A PRACTICAL GUIDE TO UNDERSTANDING BEARING DAMAGE RELATED TO PWM DRIVES

Don Macdonald
IEEE Member
Toshiba International Corporation

Will Gray
IEEE Member
Toshiba International Corporation

***Abstract* – The performance and reliability of AC Adjustable Speed Drives (ASDs) is continually improving. One of the key reasons for improvement has been the advent, development and use of Pulse Width Modulated (PWM) drives utilizing faster switching devices, primarily Insulated Gate Bipolar Transistors (IGBTs). As with many other developments, improvements in some areas may cause problems in others. An increased bearing failure rate in motors is one of the negative effects of these types of drives.**

To mitigate bearing current damage in motors, as well as in loads and other auxiliary equipment attached to the motor shaft, it is important to understand how these currents are generated.

In addition to theoretical explanations, actual field cases and solutions will be reviewed.

1. INTRODUCTION

The phenomenon of motor shaft voltages producing circulating shaft currents has been recognized since the 1920s. When a motor is operated by sinusoidal power, shaft voltages are caused by alternating flux linkages with the shaft. The linkages are associated with flux unbalance caused by:

- rotor static or dynamic eccentricity
- rotor and stator slotting
- axial cooling holes in the stator and/or rotor laminations
- shaft keyways
- rotor core support arms
- joints between segmental laminations
- directional properties of magnetic materials
- supply unbalance
- transient conditions.[1]

Shaft voltages exceeding 300mV require one bearing of the motor to be insulated to prevent circulating current damage to the bearings (see Fig. 1). Typically this phenomenon only occurs on 500 frames and larger machines.[2] Normally the Opposite Drive End (ODE) bearing is chosen. If the Drive End (DE) is insulated, the driven load can provide an electrical path that completes the loop to allow current to flow.

PWM drives can cause increased circulating currents to flow due to a high-frequency flux produced by common-mode currents which link the stator, rotor and bearing loop. This is an inductive rather than capacitive effect.[3] Motors become more asymmetrical at high frequencies because the high-frequency capacitively coupled currents depend heavily on the location of the first few turns within the slot. Since placement of the turns in random-wound motors is not well controlled by any manufacturer, even a motor which is symmetrical at low frequencies becomes asymmetrical at high frequencies.[4]

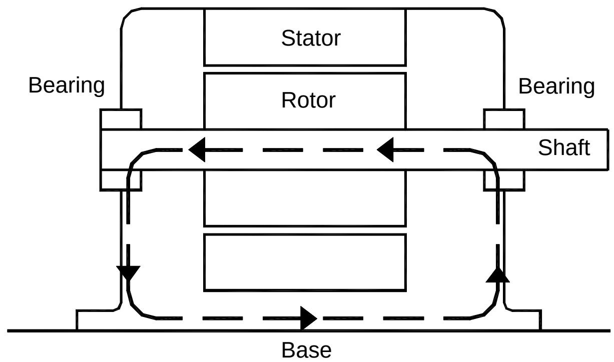

Fig. 1 Inductive circulating currents

In addition to the preceding, PWM drives utilizing Bipolar Junction Transistors (BJTs) or IGBTs can cause Electric Discharge Machining (EDM) currents.[5] PWM inverters excite capacitive coupling between the stator windings, the rotor and the stator frame. This common mode current does not circulate but rather travels to ground see Fig. 2). The path to ground can be through both motor bearings and/or load or auxiliary equipment bearings.

This paper will investigate the phenomenon of induced shaft voltages caused by PWM, AC variable-speed drives and will discuss methods of mitigating their harmful effects.

