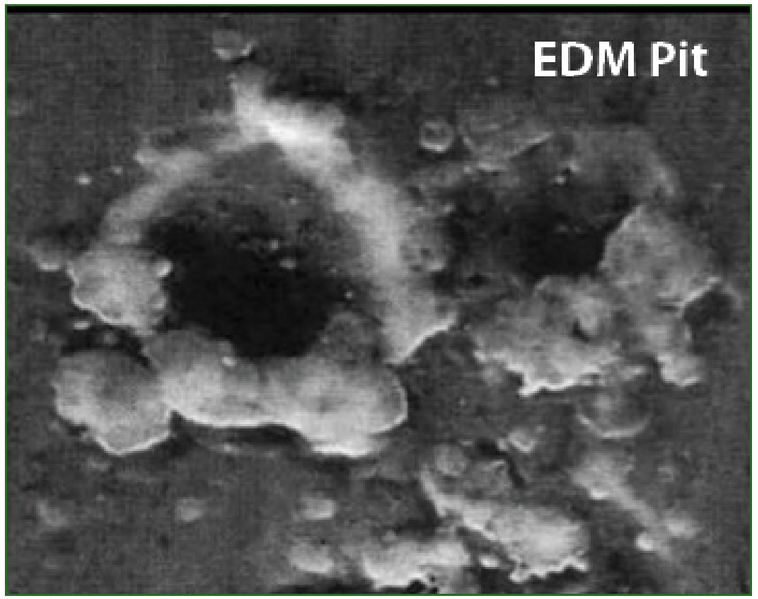


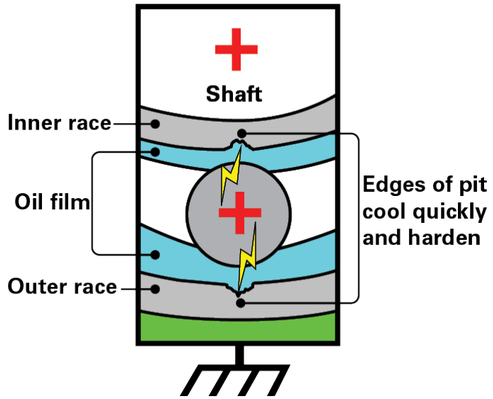




EDM Pit in the Motor's Bearing Race

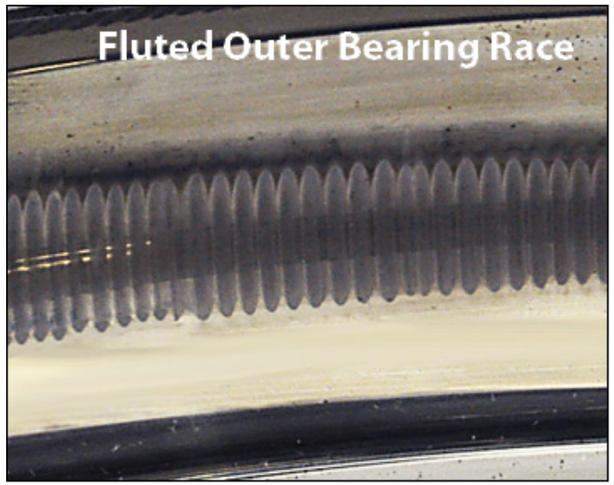
- These voltages reach a level sufficient to overcome the dielectric properties of the bearing grease, they discharge along the path of least resistance — typically the motor bearings — to the motor housing.
- When this event happens, temperatures are hot enough to melt bearing steel and severely damage the bearing lubrication.
- During virtually every VFD switching cycle, induced shaft voltage discharges from the motor shaft to the frame via the bearings, leaving a small fusion crater (fret) in the bearing race.





Frosting and Fluting in Bearing Race

- These discharges are so frequent (millions per hour) that before long the entire bearing race becomes marked with countless pits known as frosting.
- A phenomenon known as fluting may occur as well, producing washboard-like ridges across the frosted bearing race.
- Fluting causes excessive noise and vibration and in heating, ventilation, and air-conditioning systems, it is magnified and transmitted by the ducting.

