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Inverter-Driven Induction Motors Shaft and Bearing Current Solutions

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Executive Summary

The vast majority of bearing failures in electric motors are due to mechanical and thermal causes. Potential causes of these types of failures include misalignment of the motor and load, vibration, incorrect lubrication, excessive radial or axial loading, lubricant contamination or inadequate maintenance. In a small fraction of electric motor applications, bearings prematurely fail due to electrical causes.

Currents flowing through induction motor bearings have the potential of creating premature failure of these bearings. Shaft and bearing currents in sine wave driven motors are well understood. These currents are either localized in the bearing or are driven through the bearing due to asymmetries in the motor material properties or construction. The low frequency nature of bearing and shaft currents in sine wave driven motors results in current paths through what are generally considered to be conductive materials (motor shafts, frames, bearing races and bearing balls). Interrupting the conducting current path with insulating materials can eliminate these low frequency shaft and bearing currents.

Electric motors powered by fast switching pulse width modulated (PWM) voltage source inverters experience high frequency voltage pulses with respect to motor ground. At these high frequencies (up to several MHz transitions) capacitively coupled currents can flow through paths that would normally be considered to be insulators. Currents now can flow through the magnet wire insulation, stator slot liners, motor air gap, bearing grease and stator slot top sticks. These high frequency current paths offer new opportunities for shaft and bearing current flow that can result in premature bearing failure. With inverter driven motors, a clear understanding of high frequency current paths from the motor terminals back to the inverter and to ground is

key to determining potential bearing current problems and remedies. Current paths both internal to the motor and between the inverter, the motor and the driven equipment must all be considered when looking for methods to reduce unwanted bearing current flow. Consequently system related issues, such as grounding and cable shielding, become very important to inverter powered electric motor bearing current remediation.

It should be pointed out that inverter-induced bearing currents have not been found to cause significant problems in the majority of applications. This report focuses on that small percentage of installations and applications in which damage as a result of bearing currents is possible. Topics to be presented include:

1) root causes of inverter induced motor bearing currents,
2) potential current paths of capacitively coupled currents,
3) bearing damage due to these currents,
4) preferred current paths for capacitively coupled currents,
5) examples of application problems and solutions,
6) field measurements of important voltages and currents,
7) remediation methods and
8) on-going research into motor bearing current modeling.

Sine Wave Bearing And Shaft Currents

Electric motor bearing and shaft currents are not new; in fact, they have been around since electric motors were invented. The most common underlying causes of unwanted bearing and shaft currents for sine wave driven motors is a lack of motor symmetry. C. U. T. Pearce, writing as early as 1927 in The Electric Journal, said of the subject: "If it were possible to design a perfectly balanced and symmetrical machine, both theory and practice indicate that no bearing current could exist." To this point, however, perfect balance and symmetry have been beyond the technological capabilities of manufacturing, especially in large electric motors. Therefore, methods to reduce the detrimental effects of shaft / bearing currents have been developed for sine wave powered motors. It is important to understand these low frequency, internally sourced bearing current issues and accepted remedies. These remedies must be kept in mind so that when remedies for the high frequency, externally sourced, inverter-driven motor bearing currents are applied, they do not re-introduce a sine wave bearing current problem. Low frequency, internally sourced sine wave bearing current flows exist even with inverter-driven motors.

The two primary causes of shaft and bearing currents in sine wave driven motors are 1) homopolar flux, i.e. flux flowing down the center of the motor shaft and 2) alternating flux linking the motor shaft. The second cause is much more common than the first. Consider the homopolar flux condition as shown in Figure 1.
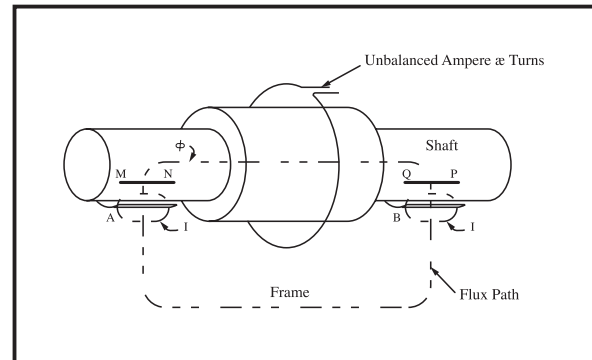
Figure 1: Homopolar flux condition creating bearing currents.

The homopolar flux condition describes the flow of flux down the motor shaft, through the bearing system, and back through the frame. Generally seen in high-speed, fast-rotating machines, this axial shaft flux is created by unbalanced ampere turns that encircle the shaft, a broken rotor bar, residual magnetization or, occasionally, an eccentric air gap. It most commonly occurs in sleeve bearings. Currents are usually localized to the bearing so there is no way to provide measurement. The effects of homopolar flux induced bearing currents are generally minor and are remedied by providing a homopolar flux barrier such as a nonmagnetic shaft or insulated bearings.

The more common type of bearing current is caused by alternating flux linking the motor shaft, as a result of asymmetrical magnetic properties of the stator or rotor core. Electric steel is not totally homogenous therefore flux paths in the motor are not entirely symmetrical. Asymmetrical flux through the steel results in flux lines that enclose the shaft. This can drive a current down the shaft, to the bearings, through the frame and back again through the bearings as shown in Figure 2.
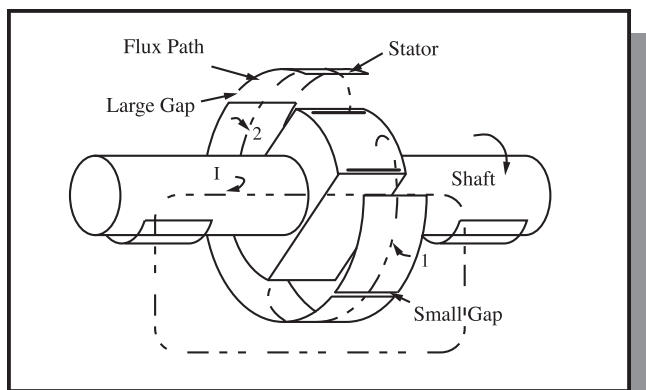

Figure 2: Alternating flux linking the shaft.

The resulting current is not localized within the bearing. Its driving voltage can be measured on motors with at least one bearing that is electrically insulated from the motor frame. (See Institute of Electrical and Electronics Engineers' (IEEE) Standard 112-1996). When both bearings in the current path are conducting, the impedance of this path is small; therefore, an axial shaft voltage as little as 500 millivolts rms can create a current of up to 20 amps rms through

the bearing and can cause significant bearing damage, particularly in larger machines. Remedial action entails employing an electrical insulator outside the bearing outer race to break the current path.

Bearing currents in sine wave driven motors can be reduced or eliminated through current or flux barriers. This is because the bearing currents are internally sourced. Notice that these types of bearing currents are not dependent upon system installation issues, such as grounding.

Inverter-Driven Motor Bearing Currents

With PWM inverter-driven motors, both internally and externally sourced bearing currents may exist. The internally sourced currents are the same as those discussed for sine wave motors above. The externally sourced currents are a result of the voltage wave shape that is applied to the motor by the inverter.

Modern PWM inverters switch a DC bus voltage (Vdc) onto the three phase terminals of the motor in a switching pattern that creates the proper fundamental component voltage and frequency. Since the motor line to line terminal voltage must be either + Vdc or – Vdc, it is not possible to have the three terminal voltages add to zero at any instant of time. Most rectifiers that create the DC bus also introduce a common mode

voltage to the DC bus itself. The average voltage applied to the motor (over a cycle) is kept zero, but the instantaneous sum of the voltages at the motor terminals is nonzero. This instantaneous voltage sum is called the common mode voltage. It can be measured by creating an artificial Y connection at the motor terminals using three large resistors (Mega ohms). The voltage from the center of this Y to the motor ground is the common mode voltage.

See Figure 3 for a typical wave shape of the common mode voltage of an inverter-fed motor. This voltage exists between the motor windings

In sine wave driven motors, the common mode voltage is virtually zero at all instants of time. The common mode voltage circuit is not important for sine wave motors, since little or no voltage is applied to this circuit and no common mode current will flow.

For inverter-driven motors, the common mode voltage circuit becomes important. Common mode currents (I) are created due to capacitive coupling since I = C dv/dt, where C is the capacitance of the common mode circuit element (see appendix on capacitive currents). There are many potential current paths via this capacitive coupling from the motor stator winding to ground. Most of these paths are normally considered to be insulators, for example: stator slot liners, stator to rotor air gap and the bearing grease film between race and ball. A detailed model of the common mode circuit will be presented later in this paper. For now, the most common current paths will be identified and their impact on bearing damage will be qualified. The challenge, then, is to provide sufficiently low
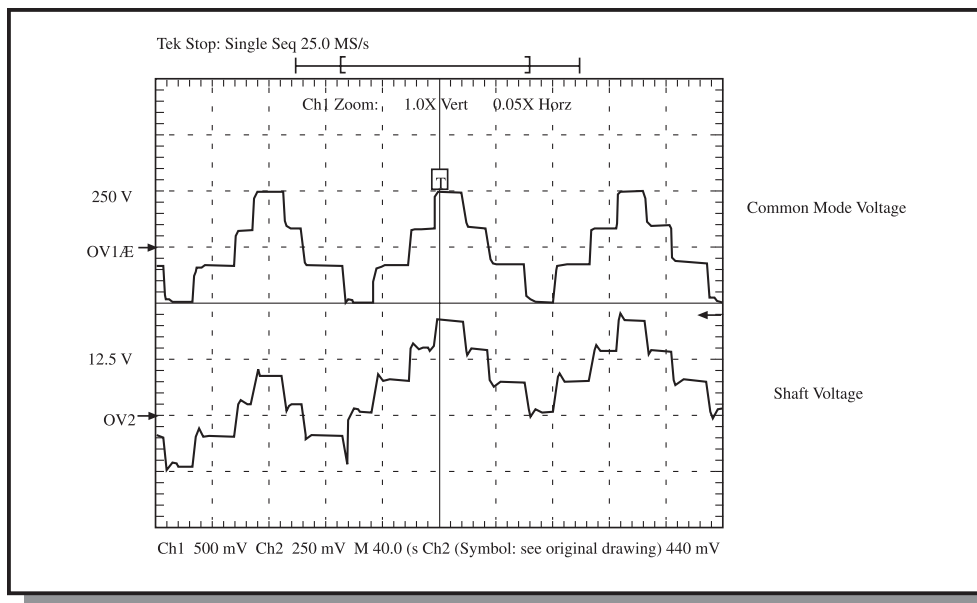

Figure 3: Typical common mode voltage and motor shaft voltage wave forms. (Horizontal scale - 40 microsec per div)

and the motor ground. It contains high rates of change of voltage with respect to time (i.e. high dv/dt). The high dv/dt creates frequency content in the common mode voltage in the MHz range.

impedance ground connections or alternate conductive paths to ensure that the flow of current is properly channeled away from the bearing.

Figure 4: Current paths of capacitively coupled currents.

In Figure 4, the various current paths of capacitively coupled current are presented. The high dv/dt created in the stator winding couples capacitively with the stator core and frame and with the rotor. The relative magnitude of the currents flowing in these paths is strongly dependent upon the impedance of these paths. As will be shown later, bearing damage can be reduced or eliminated by creating low impedance current paths that route these currents away from the bearings. Let's first take a look at each current path shown.