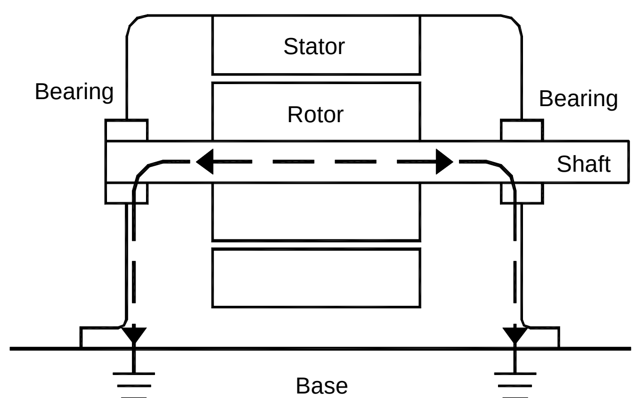

Fig. 2 Capacitively coupled current flow

II. Recognition of Shaft-Current Damage

Ideally, when a bearing fails, the cause of the failure is investigated. Often, however, bearings are replaced during normal maintenance procedure and the root cause of the problem is not always immediately discovered. This makes elimination of the failure source much more difficult since the equipment is back in service.

Electrical damage to anti-friction bearings primarily appears as fluting. Initially, EDM currents cause permanent microscopic marks in the bearing race. The marking interval is evenly spaced according to the ball spacing. The initial microscopic marks cause slight vibration which is too small to be picked up by vibration-analysis equipment. Bearing balls or rollers fall into these microscopic pits in the race's load zone, displacing a small portion of lubricant. Slight removal of some of the lubricant reduces the dielectric value, allowing a voltage transient to cause a larger current to flow. This damage causes the bearing threshold voltage to be lowered, allowing lower-level transients to further mark the bearing. Continued deterioration usually occurs at the bottom of the original race markings. This is why fluting marks occur in the same place on the bearing-race load zone and why many bearing fluting failures appear the same.[6] An example of fluting damage is shown in Fig. 3. (Current damage often initially appears as frosting which looks like a satin finish on the raceways and balls or rollers).

One study[7] investigated 1150 ASD powered AC motors in similar clean-room applications. The results showed that 25% of motors in operation for less than 18 months had bearing damage caused by electrical discharge. It also showed that for motors which had been in operation longer than 18 months, with an average age of two years, 65% had bearings damaged due to electrical discharge. Note that clean-room applications generally use drives running with high carrier frequencies (typically 12KHz or higher) to minimize motor audible noise and run at the same speed continuously (24 hours per day, 7 days per week).

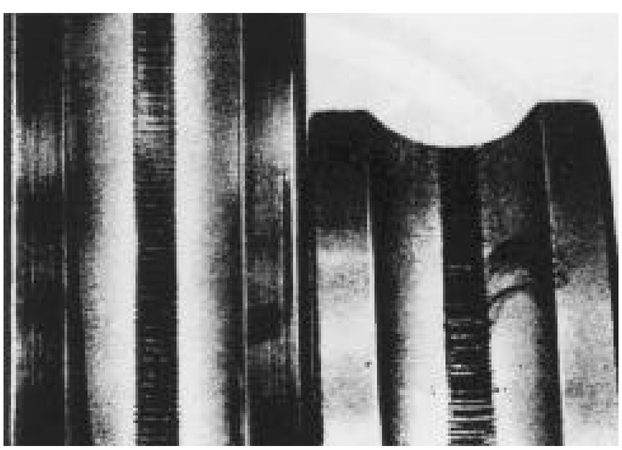

Fig. 3 Typical fluting damage to anti-friction bearings.

Theoretically, a periodic square wave is composed of a fundamental frequency plus infinite harmonic frequencies. Because of the very fast rise times of IGBTs, the PWM pulses produced are almost perfect square waves, rich in high frequencies. Since a capacitor approximates a short circuit at high frequencies, IGBTs induce more capacitively coupled current than slower devices ($I \approx C \times dv/dt$).

Higher carrier frequencies induce more capacitive energy to the rotor and the stator frame since there are more pulses in a given period.

Our field experience has shown that IBGT drives with high carrier frequencies (e.g., above 8 KHz) lead to significantly faster bearing deterioration than those with lower carrier frequencies.

An example of problems related to ASDs occurred at a large semiconductor manufacturer in the US Pacific Northwest. After 18 months of operation a pattern of bearing noise and vibration was noticed in a population of approximately 100 motors. The 15 HP, 460V, 900RPM, open drip proof (ODP) motors were powered by high-carrier-frequency PWM IGBT inverters. The application was plug fan drives in a clean-room chip fabrication facility. Even though the noise and vibration were at relatively low levels and the motors continued to operate, the application was still considered a failure. Initial inspection verified that bearing damage was a result of shaft current caused by the IGBT inverters.