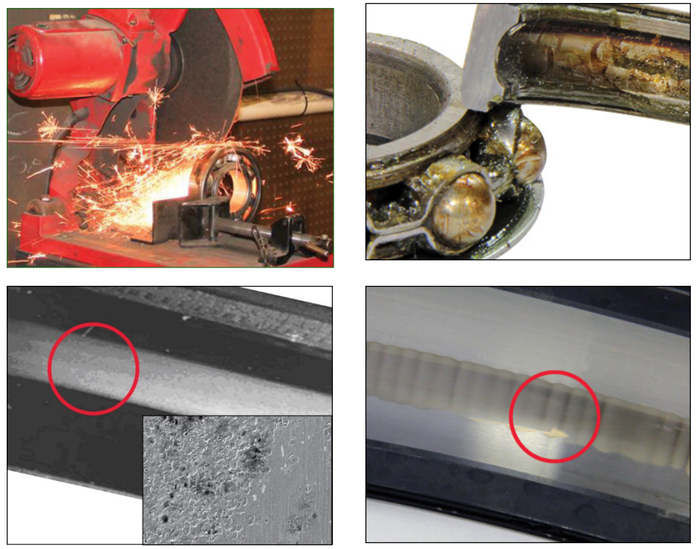


When Bearings Fail, Cut and Inspect

ANSI/EASA Standard AR100-2015, Section 2, Mechanical Repair: *2.2 Bearings*

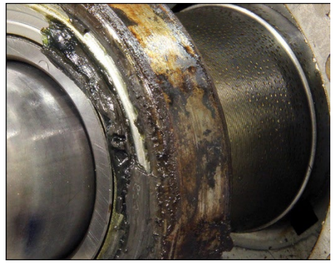
"Bearings should be inspected for failure modes such as spalling, contamination, fretting, fluting, and scoring."

- Burnt bearing grease is blackened and often times contaminated with metal particles. Compare to new bearing grease - is available in many colors.
- Look for evidence of Electrical Discharge Machining (EDM) in the bearing race and ball
- EDM are millions of microscopic electrical pits created when current discharges through the motor's bearings. The individual pit is usually between 5 and 10 micron diameter.



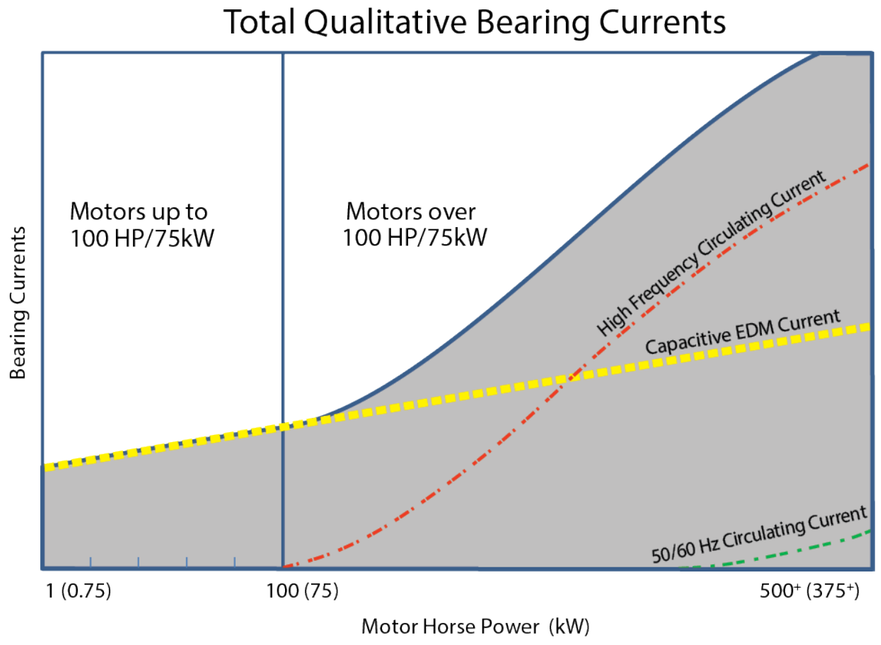
Bearing Failure – A Problem Worth Solving

- Regardless of the type of bearing or race damage that occurs, the resulting motor failure often costs many thousands or even tens of thousands of dollars in downtime and lost production.
- 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.