The current path marked in red (———) is a capacitive current coupled to the rotor, with a return path to the motor bearings, motor ground connection and finally to the drive ground. This path creates current through the motor bearing with possible bearing damage as a consequence. Current flow through 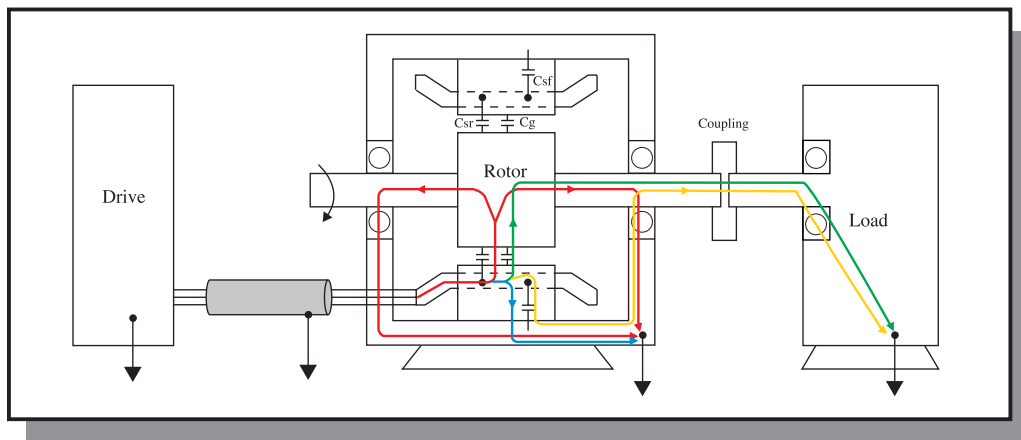the bearing is a consequence of two phenomena. Conduction current may flow through the motor bearing if the shaft happens to be shorted to the frame (by bearing ball contact, for example) at the instant that the dv/dt transition occurs in the common mode voltage. Dis-charge current may flow through the motor bearings if the bearing becomes conductive after first acting as an insulator. Discharge current may occur when the voltage across the bearing lubricant film exceeds the film breakdown voltage. The red current may not be directly measured without a specially instrumented motor since the entire current path is inside the motor.

The path marked in green (———) shows current that is again capacitively coupled from the stator winding to the rotor. The coupling could be through the same mechanism as the red current path, but this green current component finds a preferred path that passes through a

conductive coupling, and through at least one load bearing, to the load ground and back to the drive ground. The same two phenomenon discussed for the red current can occur with the green current, only now the conductive or insulating state of the load bearing will determine the type of current flow. This path creates current through the load bearing and the motor to load coupling with the potential of creating damage in the load bearing or, for some types of couplings, the coupling itself.

potential to damage the motor and load bearings, as well as the motor to load coupling. This gold path would also include currents due to a transient voltage difference between the motor frame and the driven equipment.
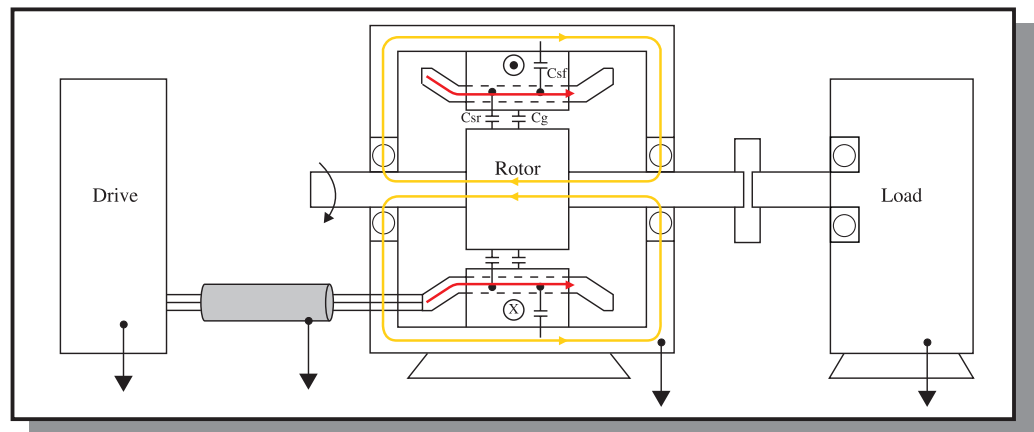
Figure 5: High frequency flux encircling the rotor causing shaft and bearing current.

This current can be measured by putting a high frequency current sensor around the motor shaft. (See Table 1).

The gold path in Figure 4 (————) indicates capacitively coupled current between the stator winding and the frame. This current flows through the stator winding insulation (which is capacitively conductive at high frequencies). With a poor motor to drive high frequency ground connection, the gold current flows through the motor frame, the motor bearing, the motor shaft, the conductive coupling, the load bearing, the load ground and finally to the drive ground. Current through this path has the

The preferred path for all these currents, to reduce bearing damage, is the blue path (————) in Figure 4. Here, no current flows through the motor or load bearings.

The current paths shown in Figure 4 are shown as lumped circuit currents. In fact, the capacitively coupled current flow is distributed along the stator winding. This implies that current "leaks" from the winding over the length of the winding, so that the axially directed current at the winding input is more than at the winding exit point. The result of this phenomenon is shown in Figure 5, where a net axial current is shown flowing in the motor stator winding.

Figure 6: Relative magnitude of bearing current components.

There is also a simultaneous drawing of current to the stator core and stator frame that represents the current that has bled from 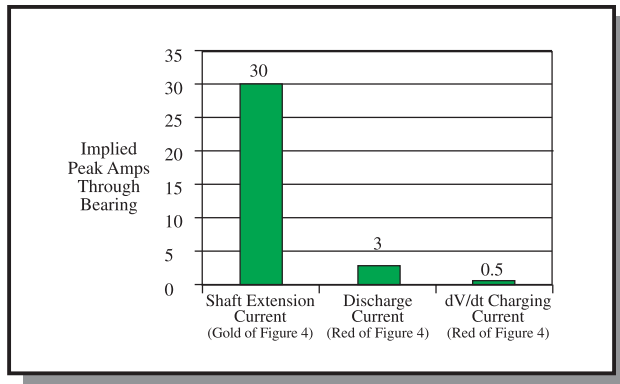the stator winding due to capacitive coupling. The combination of these events creates an encirculating flux and a high frequency current flow down the shaft, through the bearings and the motor frame. This current may have the potential to damage the motor bearings. This type of current is neither well understood nor easy to measure. It can be reduced by placing an insulator (that must be sufficiently high impedance to high frequencies as well) in the current path and is usually accomplished by insulating one motor bearing from the motor frame.
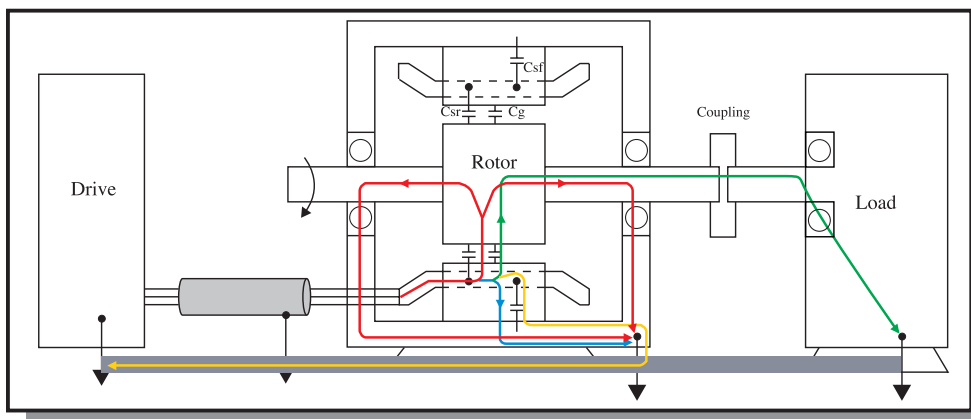
The relative magnitude of some of the various current components shown in Figures 4 and 5 is shown in Figure 6. As shown, the largest inverter induced bearing current is the gold current in Figure 4, the magnitude of which is 10 to 60 times as large as the other components. Providing a low impedance high frequency ground path from the stator core to the drive ground most easily reduces this bearing current component as shown in Figure 7. Low impedance, high frequency ground paths may be obtained through the use of continuous armored or shielded motor to drive cables.

Grounding In Inverter-Driven Motor Systems

The illustrations presented in the previous sections show various locations throughout an inverter-driven motor system that are connected to ground. Each of the grounds in these illustrations (black arrows) is presented as an ideal connection with zero impedance between them. There is, however, nonzero ground impedance between the motor and the drive and between the driven equipment to other points in the grounding system. If there is a significant

Figure 7: Good grounding reduces shaft current.

pulse of high frequency current, all various paths available will be used, and the current will split in inverse proportion to the impedance offered by the respective paths. With equal impedance – for a desired path from the motor back to the drive and for the undesired one through the bearings to the driven equipment – the situation arises in which half the current might be carried by each path, creating an undesirable situation. The current generated by the common mode voltage (the I in the $I = C \, dv/dt$ equation) is the common mode current. It is important to provide low impedance grounding paths for the common mode current to keep current from flowing through the bearings.

One important ground current path connection is between the motor and the inverter. The magnitude of the motor frame voltage, as well as the common mode current, is influenced by the type of ground and shield connection of the inverter to motor cabling system. Cables that provide continuous, low resistivity shielding around the three phase conductors provide the lowest motor common mode current and motor frame voltage. Continuous corrugated aluminum sheathed cables provide this optimum performance and are highly recommended for motor/inverter installations. The continuous aluminum sheath provides low resistance and low inductance, an important feature that results in minimum high frequency impedance.

Optimum cable performance is obtained when the cable sheath is connected to the motor frame and drive cabinet through a low impedance path. Cable connectors that provide 360 degree

Figure 8: Ground bus connection pad in variable speed motor conduit box.

surface contact between the cable sheath and the connector and the connector and the motor and drive frame are recommended to provide this low impedance path. The ground conductor(s) within the cable should ideally be symmetrically spaced with respect to the three power conductors. Connection of both the shield / sheath, as well as the ground conductors at both the motor and the inverter ends, creates a high frequency, low impedance path for pulses of common mode current. The termination of the ground conductors and the sheath / shield should avoid adding impedance in the connections themselves. Landing these connections on a prepared ground surface intended for this

purpose is a good way to accomplish this. Motor conduit boxes can be provided with a multipoint "ground bus" connection pad, as seen in Figure 8.

Proper grounding of the motor frame is also important. Capacitively coupled currents from the stator winding to the motor frame are the largest potential component of bearing current in applications with conductive shaft couplings (shaft extension current in Figure 6). Besides the cable's low impedance ground path from the motor to the inverter, ground straps should also be connected between the motor frame and the driven load equipment frame to allow a low impedance, alternate path for shaft currents. This is particularly important in applications where a conductive coupling connects the motor shaft to the driven equipment and where the motor and driven equipment are NOT on a common metal baseplate. High frequency ground strap impedance is lowest for straps with fine conductors and the largest width to length ratio. Therefore, the widest ground strap that is practical should be used for this ground connection. In all cases, ground straps should be connected directly metal to metal (not through a painted surface) to provide the lowest impedance path for high frequency currents.

Field Measurement Of Inverter-Induced Bearing Currents

Measuring bearing voltages and currents presents significant challenges. As stated earlier, it is difficult to accurately measure current flow through the bearing. This difficulty arises because it is not possible to place a current transducer in the part of the bearing where the current actually flows. Therefore, field measurements are largely relegated to methods that will provide insight into symptoms of potential bearing current problems. Many field measurements are done after bearing damage has occurred, where causes are being determined so that the proper remediation action can be taken. Since the source of the high frequency bearing currents is the common mode voltage transitions from the inverter, it is important to reference all system measurements to the common mode voltage wave form. Shaft to ground voltage measurement (both magnitude and wave shape) provides insight into potential bearing current flows. Although bearing currents cannot be directly measured, current flow through various grounding and ground current return paths can and should be measured, including current flowing through the motor drive shaft to the load. Typical field measurement goals include:

1) determine common mode voltage level and wave shape,

2) compare shaft to frame voltage

Table 1: Bearing Current Measurement Equipment Requirements

Quantity Measured	Equipment	Equipment Specification	Example Equipment
Shaft voltage/current, common mode voltage/ current	High speed oscilloscopes (2 or more channels)	100 Megasamples/sec 5 to 10 MHz bandwidth	Tektronix TDS540, TDS1354, TDS3054 Yokogawa DL1540, DL4100, DL7100 Agilent 54622A, 54624A LeCroy LT322, LT224 Fluke PM 3394B, PM 3390B
Common mode voltage	High voltage, high frequency voltage probes	50 MHz	Tektronix P5210 differential probe Yokogawa 70924 differential probe
Shaft to frame voltage	High bandwidth passive probes	100 Megasamples/sec 50 MHz bandwidth	Tektronix P6139A Yokogawa 700998 Agilent 10074C
Common mode current	High frequency current probes	100 Megasamples/sec 50 MHz bandwidth	Tektronix A6303/ CT-4/AM503B, A6302/AM503B current probes, PEM high frequency Rogowski Coil
Net cable current	High frequency current probes (large cable diameter)	100 Megasamples/sec scope 50 MHz bandwidth	Tektronix A6303/ CT-4/AM503B, A6302/AM503B current probes, PEM high frequency Rogowski Coil
Motor drive shaft current	High frequency current probes (flexible and with a large cable diameter)	5 to 10 MHz bandwidth	PEM high frequency Rogowski Coil

magnitude and wave shape with common mode voltage wave shape to deduce bearing current activity, and

3) determine common mode current flow both in preferred current paths and alternate ground current paths.