The next step was to repair the motors and apply countermeasures to prevent further problems. In an effort to minimize downtime and cost, a single insulated bearing bracket was fitted. As discussed earlier, this was the most common solution used on large machines for many years. Insulating one bearing proved to be unsatisfactory because the uninsulated bearing failed at a faster rate. The next measure was to install shaft-grounding brushes. This was also not completely successful, due to improper installation. In addition, brushes posed maintenance problems and contamination concerns due to the carbon brush material. As a retrofit, insulating one bearing and adding a ground brush was the most practical choice; however, in hindsight, it would have been better to insulate both bearings. At the time, the phenomenon was not as well understood and this preventative measure was not considered.

III. Bearing Damage Mechanism

The degree of damage caused by EDM currents depends on many factors. The contact area consists primarily of irregularities on the surfaces of the balls or rollers and races touching each other. This determines how much current can flow without causing localized overheating to the bearing assembly. At standstill, there is significant contact area and low resistance. As the motor speeds up (typically above 10% of rated speed), the bearings "float" on a film of oil. The effective resistance of this film is a function of the film thickness and the type of lubricant.

When a high-resistivity grease is used and the bearings are "floating" on the oil film, the equivalent-circuit characteristic changes from a resistor to a capacitor. Imperfections on the bearing surfaces occasionally puncture the oil film and discharge the rotor. (Discharges due to metal-to-metal contact occur at low voltage levels and do very little direct damage to the bearing surface.)

The better quality the bearing, the less often these low level discharges occur, allowing the rotor to charge for longer periods of time and hence attain higher voltage levels. (Typically, high-quality bearings charge as much as 80% of the time due to a uniform oil film. Low-quality bearings charge as little as 5% of the time due to frequent metal-to-metal contact.) If the rotor voltage exceeds the threshold voltage (V_{th}) of the oil film between the balls or rollers and the races of the bearing, the oil film's dielectric strength is exceeded. At this point, destructive EDM currents and arcing occur. It is interesting to note that contact time between the balls and outer race is longer than contact time between the balls and inner race, hence the bearing wear from EDM and dv/dt currents is greater in the outer race.[8]

The existence of EDM currents with PWM voltage source inverter drives depends on the presence of all of the following conditions:

1. Excitation, which is provided by the source voltage to ground (V_{sg})
2. A capacitive coupling mechanism, between stator and rotor (C_{sr})
3. Sufficient rotor voltage build-up which is dependent on the existence of bearing capacitance (C_b)

There are two basic groups of variables which affect capacitive bearing current:

1. Mechanical Variables – Shaft voltages and bearing currents depend on the existence of C_b. Bearing impedance becomes capacitive only when a lubricating film occurs in the contact regions between the balls or rollers and the raceways. The capacitance is dependent on film thickness, which is a function of radial load, velocity, temperature, lubricant dielectric strength and lubricant viscosity. The contact area increases proportional to the bearing load raised to approximately the ½ power.[9]
2. System Impedance – The system impedance (see Figs. 4 and 5) is composed of the stator winding to frame capacitance (C_{sf}), the stator winding zero sequence impedance (L_o and R_o), rotor to frame capacitance (C_{rf}), C_{sr} and C_b. Z_l accounts for the mechanical and electrical abnormalities and randomness of the bearing.

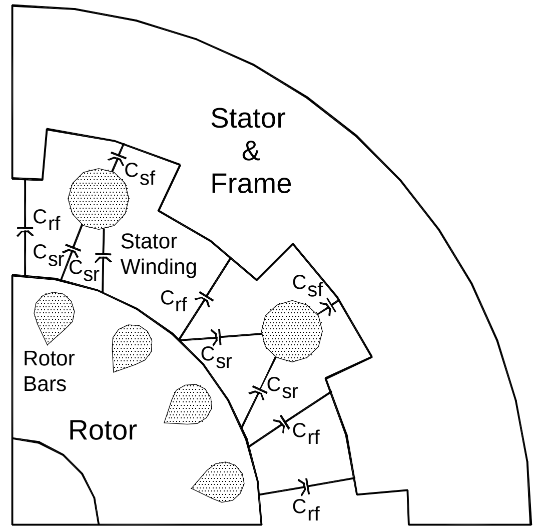

Fig. 4 Pictorial Diagram of Motor Capacitances[5]