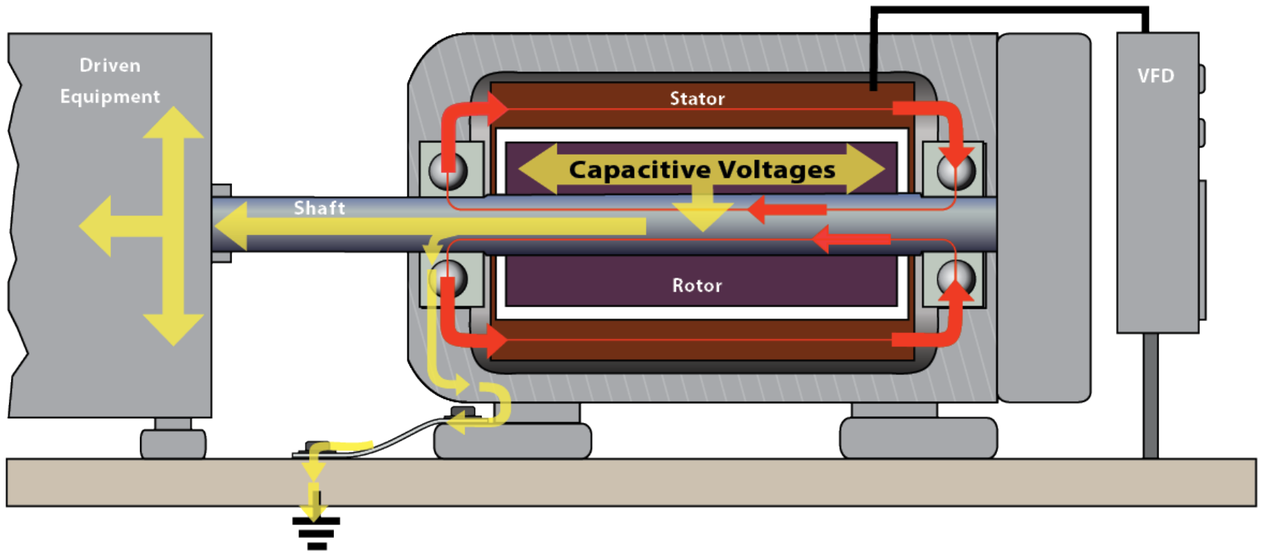
High Frequency Circulating Currents on VFD Driven Motors

- High frequency circulating currents may flow due to a high-frequency flux produced by common-mode currents in KHz or MHz frequencies.
- Usually present in motors above 100 HP (75kW).
- Circulate through the motor bearings, shaft to frame