To reach these goals, equipment capable of measuring high frequency events is required. Table 1 lists required capability of measurement equipment for various field measurements.

Common mode voltage measurement is usually done by creating an artificial neutral for the three phase voltages applied to the motor terminal. Three high-value low inductance type symmetric resistors are connected in Y. One end of each resistor is connected to the three phase leads. The measurement is taken from the center point of this resistor Y to the motor ground. The common mode voltage is to be used as a reference for shaft voltage and common mode current measurements, so it is usually displayed on one of the scope channels for all further measurements on the motor system. The rise time and overshoot of the common mode voltage provides insight into the level of dv/dt and peak common mode voltage of

this motor/inverter system. Figure 9 (top trace) contains a typical common mode voltage wave shape.

Motor shaft to frame voltage measurements should be made with a brush or pick up that can make contact with the shaft while in motion. The shaft voltage is measured relative to a ground reference point. The ground point should be a non-painted, and preferably external, motor ground connection point as close as possible to the bearing outer race. A high frequency oscilloscope is required, often combined with a high voltage, high frequency probe (see Table 1). Among the challenges in measuring shaft to frame voltage is that the bearings exhibit a significantly stochastic behavior. Bearings change from insulating mode to conducting mode in a somewhat random fashion and in response to applied voltage. Factors such as the
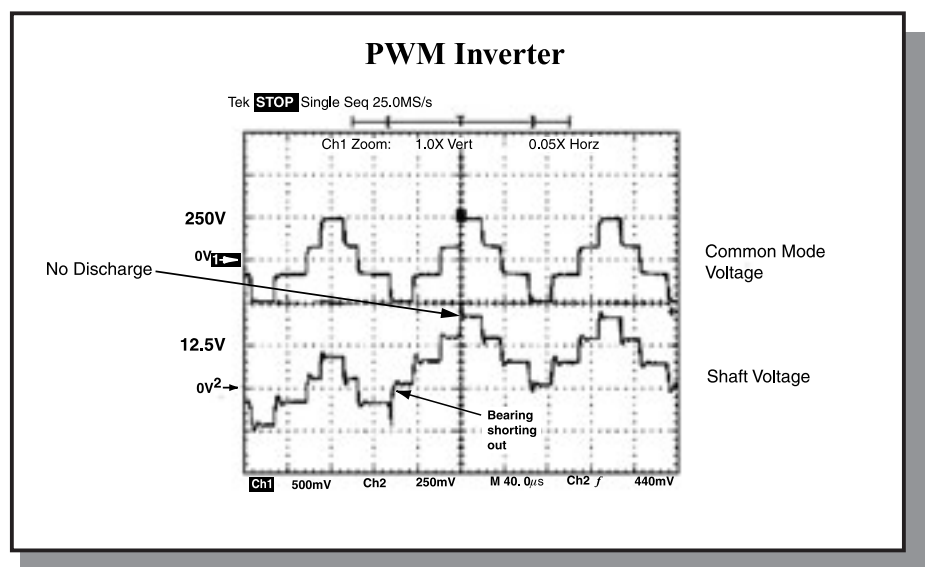

Figure 9: Typical common mode voltage and motor shaft voltage wave forms.
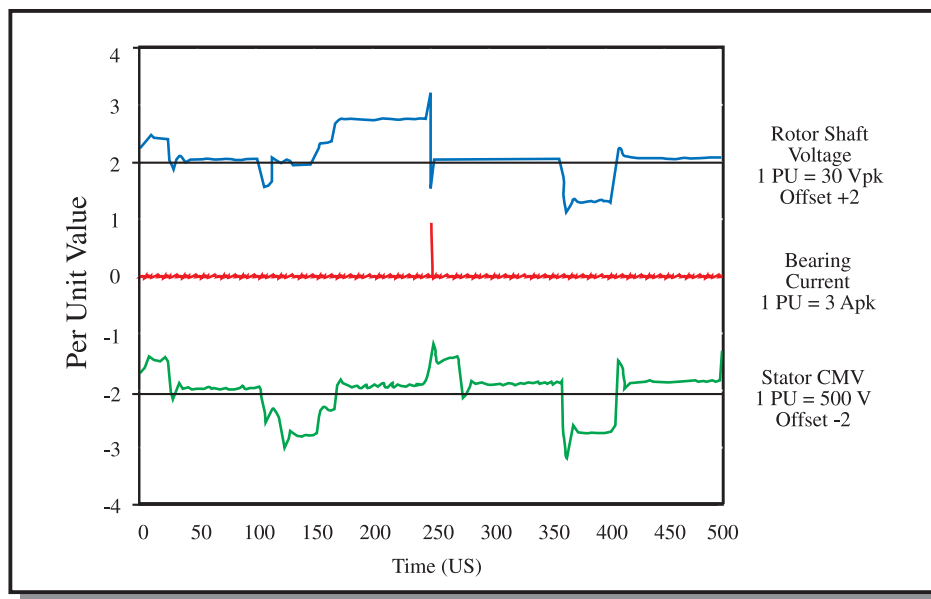
**Figure 10: Bearing current due to rotor voltage discharge.
(Stator Neutral Voltage = Common Mode Voltage)**

shape (but with reduced amplitude) for most time ranges. In this case, there may be sudden occurrences of zero shaft to frame voltage after a voltage charge-up (see Figure 9), which implies a bearing conducting mode and a pulse of bearing current. The current that flows during this conducting period can damage the bearing.

An illustration of this phenomenon is shown in Figure 10, which shows measurements taken on a special lab motor constructed with an insulating ring between the bearing outer race and the motor frame and with a single wire shorting across that ring. The current flow through this wire is indicative of the bearing current. As shown, just before t=150 μsec, the shaft to frame voltage is zero, due to a previous bearing shorting and reopening. At t = 150 μsec, the shaft to frame voltage is following the common mode voltage transitions until just before t=250 μsec. At t=250 μsec the shaft voltage drops to zero and a 3 amp current pulse appears in the bearing.

The instant the current pulse occurs, the trapped charge on the rotor discharges through the bearing balls and race. One method for this to

state of the bearing grease (temperature, contaminant level, churning), rotation speed and the applied voltage level impact the voltage wave shapes. Additionally, the PWM transitions are not all identical. If the turn on time of a transistor is nominally 50 nanoseconds (ns), the actual turn on time might be 50 ns in one instance and 150 ns in another. Since each transition is different, the scope should be DC triggered and with the trigger level set to display the highest voltage excursions in order to measure the maximum voltage across the bearing.

The shaft to frame voltage may exhibit one of several possible phenomena. If current through the bearing due to common mode voltage is infrequent, the shaft to frame voltage wave shape will mimic the common mode voltage wave

occur is random direct contact of the balls to the race, which can result in the shorting out of the bearing. This is most likely to happen at low speed, but not exclusively so. A second method is current shoot-through of the bearing lubrication film, which generally happens at high speed where the balls are separated from the race by a lubricant. Discharges through the bearing may also be some combination of these two methods. In any case, a conducting path is created that may be small in area so that a high current density can be created.

In some cases, the shaft to frame voltage wave shape will show instances of mostly zero voltage with attempts to charge up. This implies that the bearing may be staying in a conducting mode so that the rotor does not build up a substantial voltage.
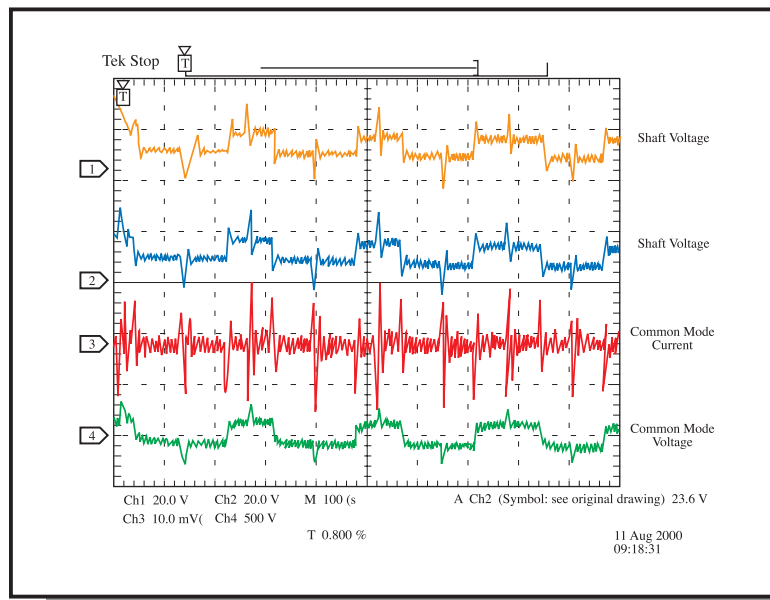
Common mode current measurements are made to determine if current flow is occurring in undesirable paths. Undesired paths include through the motor bearing and the motor shaft extension into driven equipment. Common mode current into the motor is the instantaneous sum of the three phase currents going into the motor. Common mode current flows into the motor from the inverter and eventually returns back to the inverter. The preferred return path (as mentioned above) is through a low impedance ground conductor from the motor to the inverter. The common mode current into the motor can be measured by placing a current transducer around the three motor power leads (without ground leads, shields, etc.). By comparing this measurement to the current through the ground conductors (including the conductor shields), stray common mode current can be determined.

If the ground conductors are the preferred ground paths, they should carry all of the common mode current. Figure 11 shows measured common mode current into a motor. Common mode current pulses occur at each transition of the common mode voltage (the dv/dt capacitively coupled effects). A difference between the ground conductor current and the common mode input current can lead to a diagnosis of a grounding system problem. Another technique to

Figure 11: Measured common mode current wave.

determine if currents are flowing in undesirable paths is to measure the net cable current. Here a high frequency current transducer is placed around the entire motor incoming cable, including the ground and shield connections. Any current spikes measured are an indication of poor grounding or poor cable connections or the existence of low impedance paths for the common mode current through the coupled equipment.

Current down the output shaft of the motor is also important to measure. This can be done using a Rogowski Coil, high frequency response current transducer (see Table 1). Any measured current indicates bearing current flow either in the motor bearing or the driven equipment bearing or both.

Voltage and current measurements, as described above, provide an indirect indication of the potential of bearing current problems. With experience, these measurements can lead to proper diagnosis of causes of bearing current damage in a given installation. There is no known set of measurements, however, that can lead to a definitive prediction of future bearing current damage. There is no established threshold of shaft to frame voltage above which bearing damage can be assured and below which no damage is expected. In fact, a low shaft to frame voltage may indicate continuous conduction of the bearing which may lead to bearing damage. On the other hand, a high shaft to frame voltage without evidence of discharge may not result in bearing damage since little or no current will be flowing in the bearing. This is one of the challenges of dealing with inverter driven motor bearing current problems.