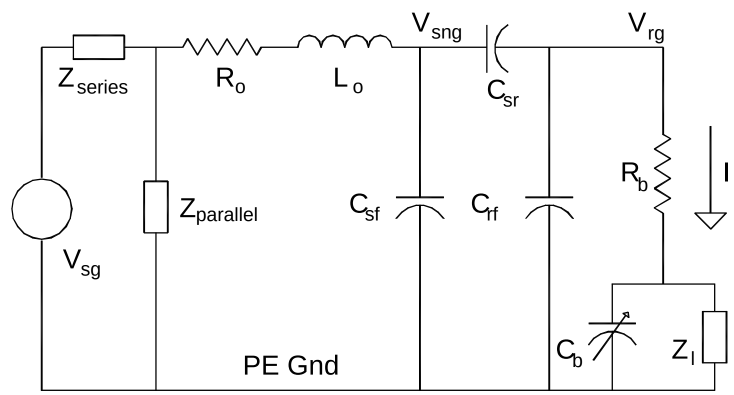

Fig. 5 Common mode equivalent model[5]

R_o & L_o are stator winding zero sequence impedance
V_{sg} is the Source Voltage to Ground
V_{sng} is Stator Neutral to Ground Voltage
V_{rg} is Rotor to Ground Voltage
C_{sf} is Stator Winding to Frame Capacitance
C_{sr} is Stator Winding to Rotor Capacitance
C_{rf} is Rotor to Frame Capacitance
C_b is Bearing Capacitance
R_b is Bearing Resistance
Z_l is the variable impedance of the bearing, often represented as a switch which randomly closes due to quasi-metallic surface contact
PE Gnd is Protective Earth Ground

IV. Mitigation Of Bearing Damage Due To Electrical Discharge

As mentioned previously, low-quality bearings have more contact between balls or rollers and the raceways because of surface irregularities. This increased contact provides less opportunity for damaging EDM currents and arcing to occur. The implication is that a low quality bearing may, given a certain set of circumstances, provide longer life than its higher-quality counterpart. This paper is not suggesting use of low-quality bearings as a recommended solution.

EDM discharge can be virtually eliminated by providing electrostatic shielding between the rotor and stator. The same concept has been used for many years in transformers and is referred to as a Faraday shield. One method of accomplishing this is to install a grounded metallic foil tape so that it covers the stator slots and the end turns of the windings. Experiments on an unloaded motor have confirmed that this dramatically reduces the rotor voltage and the dv/dt currents produced through the bearings.[8] This solution may not be practical since special motors and spares are required.

Another solution to reduce rotor to ground voltage (V_{rg}) buildup is to use a low-conductivity grease. The associated drawback is that experience with conductive grease shows that bearing life can decrease by a factor of three as compared to conventional grease.[3] One bearing manufacturer suggests that damage due to bearing currents can be considerably reduced by using a low-viscosity grease of about 7 centistokes with the addition of graphite to reduce current density. The size of the graphite particles should be approximately the same as the thickness of the lubricating film between contact surfaces so that the conducting area is increased, but not so small that the particles are suspended in the oil film.[10] (A point of interest is that as bearings age, contaminants from EDM and mechanical wear can significantly change the lubricant's electrical characteristics.)

The most common way to eliminate bearing currents is to insulate the bearings. Please note that both bearings must be insulated because capacitively induced currents flow to ground. If only one bearing is insulated, all the current will flow through the uninsulated bearing, causing rapid failure. If the insulated bearing solution is chosen, any connected mechanical load must be insulated or the current will flow from the motor shaft through the load bearing(s) to ground or through other connected components such as tachometer bearings. If it is not possible to isolate the mechanical load and connected components, a shaft-grounding brush should be added to provide a low-impedance path to ground.