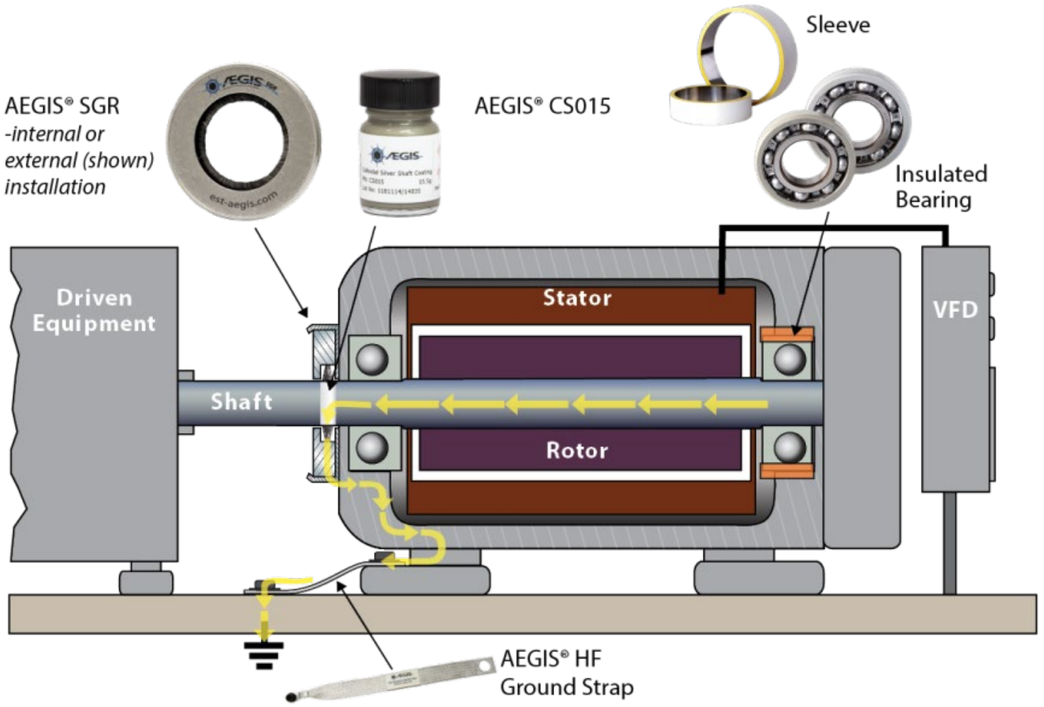
Best Practice: Install AEGIS® Ring for capacitive EDM current on one end and interrupt the high frequency circulating current in the bearing by insulating the opposite end.

Voltage Discharges in Attached Equipment and Gear Boxes



Along with the high frequency circulating currents you will also have capacitive EDM current which can travel down the shaft to attached equipment. Therefore it is important when considering high frequency circulating current to also mitigate capacitive EDM current with the AEGIS® Shaft Grounding Ring to divert the voltages away from the drive end motor bearing and/or the attached equipment to ground.

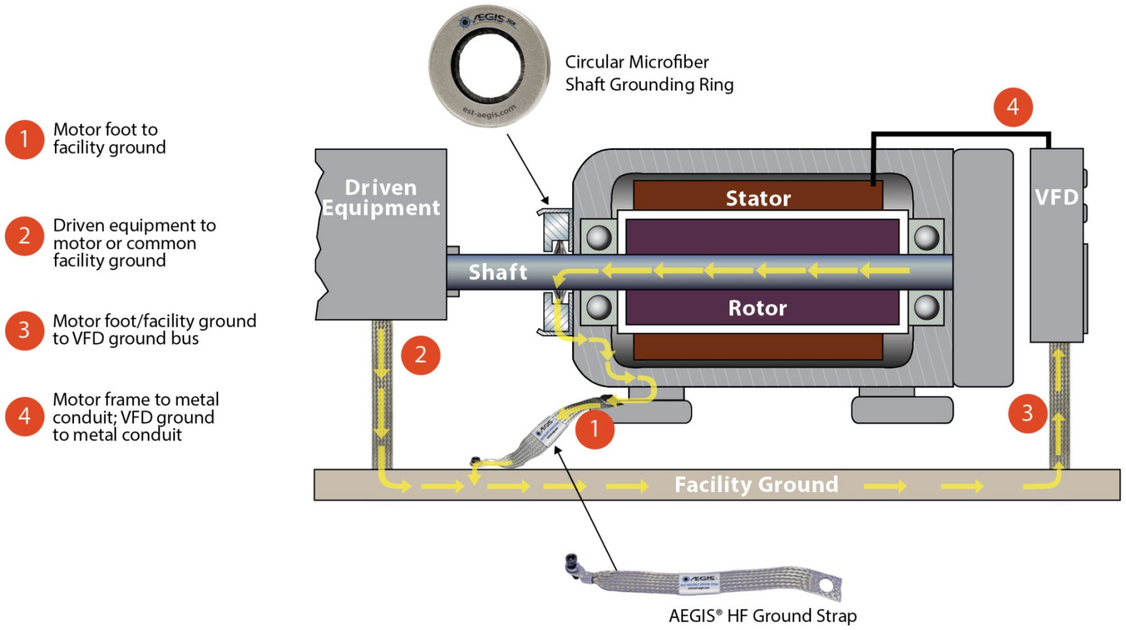
Best Practice - Protect from Both Capacitive EDM Current and High Frequency Circulating Current



Install an AEGIS® Bearing Protection Ring on the drive end of the motor for capacitive EDM current and stop the high frequency circulating currents by insulating the non-drive end bearing of the motor. This practice will protect both the motor's drive end bearing and the attached equipment.