Proper interpretation of the measurements can be realized by being aware of the measurement challenges which include:

- Bearing electrical behavior is random in time and shows nonlinear and hysteretic behavior with temperature, bearing speed and shaft to frame voltage.
- All important voltage and current data is at high frequency.
- Key information does not occur at each PWM transition. Single triggering with appropriate choice of trigger levels will result in the most useful information.
- Sine wave bearing voltage and current standards for potential damage cannot be directly applied to the prediction of inverter sourced bearing damage.
- Bearing current must always be implied (unless in special laboratory setups) since current through the bearing is impossible to measure directly.

Bearing Damage From Currents

We have seen that there are several methods for bearing currents to flow in inverter-driven

motors. Current flow in the bearing can lead to premature bearing failure.

Figure 12: Fusion craters in a bearing race from Scanning Electron Microscope image.

Initial damage is, in fact, relatively minor (see Figure 12). Bearing damage begins with the formation of small pits or fusion craters in the bearing races. As this progresses, mechanical defects arise that make the damage more the bearing balls run through the craters in the races for a time, a fluting pattern develops (see Figure 13) that may or may not incorporate fairly regular spacing. This fluting is common in most current related bearing damage. The resulting lubrication breakdown and mechanical wear ultimately lead to bearing failure.

Other authors have proposed that the fluting pattern is somehow related to the synchronization of PWM pulses and bearing ball to race travel causing a regular pattern of damage along the bearing race. This is supposedly reinforced by a general industry trend that a majority of the inverter-driven motor bearing failures have occurred in air handling applications where the motor is "reported" to be operating at a fixed speed for a majority of its operating life. Typical air handling applications, however, do not operate at fixed speed, as speeds cycle with temperature conditions within the building that is being heated or cooled. Fluting patterns have been observed in applications where the motor is not operating at fixed speed. It is unlikely that the fixed speed aspect of any application is a contributing significant force behind bearing failures. A more likely cause of the increased occurrence of bearing current damage in air handling systems is due to the less than ideal motor to drive ground connections found in many of these applications. Often these motors are mounted with flexible

Figure 13: Bearing race fluting.

conduit as the ground return path from motor to drive, which is not a good high frequency, low impedance ground. This leads to higher intermittent bearing voltages that can cause increased bearing damage.

Bearing Current Remediation For Inverter-Driven Motors

Figures 4 and 5 earlier in this document schematically showed bearing current paths that exist in inverter driven electric motors. A number of solutions are available to reduce or eliminate these current flows, the appropriateness of each depending upon the type and source of the bearing current found. Eliminating or reducing the common mode voltage and current addresses the problem at its source. This, however, is a drive design issue and therefore cannot be easily addressed in existing applications. Drive designs that reduce or eliminate common mode voltage and common mode current flow will be discussed at the end of this paper. In all cases, a drive with reduced common mode voltage is more costly to manufacture than typical PWM voltage source inverters that are widely marketed today. Since elimination of the source of the high frequency bearing currents is not likely due to this increased drive cost, improvements in the system grounding and/or modifications of the motor are often the preferred method to reduce the potential for bearing current damage.

Table 2 provides a summary of bearing current remediation methods for each bearing current flow path. If multiple current paths are expected in a given application, multiple remediation methods may be required to eliminate potential bearing damaging current flow. Methods that are available are:

1. Improve high frequency grounding connection from the motor to the drive.
2. Improve high frequency grounding connection from the motor to the driven equipment.
3. Insulated coupling between the motor and the driven equipment.
4. Shaft grounding brush without any insulated bearings.
5. One insulated bearing on the motor. Two insulated bearings on the motor.
6. Electrostatically shielded induction motor (ESIM).

Each of these options will be reviewed to identify current flow paths and their elimination.

Improve High Frequency Grounding Connection From The Motor To The Drive And From The Motor To The Load

The largest potential component of inverter induced bearing current is the common mode current that flows from the stator winding to the stator core and through the bearing to the load

Table 2: Bearing Current Remediation (motor-based)

Souce of Current	Action	Comments
Internal, circulating, due to magnetic dissymmetry leading to net flux linking shaft (fundamental frequency or sine wave)	Motor design optimized for symmetry Insulate one bearing	Design electromagnetics to achieve maximum symmetry and minimize net flux linking the shaft. Insulating just one bearing interrupts flow. Since coupled equipment can also provide a path from shaft to ground, usually choose opposite drive end bearing to insulate. Need to avoid "defeating" the bearing insulation, so (a) no ground brush at same end as a single insulated bearing, and (b) insulated coupling/mounting of accessories (e.g. encoder) at the end with a single insulated bearing.
Common mode (ground) current (induced by common mode dv/dt) taking a return path via the motor shaft extension and coupled equipment	Insulate both bearings Insulate coupling Bonding strap between frames Well terminated cable ground connections	Bearing insulation has to be of sufficient thickness to present a high impedance to this high frequency current. Coupling insulation must provide a high impedance at high frequencies. By bonding the motor frame and the coupled equipment together, a path is provided that should be much lower impedance than that through the shaft and bearings. To this end, the bonding must be a low impedance strap well terminated at each end. By providing the lowest impedance path back to the source, the tendency for any current to take a path through the shaft / bearings/coupled equipment is minimized.
Discharge through bearing of capacitively coupled common mode voltage (scaled by capacitor divider)	Motor design to reduce voltage ratio Faraday shield Insulate both bearings Shaft ground brush	By controlling the internal design of the motor, the ratio of the shaft voltage to common mode voltage can be minimized. By interposing a grounded conductor between the stator winding and the rotor, the capacitive coupling can be "shorted to ground," reducing the bearing voltage to prevent damage. Since a bearing goes from a non-conducting to a conducting mode in a very short time, this presents a high frequency event — so the insulation needs to be a significant impedance at high frequencies. This can be effective, but presents maintenance issues.
Capacitively coupled common mode voltage causing discharge through or conduction through load bearings	Insulate coupling Shaft ground brush Faraday shield	Coupling insulation must provide a high impedance to high frequencies. Preferred path may now be through motor bearings. This can be effective, but presents maintenance issues. By interposing a grounded conductor between the stator winding and the rotor, the capacitive coupling can be "shorted to ground," reducing the bearing voltage to prevent damage.

(the gold current in Figure 14). Providing a low impedance path from the motor ground to the
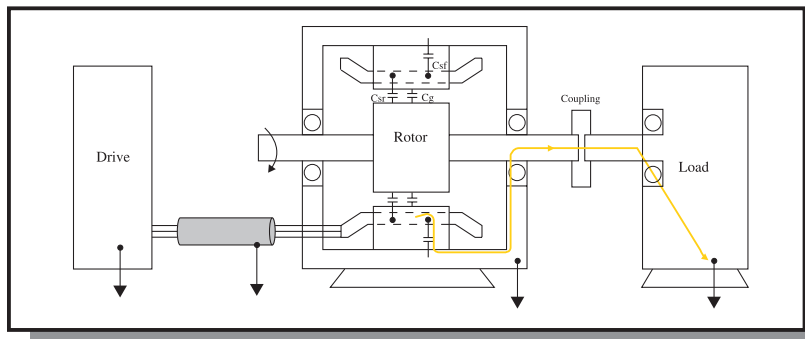

Figure 14: Common mode shaft current.

inverter and from the motor to the load (if there is a conductive coupling between the motor and the driven equipment) most easily reduces this current. Figure 7 previously showed the current flow when this improved ground path is provided. High frequency impedance of cable shielding and ground strapping options were discussed in an earlier section of this paper. The desired result is to carry the ground current back from the motor to the inverter, as well as to prevent transient differential voltages from the motor to the coupled equipment. The best method of creating the lowest impedance path between the motor and the inverter is by focusing on cabling in order to generate a ground current path closely coupled with the power leads that supply high frequency currents. Good termination of the cabling at both the motor and the inverter assists in the establishment of a low impedance path.

Insulated Coupling Between The Motor And The Driven Equipment

Inverter induced currents have the potential of flowing down the motor drive shaft to the load causing load bearing and/or coupling damage. There are two components of current that can make up the shaft extension current of this type (see Figure 4), one due to capacitive coupling across the air gap (green) and the other due to common mode current from the stator core to the load (gold). Current flow to the load bearings can be eliminated through the use of an insulated coupling (see Figure 15). Notice that by
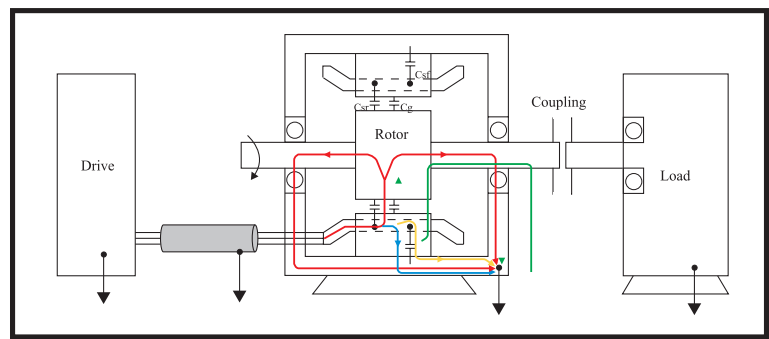

Figure 15: Insulated coupling eliminates shaft current.

eliminating the current flow path to the load bearing, that there may be an increase in current flow through the motor bearings, which now become the only path for all current that is coupled across the air gap.

Shaft Grounding Brush Without Insulated Bearing

A shaft grounding brush can be added to a motor bearing to provide a preferred path for bearing currents around the bearing. If the brush impedance is low enough, all shaft to ground currents will flow through this brush and will avoid an alternate path through the motor bearing
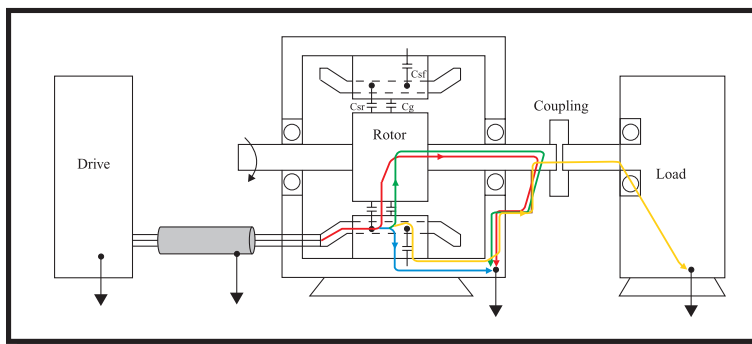

Figure 16: Shaft grounding brush on drive end bearing.

without the brush. Figure 16 shows the current flow paths with a brush on one bearing. Notice that, without good high frequency ground connections in the system, the brush has the potential to increase current flow down the shaft by providing a better current path than through the bearing itself. Adding a brush to a motor also reduces the impedance seen by any circulating currents within the motor that may be sine wave induced (see Figure 2). Since sine wave bearing currents are most common in larger motors, it is not recommended to add a shaft brush to a motor above a 400 frame size that does not have insulated bearings.

One Insulated Bearing On The Motor

Motor bearings can be insulated to break the high-frequency current paths from the shaft to ground. For inverter induced bearing currents, usually an insulated bearing is combined with an opposite end shaft grounding brush. It is wrong to add a shaft brush at the same end of the motor where a single insulated bearing has been applied, as this could facilitate internally sourced (sine wave type) current flow in the uninsulated bearing at the opposite end. A single insulated bearing will not prevent shaft to ground current flow in the uninsulated bearing at the other end of the motor. A single insulated bearing, however, is effective in preventing circulating currents from flowing, either from sine wave excitation or from high frequency flux induced bearing currents
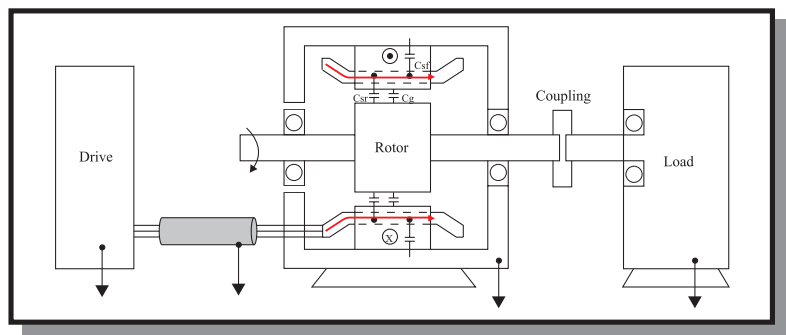

Figure 17: One insulated bearing to eliminate high frequency flux induced current.