A common solution, which has been used with DC machines for many years, is to simply add a shaft-grounding brush without insulating the bearings. When adding a grounding brush, it is important that the motor frame be adequately grounded for high frequencies. If not, there is still a potential current path through the load bearing(s).

Induced voltage is created by the steep wave front of each PWM pulse. The faster the rise times, the higher the orders of harmonic currents present. The spectrum ranges from almost DC to as high as 30 MHz for IGBT drives, which switch at 0.1µs.

High frequency currents only travel on the surface of the grounding conductor. If the ground conductor is long it is very possible that a portion of the current will still flow from the motor frame through the load bearings to ground.

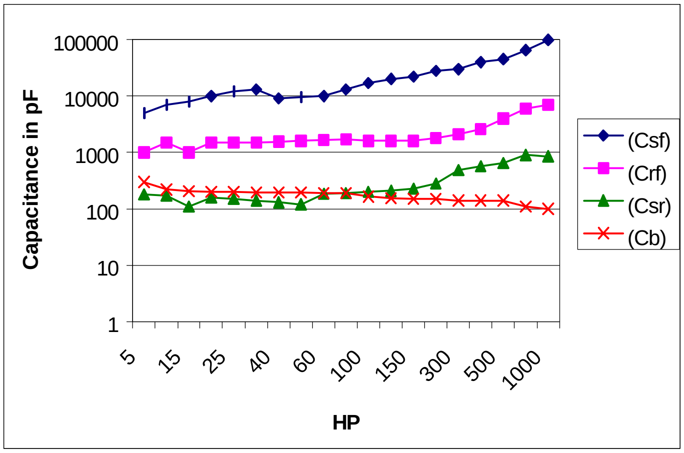

Fig. 6 Relative Motor Capacitance Values[5]

Effective high frequency grounding can often be accomplished by simply making sure that the motor mounting base is welded to the mechanical load's base. A braided copper grounding strap bonding the motor frame to the mechanical load's base will serve the same purpose. (Sometimes the load is connected to the framework of the building through piping, etc. which, to the high frequency components, is a lower impedance than a conventional ground wire from the motor frame to the electrical ground.)

As seen in Fig. 6, the calculated capacitance between the windings and the stator frame C_{sf} is typically in the order of 30 - 100 times higher than the capacitance between the windings and the rotor C_{sr}. This means that stator-coupling currents, though not normally taken into account, are considerable. If the motor is not adequately grounded for high frequencies or not grounded at all, these currents can flow through the shaft brush and then through the load bearings. In this case, adding a shaft brush can actually increase bearing currents in the driven equipment (see Fig. 7).

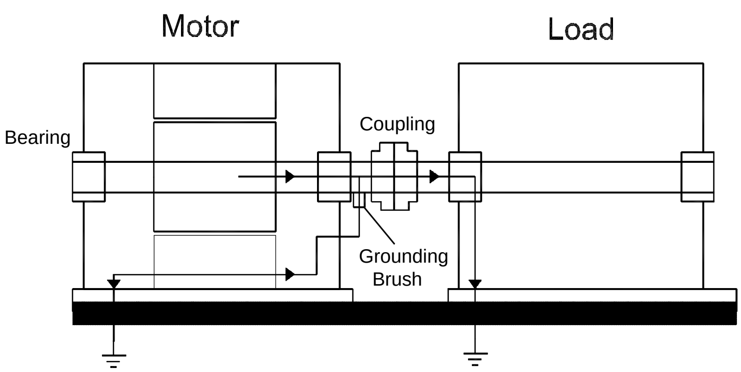

Fig. 7 Paths for common-mode currents to ground

TABLE I[11]
TEST RESULT COMPARISONS FOR A 20HP MOTOR

	Without Filter	Conventional Filter	Proposed Filter
Peak Voltage at Motor Terminal	1260V	750V	730V
Differential mode dv/dt at motor terminals	3037 V/µs	1267 V/µs	120 V/µs
Induced shaft Voltage to Ground	864 mV (RMS)	442 mV (RMS)	234 mV (RMS)
Leakage Current to Ground	430 mA (RMS)	252 mA (RMS)	132 mA (RMS)
Total Filter Power Loss	0 (Watts)	53.5 (Watts)	125 (Watts)

Following the same logic, if a shaft brush is not used, it is very important that the motor frame be well grounded. This is because the voltage produced by the capacitance between the windings and the stator frame (C_{sf}) may discharge through the motor bearings and to ground through the load bearing(s).