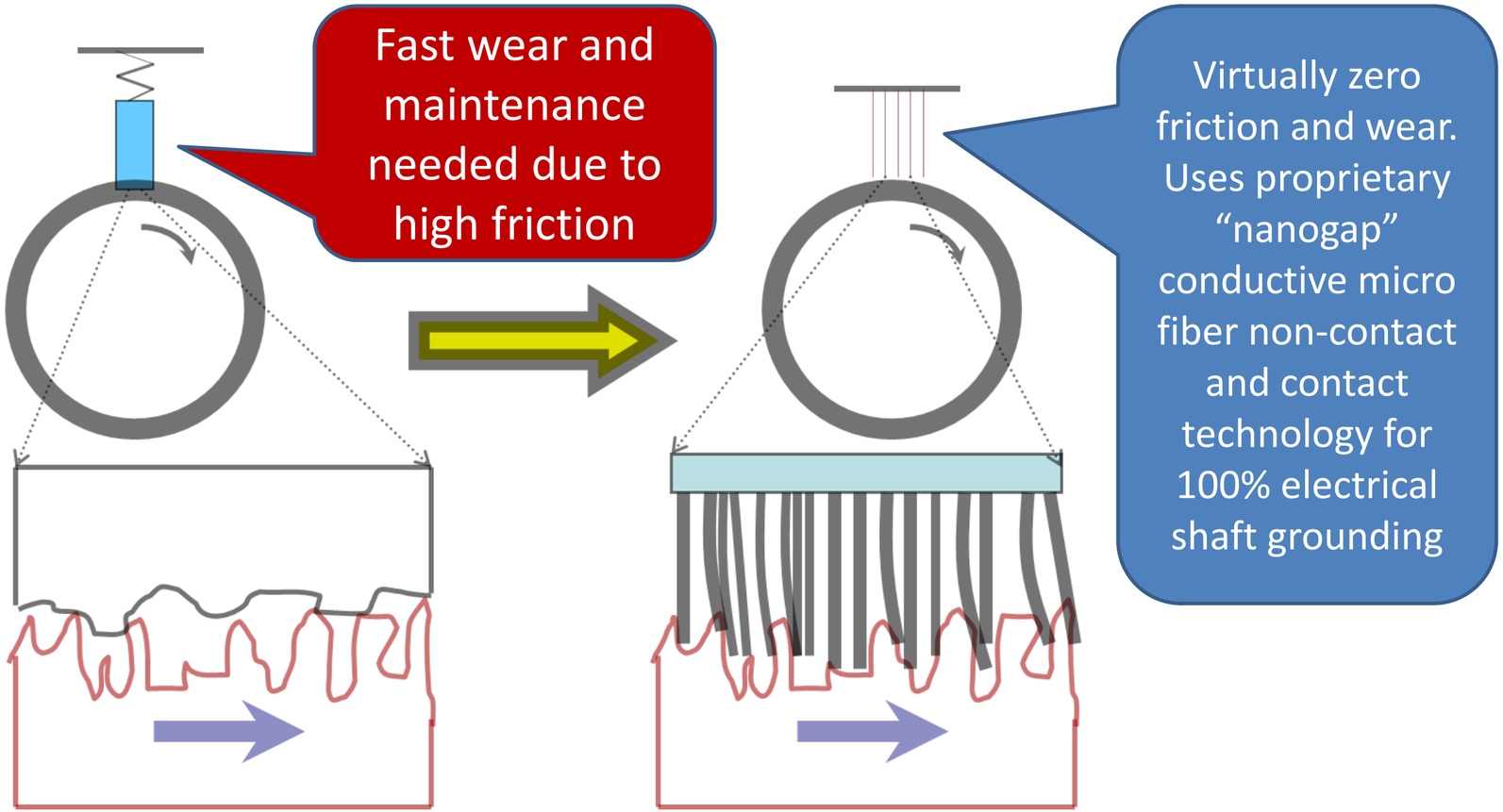
High Frequency Ground Path from Motor

- While the AEGIS® Ring conducts harmful shaft voltages away from the bearings to the motor's frame, it is advisable to also ensure a low impedance path to earth ground.
- Recommended by motor and drive manufacturers, this high frequency grounding path is best accomplished with a braided strap from the motor to ground.
- The AEGIS® HFGS (High-Frequency Ground Strap) is a braided cable used to lower the impedance between the