(see Figure 5). Figure 17 shows the effect of a single insulated bearing in eliminating the circulating current flow of this type of bearing current.

Shaft Grounding Brush With One Or Two Insulated Motor Bearings

Shaft grounding brushes are more commonly applied in combination with insulated bearings. The opposite drive end bearing is typically insulated and a drive end shaft grounding brush is applied for a single insulated bearing system.

Figure 18: Drive end shaft grounding brush and opposite drive end insulated.
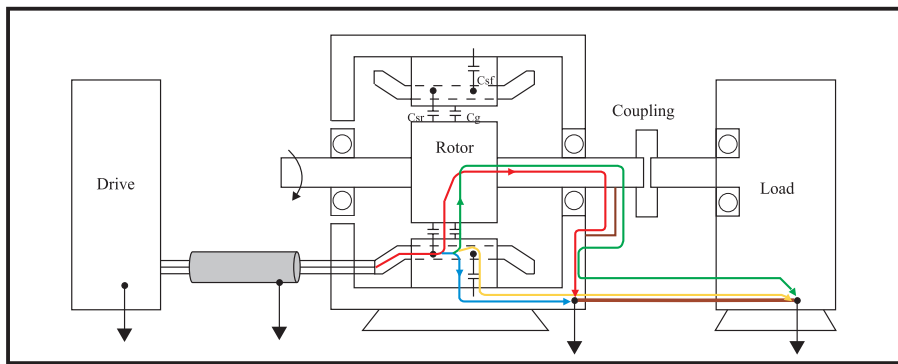
Figure 19: One insulated bearing, shaft brush and ground strap.
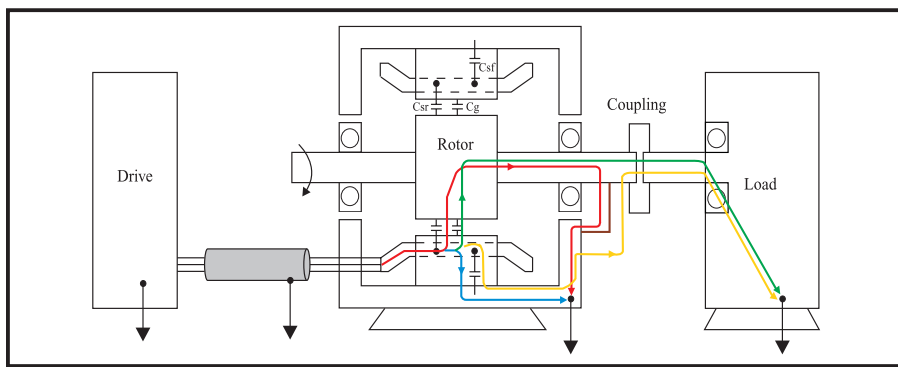
Figure 20: Two insulated bearings and shaft grounding brush.

Figure 18 shows the current flows with this remedy. The potential exists, still, for a flow of current through the capacitive coupling to the rotor of the motor, down the shaft and into the load.

A good ground connection between the motor and drive, as well as the motor and load, is still essential (see Figure 19). Care must be taken not to install the shaft brush on the opposite drive end since that would result in a very good current path on the drive end bearing for circulating currents (sine wave based), defeating the purpose of the insulated bearing.

It is possible, of course, to insulate both bearings on the motor, protecting both from current flow. In this instance, the bearings are protected even if the shaft grounding brush should fail. Figure 20 shows this remedy. To eliminate current flow down the shaft with this system, a good high frequency ground from motor to load is required
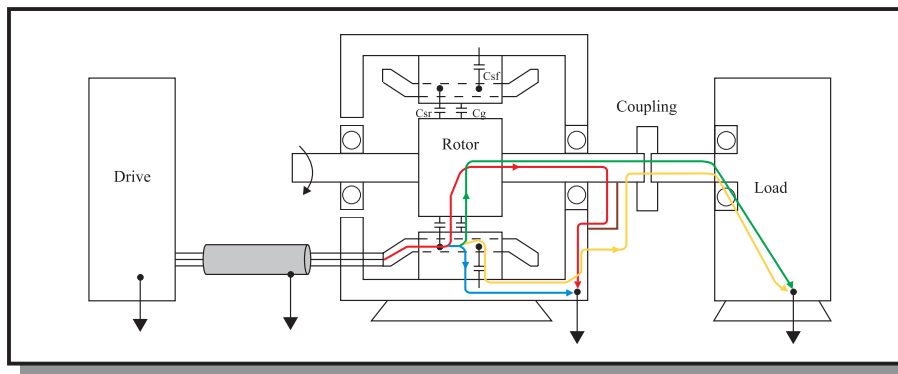
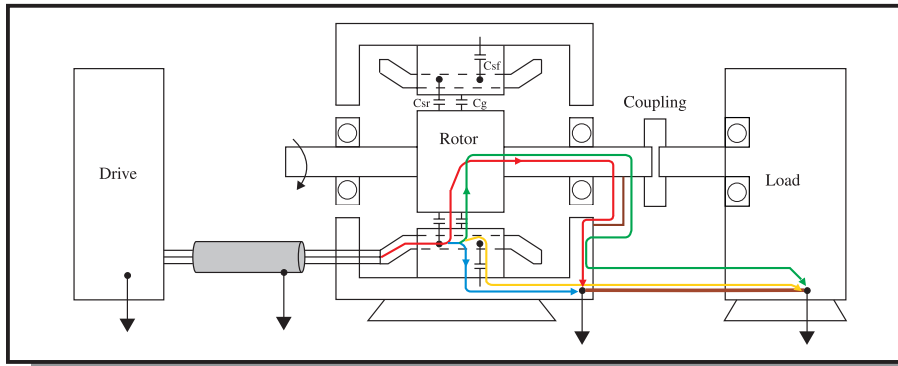**Figure 21: Two insulated bearings with shaft ground brush and ground strap.**

(see Figure 21) or, better yet, good high frequency grounds between the motor and drive and motor and load (see Figure 7).
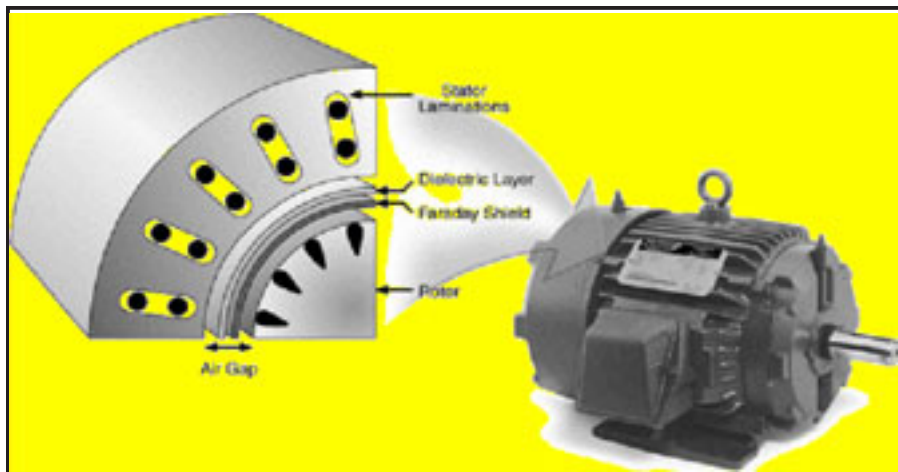

Figure 22: Electrostatically shielded induction motore (ESIM).
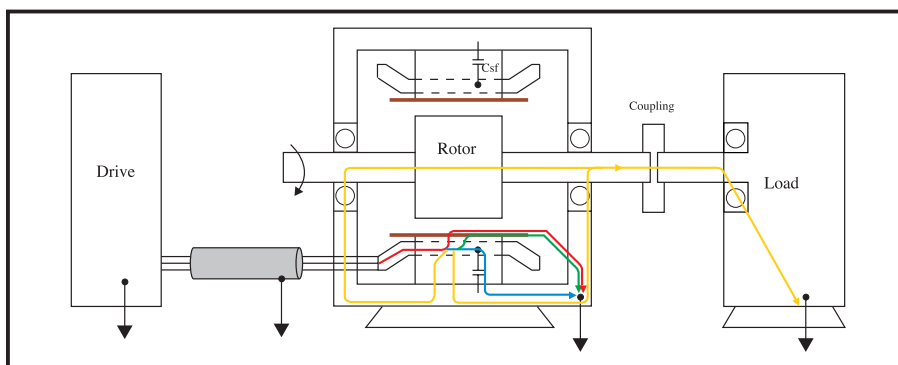
Figure 23: Bearing currents with ESIM.

Electrostatically Shielded Induction Motor (ESIM)

An electrostatically shielded induction motor (ESIM) can prevent rotor charge and discharge in installations where the motor is not coupled in a conductive way to driven equipment (see Figure 22).

Baldor-Reliance developed this tech-nology and has several patents in this area, both in concept and application. The basic goal is to create a grounded conductive path between the stator and the rotor that will bleed off capacitive coupled current. While ESIM technology eliminates stator to rotor coupling, it doesn't eliminate the potential of coupling from the stator winding to the frame and through the bearing as can be seen in Figure 23. Concern still exists about

the currents that might flow from the stator core through the motor bearings and shaft into the driven equipment due to poor high frequency ground paths for common
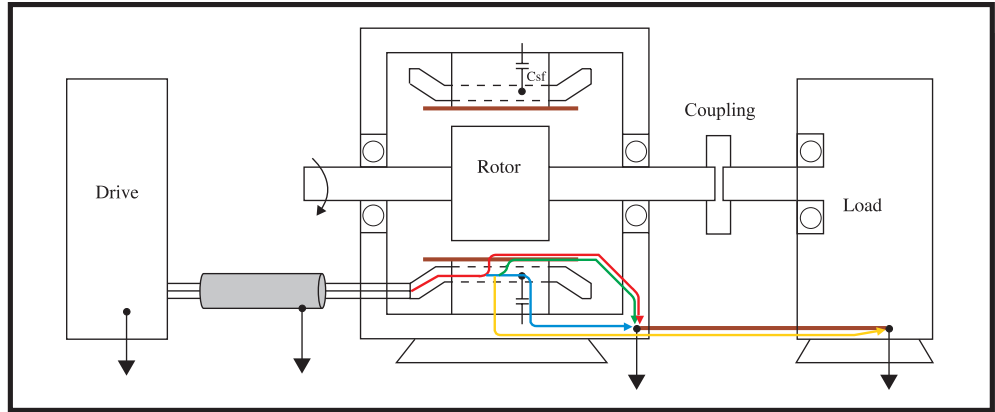

Figure 24: ESIM motor with motor to load groundtrap strap.

mode current produced by the inverter. Figure 24 shows how the addition of a motor/load ground strap can protect load bearings by shunting the currents away from the bearings in the entire system. Also, a good high frequency ground between the motor and drive is another solution (see Figure 7).

Standard Practice For Bearing Protection

Baldor-Reliance has standards in place for preventing bearing current damage with inverters. On large AC motors, insulated bearings are provided on the drive end and opposite drive end, as well as a grounding brush (see Figure 26), on either the drive end or opposite drive end. For large AC applications, the grounding brush is typically installed on the drive end. Enhanced ground connections from the stator core to the conduit box ground stud are also standard practice.

For small and medium AC motors, bearings can be insulated and ground brushes applied and an electrostatically shielded product is available.