Research is ongoing with soft-switching type PWM ASDs as compared to the conventional hard-switching types. To date there has been limited success in eliminating bearing discharge. The problem with soft-switching and other methods of improving the PWM output waveform is that when viewed phase-to-phase they look very clean but phase-to-ground (common mode) they are not. Common-mode noise is what excites the stray capacitance between the stator windings to the rotor and the stator frame, causing voltage build-up.

The ratio of common-mode noise caused by a PWM drive compared to a sine wave is in the order of 10:1 or more. The addition of a filter which combines both common-mode and differential-mode filtering can reduce this ratio by as much as 70%. Refer to Table I for test results completed with a 20HP, 460V, high-efficiency induction motor and 480V PWM IGBT inverter utilizing this output filter compared to a conventional filter or no filter. Note that with a conventional filter (without the common-mode connection), which has oversized inductance and capacitance such that a near sinusoidal line-to-line voltage is provided, common mode dv/dt is still high.[11]

Figure 8a shows the path of common-mode current flow in a typical installation. Figure 8b shows the addition of a common-mode filter which connects the wye point of the filter to a "neutral" point on the DC bus. This filter arrangement provides a low-impedance path from the output of the ASD back to a neutral point on the DC bus instead of through the motor. (Note that further research has shown that the wye point of the filter can be connected to the negative DC bus with similar results.[11])

An easily implemented mitigation is to keep the carrier frequency as low as practical. A value of between 1500 and 3000Hz minimizes the amount of energy transferred to the rotor while maintaining good drive performance. The tradeoff is increased audible noise.

Output reactors have an effect on the common mode noise generated which can increase the possibility of elevating the transfer impedance voltage drop (U_L). This adds to the probability of C_b charging, thereby causing EDM discharges. RLC-type output filters should be considered instead.

Cable length, cable type and grounding arrangement can impact the likelihood of discharge through the motor, load or auxiliary equipment bearings. Refer to Fig. 9a for a simplified physical arrangement drawing.

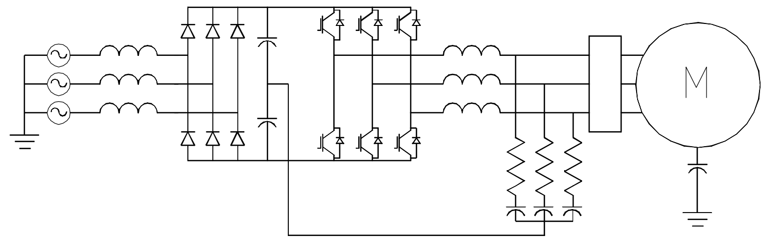

Fig. 8b Proposed output filter to reduce differential-mode and common-mode dv/dt at the terminals of the motor.[11]

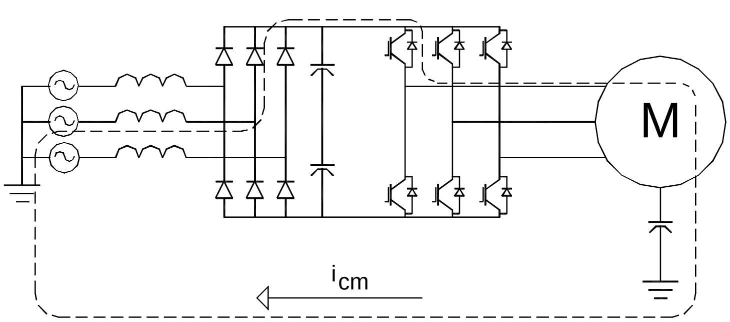

Fig. 8a Common-mode current flow in a conventional ASD and motor[11]