motor's frame and earth ground. Secure one end to motor and the other end to earth ground and from there back to the VFD.



Spring Energized Brush

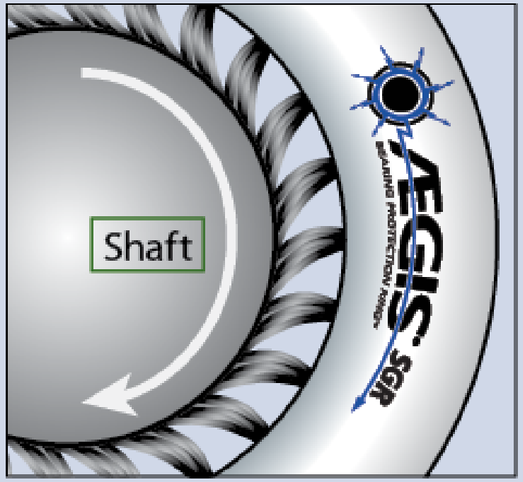
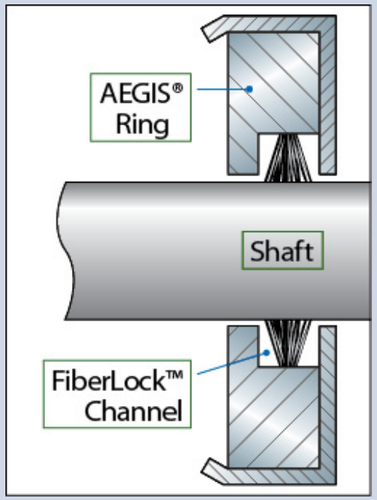
AEGIS® Conductive Micro Fiber



Conventional "Single Point" contact with carbon block – Designed for DC current

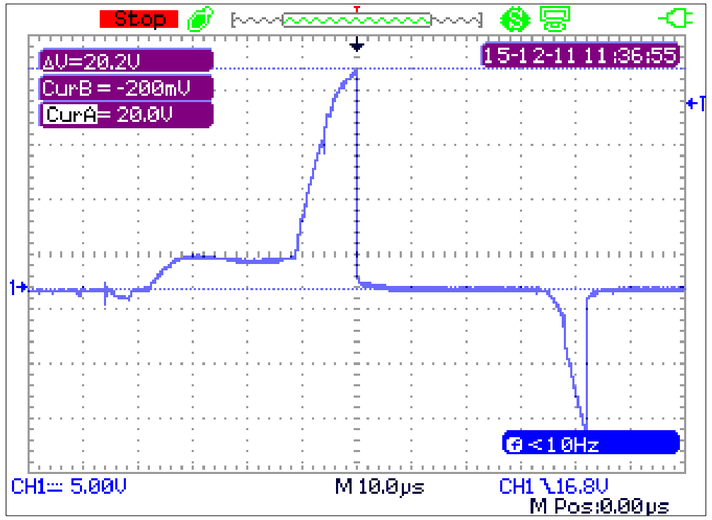
AEGIS 100% circumferential Microfiber Contact / Non Contact – Designed for high frequency VFD voltages 10 KHz to 100 MHz