Baldor-Reliance provides a variety of insulated bearing technologies that create an insulating barrier between the frame of the motor and the outer race of the bearing (see Figure 25). The
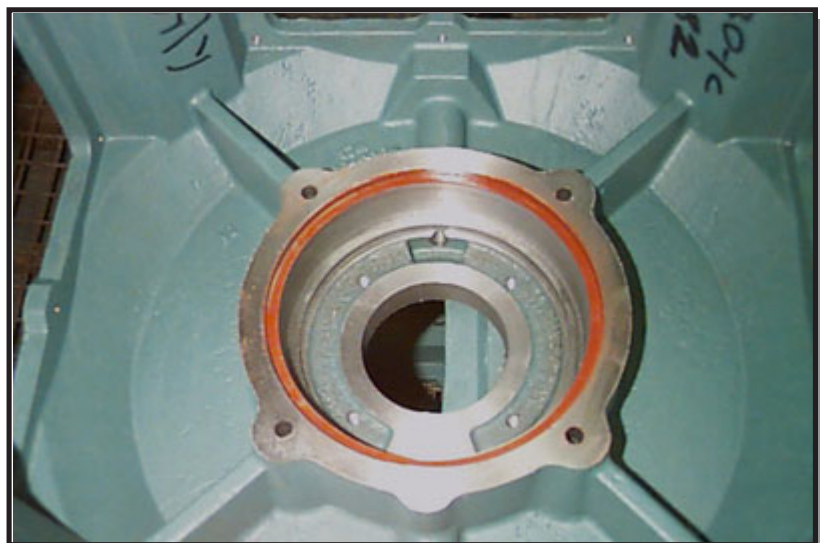

Figure 25: Insulated bearing.

barrier needs to be of sufficient thickness to prevent capacitively coupled currents from crossing the barrier.

A typical shaft brush installation is shown in Figure 26.

Figure 26: Shaft grounding brush.

Field Experiences

Examples of specific field experiences range, essentially, from fan applications with a belt driven load (i.e. a motor that does not have other conductive paths from its shaft to ground), to coupled applications where shaft extension currents may be an issue.

Systems/Process Line Installation – Motors coupled to gearboxes or other machinery (Case 1)

At this installation, one particular motor, frame size E5010, had a bearing failure after about 2½

years in service. When the bearing was replaced, an aftermarket grounding system was added at the opposite drive end of the motor.

Plant management had not realized that the bearing at the opposite drive end was insulated (as a precaution against internally generated, sine wave based, circulating shaft / bearing current). By adding the grounding brush at the opposite drive end, the drive end bearing became significantly imperiled. In fact, a drive end bearing failure occurred very quickly after the addition of the aftermarket kit. The solution then chosen was to insulate both bearings. The kit was put back in place at the opposite drive end and another drive end shaft grounding brush was also added. There were also measurements made that revealed 30-40 volt peaks from point-to-point within the ground system, which would imply opportunity for current to flow between various points in the ground system, including either a motor or gear box bearing. The use of two insulated bearings (and two shaft grounding brushes) did prove to be successful.

At the same installation, measurements of the common mode currents in the leads did not match up well with measurements of the current in the power cable ground conductors (that would be the preferred path). There was a significant discrepancy in that the "PE wires" in the cable did not carry anywhere near the sum total of the common mode current. There was
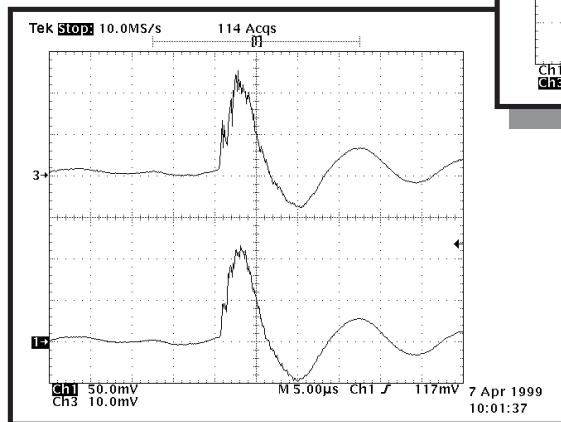
also a measurable amount of current in a ground connection to the motor base, implying there was sufficiently low impedance in that path (relative to the preferred path) to carry a portion of the common mode current – instead of running it through the preferred path of the cable ground. Current flow in the motor shaft extension toward the driven equipment was measured, and peaks of 26 amp pulses in the shaft extension were recorded.

This application demonstrated bearing damage due to common mode currents flowing through the drive end bearing and shaft extension to the driven equipment and also (temporarily) internally-sourced circulating current.

Case 1A

As a point of comparison, another similar application which had a more rigorous attention to cabling/grounding/

bonding at installation was also investigated. To illustrate the common mode currents (CMC) measured at this preferred installation, upper and lower traces in Figure 27 are the CMC and the ground currents, respectively. In both of these traces, the currents very accurately track one another, implying that the ground current / CMC is not taking any undesirable paths. It is in fact returning through the cable ground conductors, as is desired.

Trace 3 : Common mode current. (5 amps/div)

Figure 27: Common mode current and ground current wave forms.

Trace 1: Ground current. (5 amps/div)

Systems/Process Line Installation – Motors coupled to gearboxes or other machinery (Case 2)

Yet another application with the motor shaft extensions conductively coupled to driven equipment included an installation in which all of the motor-mounted encoders were applied with a shaft grounding brush option kit (at the opposite drive end of all the motors). The failures were L449 frame motors in which the drive end bearings failed. Any internally generated circulating shaft currents would have an easy time flowing through the drive end bearing because of the high conductivity path provided by the grounding brush at the opposite end. Even if this source of current was non-damaging with both bearings uninsulated (and no ground brush),

the shaft to frame short circuit at the opposite drive end of the motor made the bearing at the drive end more susceptible to damage from current flow.

There was also the potential for those drive end bearings to fail because a portion of the common mode current was not flowing through the preferred path, but rather one which included the motor bearing and shaft extension and coupled equipment. Thirty amp pulses of current were measured in the shaft extension (Figure 28), which would imply that some of the common mode current was taking paths other than through the cable grounds. Since the common mode current (Trace 2) shows only a smaller spike at the time of the 30 amp pulse (Trace 3) in the shaft, it is likely that a portion of this shaft current represents flow due to the motor frame voltage being transiently different from the voltage of the coupled equipment. If bearings are in a conducting mode during such a frame voltage transient, they can carry significant "equalizing" current. This is essentially another manifestation of common mode current, which is due to imperfect grounding.

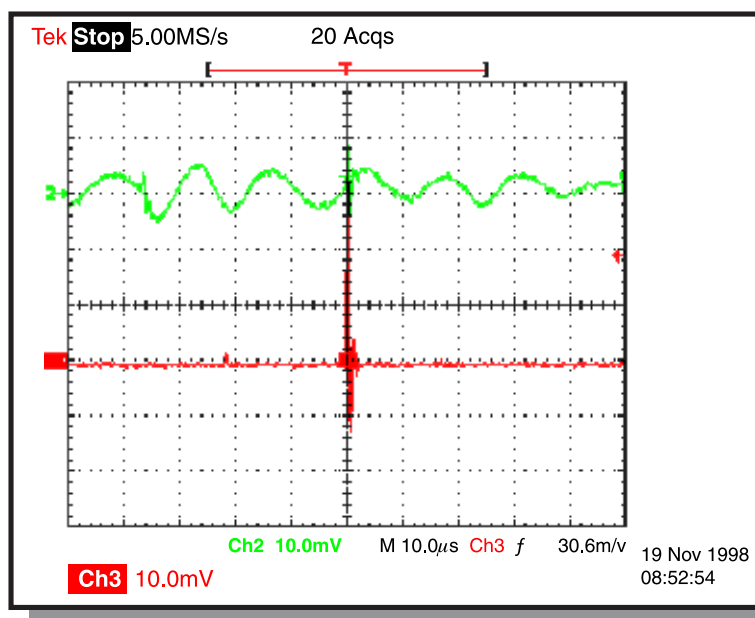Insulated bearings were utilized to resolve issues in this application.

Figure 28: Common mode current (Trace 2) and shaft current (Trace 3) in systems/process line application.
(Trace 2 - 10 Amps/div, Trace 3 - 10 Amps/div)

Another installation where bearings failed due to current flow was again an application with motors conductively coupled to well-grounded gearboxes and massive machinery with multiple conductive paths from the shaft to ground. When shaft voltages were measured, there was no detectable voltage (to ground) on the motor shafts. This implied that the driven equipment was providing a very low impedance path to ground that was keeping the motor shaft from developing a voltage. There was not a bond from the motor frame to the gearbox, which was later corrected. The motors were built with an Opposite Drive End insulated bearing. Consequently, it was the Drive End bearing that failed.

HVAC Application – Motors coupled to fans via non-conductive belts (Case 4)

In this particular application, there were 10 air handling systems which were all controlled by "variable speed." Each of those had a supply fan, as well as a return fan. A small number of failures were concentrated in just a few of the locations in this building. Motor wiring consisted of loose (individual) wires with just a single ground, no shield, randomly drawn through conduits. This would be a common wiring practice for line-powered (sine wave) applications. Because of the pivoting motor bases (for belt tensioning), the last 10 feet or so of each of the conduit runs used the flexible, spiral interlocked conduit that is not a good high frequency ground path.

At this installation, each of the inverters had an isolation transformer providing the AC input. Of those isolation transformers, a number of them had the secondary XO connection floating and others had the connection hard grounded. They were all shielded type transformers. All of the failures were on cases where the XO was grounded, even though the shaft voltage measured wasn't remarkably higher than other installations that had not failed.

Tests were conducted to check the extent to which the conduit was participating in carrying ground current (compared to the ground lead in the conduit). By disconnecting the flex conduit at the motor junction box and pulling it back, there was significant arcing and sparking, which implied that the conduit significantly participated in carrying the ground current.

The isolation transformers were set up so that all had the floating secondary as a part of the solution at this installation.

Continuing Areas of Research

Current Baldor-Reliance technology development projects underway include the building of motor/drive system simulation models that predict shaft voltage and bearing current. It is our goal to predict rotor shaft voltage based upon a motor/drive model and the motor design geometry. Initial efforts have focused on the measurement of the motor and bearing impedance and the development of a system model that enables accurate shaft voltage prediction. This measurement and modeling has initially been developed using a 30 HP inverter duty motor.
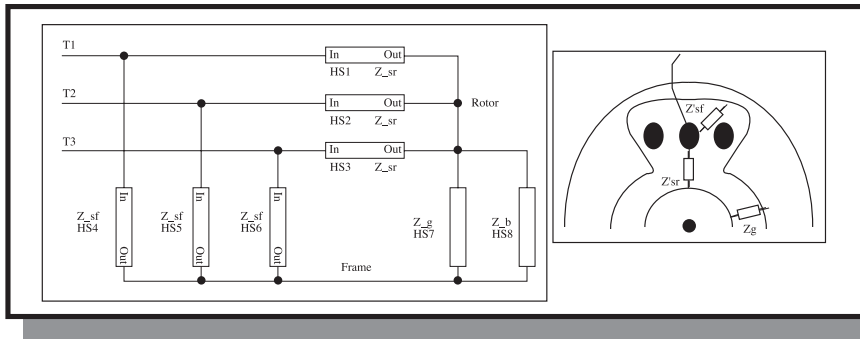
The Motor Shaft Voltage model proposed

utilize the proposed model, these four frequency-dependent circuit branch impedances must be established. To accommodate the broad frequency band occurring in the drive system, an LCR (inductance, capacitance, resistance) meter is used to measure impedance for frequencies up to the kHz range, and a network analyzer is employed to measure impedances in the MHz frequency range.

The stator winding to frame coupling impedance, Z_{sf}, is measured between the three stator windings (with shorted terminals) and the motor frame, with the rotor end bells removed. Each winding then has three times the magnitude and the same phase as the measured impedance. The measured magnitude and phase of Z_{sf} is shown in Figure 30.