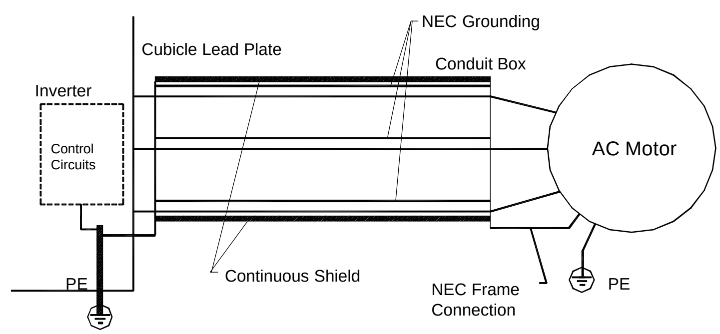

Fig. 9a Cable Configuration Diagram[12]

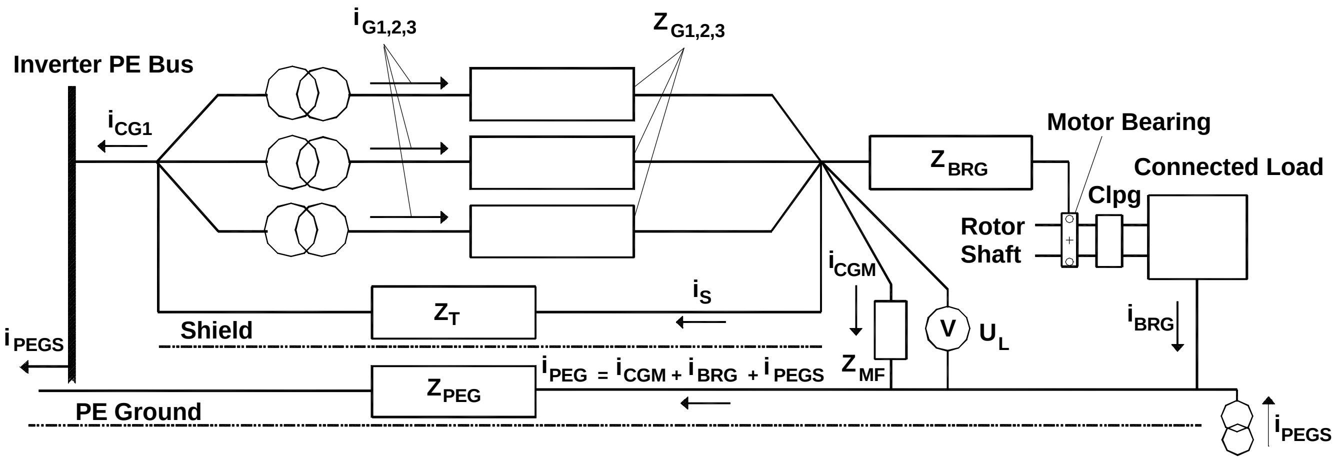

Fig. 9b Cable Equivalent Circuit1[12]

$Z_{G1,2,3}$ is the common mode impedance in each of phases 1, 2 & 3
Z_{BRG} is the equivalent bearing impedance
Z_S is the shield or sheath impedance
Z_{MF} is the common mode impedance to ground through the motor frame
Z_T is the cable-shield or sheath-transfer impedance
Z_{PEG} is impedance of the Protective Earth Ground
$i_{G1,2,3}$ is the common mode current in each of phases 1, 2 & 3
i_S is the shield or sheath current
i_{PEG} is the Protective Earth Ground current
i_{CGM} is the common mode current through the motor frame to ground
i_{BRG} is the bearing current to ground
i_{PEGS} is the Protective Earth Ground System current flowing from other parts of the system
U_L is the Transfer Impedance voltage drop

Fig. 9b is the equivalent schematic of a typical cable. Due to the existence of stray capacitance, cables cause common-mode currents to flow. If the motor frame is not grounded (Z_{MF} is open-circuited) or if Z_{MF} has a high impedance to high frequencies, the return path for common-mode current is the cable shield (or armor).

Shield currents produce a resultant cable-transfer impedance (Z_T) voltage drop, shown as U_L in Fig. 9b. The higher the value of the cable-shield or sheath-transfer impedance (Z_T) and of common-mode impedance to ground through the motor frame (Z_{MF}), the more likely discharge will occur through the alternative current return path, which is through the PE Ground via the motor and/or load bearings.