Patented AEGIS® Ring Design

Specially Designed Microfibers Flex Without Breaking – Ultra Low Friction	Patented FiberLock™ Channel Secures and Protects Fibers
	

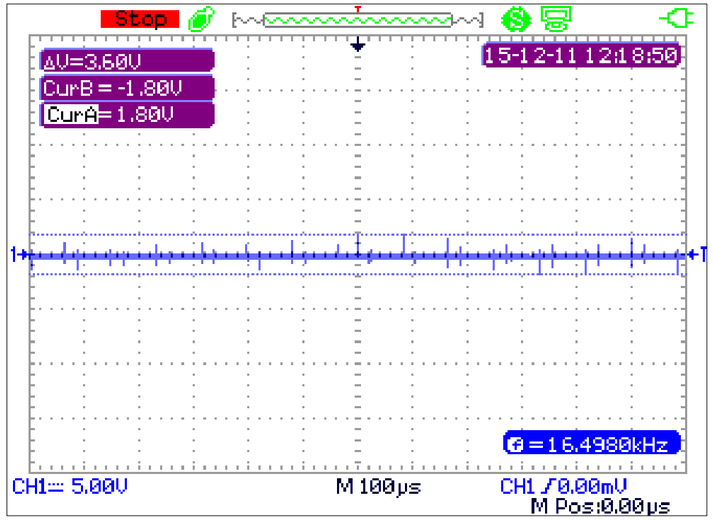
Before & After Shaft Voltage

SHAFT VOLTAGE READING
<u>WITHOUT</u> AEGIS® RINGS



PROBLEM

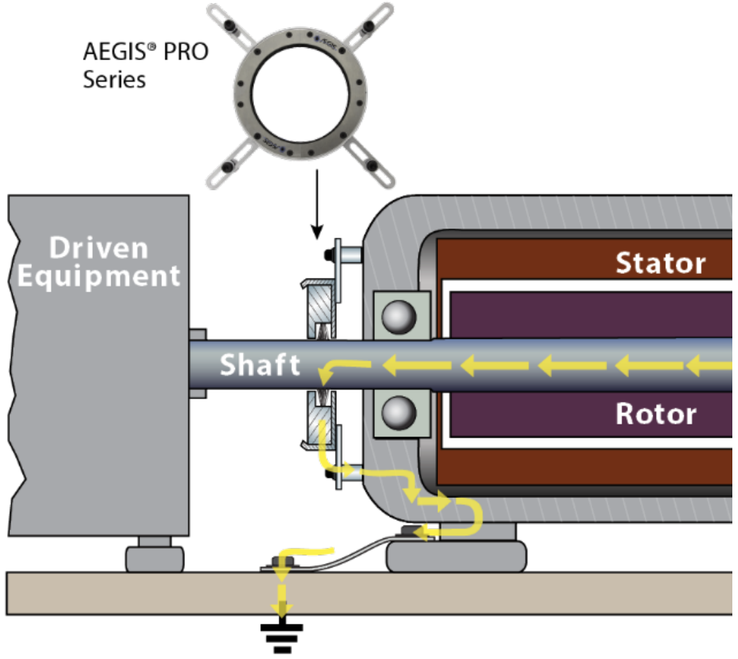
SHAFT VOLTAGE READING
<u>WITH</u> AEGIS® RINGS
INSTALLED