Figure 29: Motor shaft voltage equivalent circuit model.

includes two branches (see Figure 29). The top branch, Z_{sf}, represents the three-phase winding impedance to the stator frame. The bottom branch, Z_{sr}, represents the coupling impedance from the stator winding to the rotor. Additionally, a model is needed to represent the airgap (Z_g), as well as bearing and grease behavior (Z_b). To
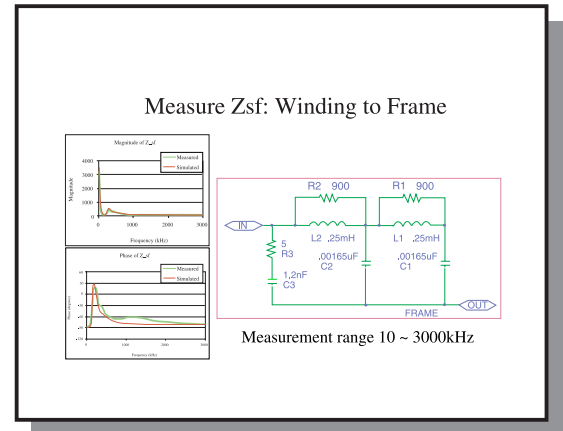

Figure 30: Stator winding to frame impedance.

A sub-circuit is then constructed to match the measured data up to 3 MHz.

The airgap impedance Z_g is assumed purely capacitive, and can be readily calculated as a flat parallel capacitor. The stator to rotor impedance Z_{sr} cannot be measured directly, instead it must be extracted from the Z_{sf} measurement data, the air gap impedance value and from an LCR meter reading taken from between the common point of the shorted stator windings and the rotor. The bearing impedance Z_b is the most difficult one to quantify because of its nonlinear and stochastic behavior as a function of rotation speed, grease temperature and applied voltage. In the present model, the bearing is modeled as a capacitor in parallel with a high resistance in the "open" state, while other end effects are assumed purely capacitive. The LCR meter is used to measure the impedance between the inner and the outer race of the bearing, with the rotor supported by end bells and turned at half rated speed by an external mover. The magnitude and phase, as well as the matched sub-circuit model for the bearing and end bell region are shown in Figure 31.

Once the four parameters in the motor are measured, the proposed model

must be incorporated into the drive system circuit model in order to predict the shaft voltage on the motor. The whole drive system diagram is shown in Figure 32. The simulated common mode voltage and shaft voltage are compared with measured results as shown in Figure 33. A very close correlation is clearly demonstrated.
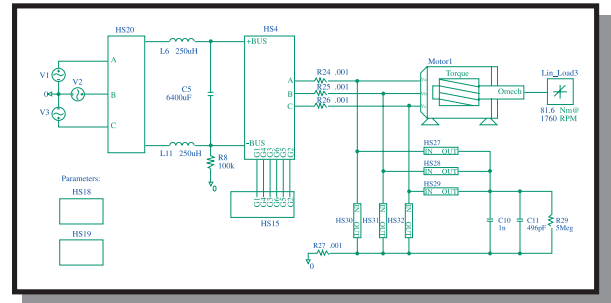

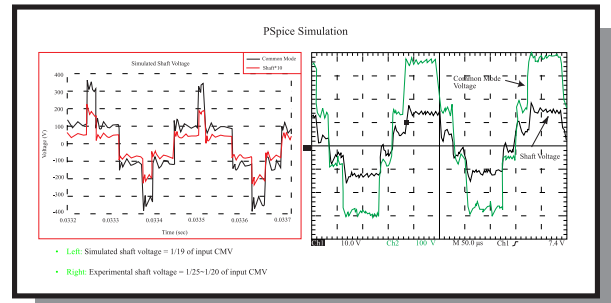**Figure 32: Drive system model for shaft voltage prediction.**

Figure 33: Comparison of simulated and measured shaft voltages. CMV = Common Mode Voltage.
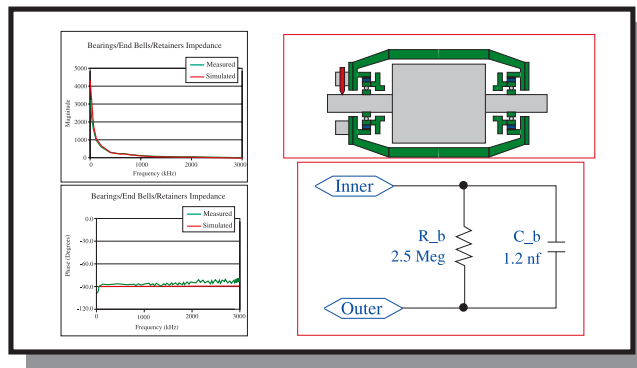

Figure 31: Motor bearing and end bell equivalent circuit.

This modeling has proved successful in predicting motor shaft voltage in the studied inverter drive system. Direct calculation of the impedance values as a function of frequency from motor geometry data is the next challenge in this modeling effort.

Drive Design Issues

So far, the present paper has focused on shaft and bearing current mitigation solutions in induction motors, given that the common mode voltage and resulting common mode currents are flowing in the motor. It is important to point out that reduction of bearing damage caused by these unwanted current flows is not solely a motor design issue, but also involves the entire drive system, including the inverter drive. Special inverter-design topologies, that can eliminate or reduce the common mode voltage from a variable speed drive system, can also reduce bearing current damage.

As outlined previously, the common mode voltage existing in modern fast-switching IGBT inverters is largely responsible for the elevated motor shaft to frame voltage as confirmed in theory/modeling and by measurement. Therefore, suppressing the common mode voltage has to be an important goal in a successful shaft current mitigation plan for induc-tion motor drive systems. Three different drive designs for common mode voltage reduction will be discussed here. The first approach consists of working on the modulation strategy solely by controlling the number and amplitude of the variations of common mode voltage, through, for example, a random space vector modulation technique. This approach is certainly very enticing since it does not incur added hardware cost. At present, however, only up to 50% common mode voltage amplitude reduction has been shown feasible, along with desirable spectrum distribution of the common mode voltage.

The second approach involves a drive topology change and/or placing a common mode reactor in series with the motor phases to achieve active cancellation or passive (low-pass) filtering. Appreciable common mode voltage reduction is feasible, but the approach places limitations on current control capabilities.

The third approach consists of new drive topologies to achieve elimination of the common mode voltage. The down side of this approach lies in increased drive/motor hardware cost, compared to a conventional drive system.

Three examples of common mode voltage reduction through drive system topology design will be explored. Two of them are from the academic community and one has been presented by a drive manufacturer.

A Four Leg Converter along with a three-phase RL filter, proposed by the University of
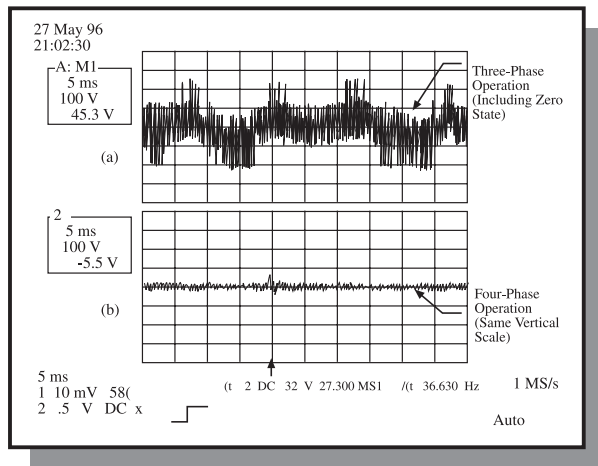

Figure 34: Common mode voltage reduction with four-phase inverter system.

Wisconsin presents the option of achieving zero common mode voltage at any moment, the ultimate desired goal. Prototype drives have been designed incorporating this technology. Figure 34 shows in the top graph the presence of common mode voltage in a typical three-phase design. With four-phase operation, however, (bottom graph), much lower common mode voltage is evident.

A another solution, proposed by von Jouanne and Zhang of Oregon State University, is a Dual Bridge Inverter Topology. This is a somewhat more costly option in that it requires two drives. The dual drives feed each group in a split motor winding design in such a fashion as to achieve

common mode voltage cancellation. Figure 35 shows a comparison of shaft voltage in a standard PWM inverter (left) versus a dual bridge inverter (right) on a 230/460V 5 HP motor. Much lower shaft voltage is evident.

The third topology was developed by PDL Electronics, a drive manufacturer, and includes a motor voltage optimizer filter. The filter design has been applied in a special environment that will improve conditions in applications where a shaft brush cannot be mounted. The filter acts to reduce the common mode voltage at the motor terminals.

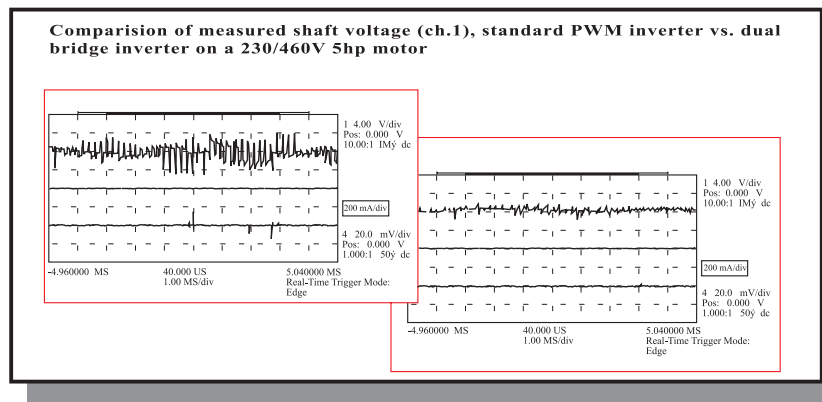**Figure 35: Shaft voltage reduction with dual bridge inverter.**

Conclusion

B bearing currents in electric motors are not new. Internally sourced circulating currents within the motor have been known to exist on sine wave driven motors for over 80 years. Externally sourced, inverter induced bearing currents due to common mode voltage are new and present new challenges. Fortunately, these common

mode voltage induced bearing currents are not seen in a vast majority of inverter-driven motor applications.

Inverter induced bearing currents can flow through multiple paths within the motor and coupled equipment system. These paths were identified in this paper and include 1) through the air gap to the rotor and through the motor bearings, 2) through the stator winding to core insulation, through the motor bearing, through the drive shaft and to coupled equipment and 3) through the motor air gap to the rotor down the drive shaft and through the coupled equipment to ground. In all of these cases 1) current flows through what would normally be considered an electrical insulator and 2) the current is seeking a return path to the inverter ground from the motor stator winding.

There are several methods to reduce or eliminate damaging bearing currents in an inverter-driven motor system. Table 3 summarizes remediation methods for various current flow paths. An X in the table indicates that the remedy, by itself, will reduce or eliminate bearing damage due to that particular component of bearing current. As is shown in the table, no single motor construction or system installation method will remedy all bearing current components. Also, note that some remediation methods may reduce currents in one part of the

system while increasing damaging current flow in other parts of the system. On a new installation, a motor with two insulated bearings and a shaft grounding brush offers the best protection against bearing currents. Baldor-Reliance provides this solution on all large AC motors in inverter applications. For new installations of smaller motors (less than NEMA 440 frame) where there is no direct electrical connection between the motor and the driven equipment (i.e. belt driven fans or motors connected to loads with insulating couplings), Baldor-Reliance provides the patented faraday shield or ESIM technology on new motors (see Figure 22).