Testing has shown that cables which have a continuous shield or continuous armor provide the lowest common-mode current plus relatively low frame voltage.[12]

The recommended cable for PWM ASD application has six symmetrical conductors, 3∅ and 3 ground conductors) with a continuous corrugated-aluminum armor-type sheath. To ensure that the cable characteristics are fully exploited, proper connectors need to be utilized to maintain low ohmic contact resistance to the armor which essentially becomes a shield.[12]

V. Conclusions

When a bearing fails, especially on a motor being powered by a PWM ASD, the bearing and lubricant should be examined to determine the cause of failure. If the damage is due to EDM, corrective measures should be considered.

As discussed, there are several possible practical solutions to mitigate bearing currents which include:

1. Selecting a carrier frequency which is between 1500 and 3000Hz if practical. This significantly reduces the energy transferred to the rotor.
2. Adding a common mode filter to mitigate common mode noise.
3. Insulating both motor bearings to prevent current flow plus isolating all mechanical load and/or auxiliary equipment bearings (such as tachometers).
4. Adding a shaft grounding brush or brushes to shunt common mode currents (ideally with the ODE bearing being insulated).
5. Making sure that the motor frame is suitably grounded for high frequency currents. This prevents stator frame currents from flowing through the connected mechanical load or auxiliary equipment bearings via the motor bearings (or grounding brush).
6. Changing the cable to the recommended type to minimize the common mode current.
7. As a temporary measure, using conductive grease.

New installations should be designed with the bearing current phenomenon in mind and take into account the issues discussed in this paper. This is particularly important if high carrier frequencies are planned to be used.

REFERENCES

[1] Pratt, J.W., “Shaft Voltages Caused By Alternating Flux Encircling The Shaft,” *Electrical Machines and Drives,* 11-13 September 1995, Conference Publication No. 412 © IEE, 1995.

[2] NEMA MG1 Section 31.

[3] Shaotang Chen, Thomas A. Lipo, Donald W. Novotny, “Circulating Type Motor Bearing Current in Inverter Drives,” IEEE – IAS Conference Record, 1996, pp. 162-167.

[4] S. Bhattacharya, L. Resta, D.M. Divan, D.W. Novotny, T.A. Lipo, “Experimental Comparison of Motor Bearing Currents with PWM Hard and Soft Switched Voltage Source Inverters,” IEEE – IAS Conference Record, 1996, pp. 1528-1534.

[5] Doyle Busse, Jay Erdman, Russel J. Kerkman, Dave Schlegel and Gary Skibinski, “Bearing Currents and Their Relationship to PWM Drives,” IECON ’95, IEEE 21st Annual Industrial Electronics Conference, Nov 6 – 10, 1995, Vol. 1, pp. 698-705, or IEEE Transactions on Power Electronics, Vol. 12, No. 2, March 1997, pp. 243-252.

[6] J. Alan Lawson, “Motor Bearing Fluting,” in Conference Record of 1993 Pulp & Paper Industry Technical Conference, IEEE Industrial Application Society, pp. 32-35.

[7] Hugh Boyanton, “Bearing Damage Due to Electrical Discharge (ED),” Publication by Shaft Grounding Systems Inc., Albony, OR,

[8] Jay M. Erdman, Russel J. Kerkman, David W. Schlegel and Gary L. Skibinski, “Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages,” IEEE Trans. Ind. Application Vol. 2, Mar. Apr. 1996.

[9] T. Harris, “Rolling Bearing Analysis”. New York: Wiley, 1984.

[10] SKF publication, “Passage of Electric Current Through a Rotating Contact.”

[11] D. Rendusara, P. Enjeti, “New Inverter Output Filter Configuration Reduces Common Mode and Differential Mode dv/dt at the Motor Terminals in PWM Drive Systems,” 28th IEEE Power Electronics Specialists’ Conference, 1997 Vol. 2 pp. 1269-1275.

[12] John M. Bentley, Patrick J. Link, “Evaluation of Motor Power Cables for PWM AC Drives,” in Conference Record of 1996 Pulp & Paper Industry Technical Conference, IEEE Industrial Application Society, pp. 55-69.