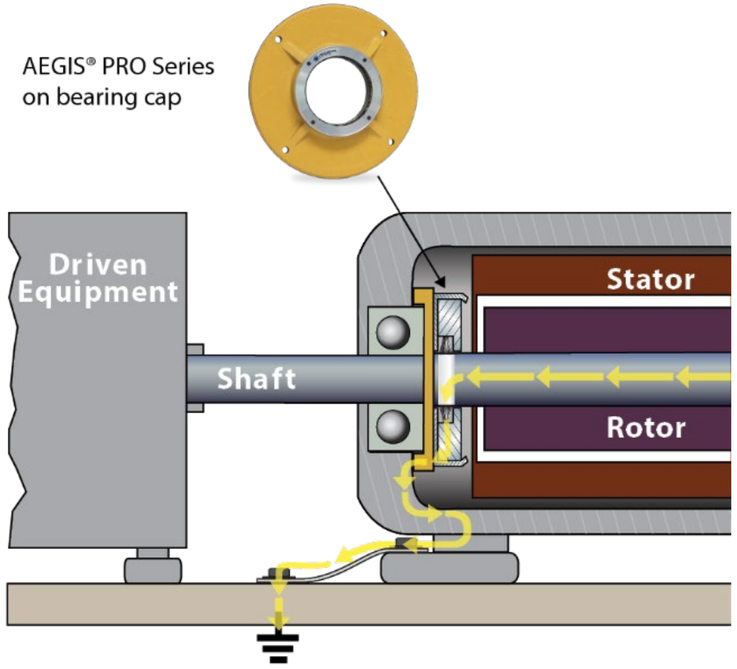
SOLUTION

AEGIS® PROSL

External Installation

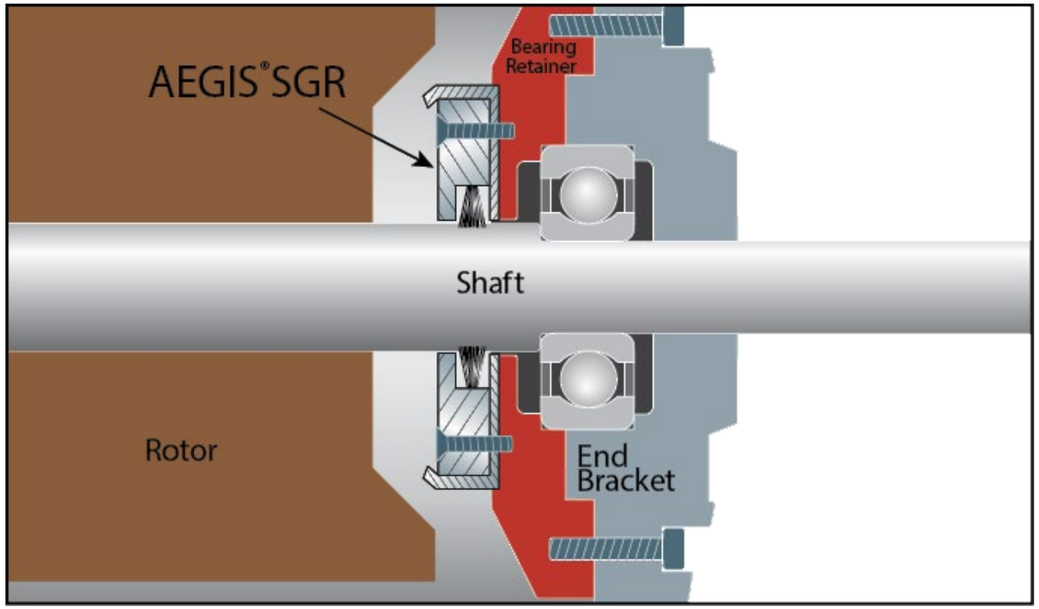


Internal Installation



AEGIS Installation - *Internal*

AEGIS® Bearing Protection Rings are ideally installed on the inside of the motor to provide protection from ingress of dirt and dust. Motor manufacturers commonly use this installation as a best practice in stock catalog motors equipped with AEGIS® Rings.



Follow AEGIS® Best Practices for motor shaft preparation and ring installation. Use AEGIS® Colloidal Silver Shaft Coating when installing AEGIS® Rings to enhance the shaft conductivity and help prevent oxidation.

Variable Frequency Drives and Electrical Bearing Damage

- Bearing currents in motors operated by variable frequency drives (VFD) can cause premature or catastrophic failure.
- High energy pulses with extremely fast rise times (dv/dt) discharge in the motor's bearings.
- Cause electrical discharge machining (EDM) damage to the race and rolling elements.
- Motors need bearing protection - AEGIS® Shaft Grounding Rings – installed on the motor.
- Attached equipment and Gear Boxes need protection