On existing installations where potential bearing current damage is of concern, the remedies will depend upon the current flow paths. In some cases, measurements of shaft voltage and/or current, common mode current or net cable current, as described in this paper, will offer insight into what current components exist in the system. Once the current paths are identified, Table 3 can be used to determine the proper retrofit solution. For example, consider an installation where shaft current is measured between the motor and the connected equipment. If the motor has one insulated bearing and a shaft grounding brush, the remedy would be to add a bonding strap from the motor to the load or improve the ground connection between the

Table 3: Bearing Current Remediation for Motor and Coupled Equipment

REMEDY	Well terminated cable ground connections: drive to motor	Bonding strap between motor and load frame	One insulated motor bearing on opposite drive end	Two insulated motor bearings	Shaft grounding brush across one motor bearing	Faraday shield (ESIM)	Insulated coupling between motor and driven load
Source of Current							
Internal, circulating, due to magnetic dissymmetry leading to net flux linking shaft (fundamental frequency or sine wave). Generally occurs on motors above NEMA 400 frame. *Figure 2*			**X**	**X**	Avoid without opposite bearing insulated		
Common mode (ground) current (induced by common mode dv/dt) taking a return path via the motor shaft extension and coupled equipment. *Figure 4 – gold current*	**X**	**X**		**X**	Avoid without insulated coupling or bonding strap between motor and load to protect driven equipment		**X**
Discharge through bearing of capacitively-coupled common mode voltage (scaled by capacitor divider). *Figure 4 – red and green current*		Only if in combination with motor shaft ground brush		Only if in combination with motor shaft ground brush or insulated coupling	**X**	**X**	May cause increased motor bearing current without motor shaft ground brush, faraday shield or insulated motor bearings

X indicates that the remedy will, by itself, reduce or eliminate motor bearing current damage and current flow to coupled equipment.

motor and the inverter.

Most applications do not have bearing current problems. Of the thousands of inverter-driven motors out there, problems have occurred with only a few. But still it is an issue that causes concern. There is still more to learn. There is no standard, no well-known direct relationship between bearing voltage magnitude and bearing damage. In fact, there are applications in which there may be no voltage measured across the bearing, but damage still occurs because of quasi-continuous current.

Bearing electrical models are not yet fully developed. In fact, measurements have been made in which the bearing characteristics change with speed and with temperature.

No standard test methods exist to evaluate bearing current problems, and one of the key aspects associated with that is the inability to directly measure bearing current. High frequency current paths in many installations are not well understood. High frequency motor models are not well developed. This is an area that has generally been ignored.

Baldor-Reliance continues to study methods to model the common mode circuit in inverter-driven motor systems. Results shown here indicate our ability to predict shaft voltage

based on high frequency impedance modeling of a motor and inverter system.

At the same time, inverter manufacturers and other research centers continue to investigate methods to reduce the common mode voltage and current in inverter-driven motor systems. A few examples were given here. Unfortunately methods identified to date require considerable added costs to the inverter and are, therefore, commercially not viable. Until an inverter topology is developed that will eliminate the source of the high frequency bearing currents, remediation methods will continue to be concentrated at the motor and system installation.

Inverter induced bearing currents continue to be studied. More and more information is being gathered through diagnostic measurements in applications where bearing damage has occurred.

A clear understanding of potential current paths in a given installation is required in order to select the proper remediation method. With the proper remediation method applied, bearing current damage can be reduced or eliminated.

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Appendix 1: Grounding/Bonding

The discussion of PWM inverter-sourced bearing currents inevitably involves some discussion of grounding. While "grounding" in the classic sense of a conductor to "earth ground" is an issue, it is not the major one. The first issue is the provision of a low impedance path (within the power lead cable) for the safe return of common mode currents to the inverter. This is best done by the ground and shield conductors in the power cable, so it could be called "properly grounding the motor." However, it is NOT equivalent to a good "safety ground" of the motor to earth. It might be better described as "bonding" the motor ground to the inverter ground (via a good high frequency path).

Also in regard to bonding, another consideration is bonding to equalize potentials (on a transient basis) between points within the ground system. An important location for such bonding is between the motor frame and the frame of coupled machinery. Non-zero impedances between points in the ground system can easily result in transient voltage excursions that can then drive ground system currents. To avoid these currents utilizing a path through bearings and shafts, a "bond strap" between (interconnected) grounded pieces of equipment can be used.

Finally, the grounding of the motor frame to the inverter ground needs to be more than just a low frequency safety ground. In addition to requiring low impedance (at the high frequencies represented by fast rising edges), the ground path should also be free from "intermittent" ground impedance changes (such as might occur with some types of flexible conduit). Such changes in ground impedance can result in higher than normal voltages on bearings.

Appendex 2: Vibration Analysis of Bearing Damage due to Passage of Current - in a PWM Environment

Vibration analysis of anti-friction bearings can identify incipient faults and give ample notice for their timely replacement. Vibration signals are often viewed in a frequency domain (rather than time domain). Formulas for calculating the frequencies generated by various types of faults are well published and the experience database for documenting these faults is over 30 years old. Typical frequencies include those associated with
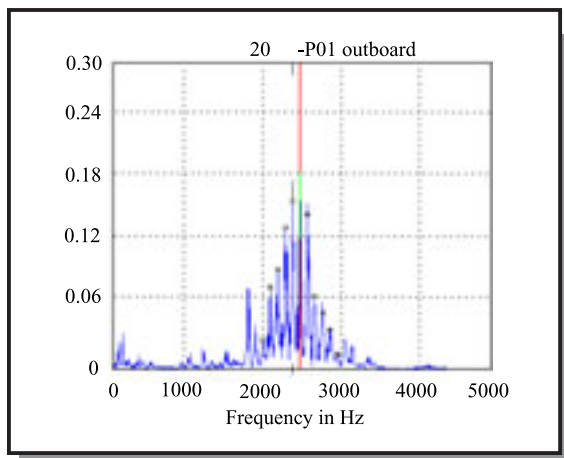
The frequencies of vibration generated by the PWM waveforms are unfortunately in the same range as those generated by bearing defects. A PWM inverter will typically create motor phase currents with frequency content including sidebands around the carrier frequency and multiples (including half multiples). The sidebands are spaced from these

Figure A2-1: Vibration frequency spectrum with bearing damage.

Figure A2-2: Fluting on a ball bearing outer race.

"ball passing" of a defect on either the inner or outer race. The vibration spectrum in Figure A2-1 is an example of what might be observed in a bearing with damage due to passage of current. The vibration energy is centered around a bearing natural frequency, with distinct sidebands spaced at essentially Ball Passing Frequency on Outer Ring (BPFO), about 95 Hz in this case. For a bearing with advanced damage as seen in Figure A2-2, even a time domain trace of the vibration signals (typically acceleration) can easily reveal problems (Figure A2-3).
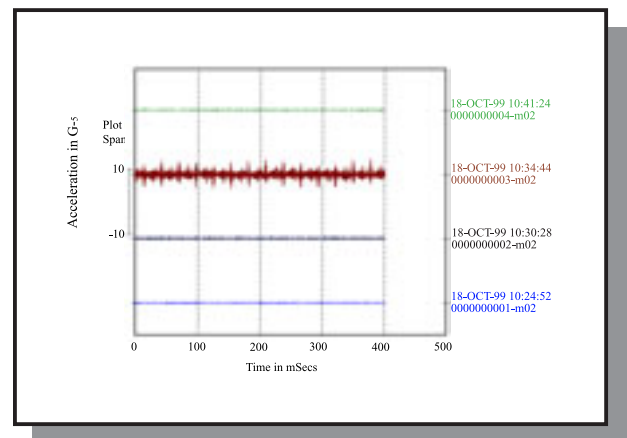

Figure A2-3: High frequency impacting in the time domain (four different motors). Obviously, second from the top is bad.

frequencies by plus and minus one, two, and four times the fundamental frequency. Bearing natural frequencies (for bearings commonly used in 3 – 500 HP motors) are typically in a range of 1 – 4 kHz. This is also a common range for inverter carrier frequencies. The sideband spacings of inverter output currents and ball passing frequencies are also overlapping to the extent that they can be easily confused. The non-fundamental frequencies in the current waveform give rise to motor vibrations at those frequencies. That is a major source of the "PWM hum" acoustic noise from PWM inverter-fed motors. By removing the input power from the motor (while at speed) and letting it coast to rest, the vibrations from the current waveform can be separated from any that might be present due to bearing damage.

Diagnosis of Damaged Bearings – Cautions

While the characteristic "fluted" pattern of damage is a characteristic common to bearings which have experienced current flow, it is not correct to assume that any bearing exhibiting this feature necessarily had current flow as the root cause of the damage. In fact, damage from subsequent running after false brinelling can exhibit a pattern such as shown in Figure A2-4.

Figure A2-4: Bearing damage from running after false brinelling.

The reality is that the fluted pattern is the result of the bearing operating with debris and damage in the ball track. This can occur with or without current flow as a root cause. One way to distinguish between fluting caused by current versus other sources is to examine the race area microscopically. By etching a polished cross section of the affected area, a thin surface layer of rehardened material (untempered martensite - which is caused by the extreme heat of interrupted current flow or discharge) can be identified. This can only be seen microscopically. This micro-structure would not be present in a bearing which was damaged by false brinelling. Another sign that current flow may be a root cause of a particular case of a fluted bearing is the appearance of the rolling elements. Balls or rollers that have been involved in current damage typically have a dull, frosted appearance, and are normally not shiny (grind marks are not visible).

Appendix 3: Capacitor Current Flow

Motor bearing currents due to inverter excitation are the result of current flow through parts of the motor that can be modeled as capacitors. These include the electrical insulation materials (slot liners, magnet wire enamel, insulating varnish or resin), the motor air gap and the lubricant film between the bearing balls and races.

A capacitor is a passive circuit element that obeys the following relationship between the voltage across the capacitor (v) and the current through it (i):

$$i = C \, dv/dt \qquad (1)$$

where C is the capacitance and dv/dt is the rate of change of voltage with respect to time (instantaneous slope of the voltage versus time waveform).

Capacitors consist of two conducting surfaces separated by an insulating layer. If each of the two conducting surfaces has surface area equal to A and two surfaces are separated by a distance d, then:

$$C = \varepsilon_0 \varepsilon_r A/d \qquad (2)$$

where ε_0 is the permitivity of vacuum and ε_r is the dielectric constant of the material in the insulating layer. Typical dielectric constants for insulating materials in an electric motor (slot liners, magnet wire enamel) are in the range of 2 to 10. The dielectric constant of air is 1. Bearing lubricants have dielectric constants in the range of 2 to 5.

Another way to look at the magnitude of current flow through a capacitor is to consider its AC impedance. The impedance of a circuit element is the resistance to current flow when alternating currents flow through the element. The impedance of the capacitor is a function of the frequency of the applied voltage.

Consider the current and voltage relationship for the capacitor in equation (1). If the voltage applied is a constant frequency sine wave with peak value V_m and frequency f then:

$$v(t) = V_m \sin(2\pi f t) \qquad (3)$$

and the capacitor current will be:

$$i = C 2\pi f V_m \cos(2\pi f t) = V_m \cos(2\pi f t)/Z_c \quad (4)$$

The capacitor is seen to have an AC impedance of:

$$Z_c = 1/(2\pi f C) \qquad (5)$$

The capacitive current flow is therefore directly proportional to the frequency of the applied voltage and the capacitive impedance is inversely proportional to the applied frequency. With the fast switching speeds (transistor turn-on and turn off times) of today's inverters, high frequency content voltage waveforms are applied to the motor terminals which results in increased capacitive current flow with the potential for damaging current flow in the motor bearings.

The magnitude of current flow through capacitive paths within the motor depends upon the rate of change of voltage and the value of capacitance in that circuit path as shown in equation (1). Notice that the faster the voltage across the capacitor changes with time, the larger the magnitude of the current through that element. From equation (2) the value of capacitance is inversely proportional to the

distance separating the two conducting surfaces that make up the capacitor and directly proportional to the area of the conducting surfaces times the dielectric constant.

The important capacitance elements in inverter induced bearing current analysis are those from the stator winding to the rotor, from the stator winding to the stator laminations / frame and across the lubricant film in the bearing. In most industrial electric motors, the capacitance from stator winding to the stator laminations is much larger than the combination of the stator winding to rotor and bearing capacitance. Therefore, for the same rate of change of voltage (dv/dt in equation (1)), more current will flow from the stator-winding conductors through the stator slot insulation to ground than across the air gap. This is why a good ground connection is important to direct these currents back to the source and not through the motor bearings, down the motor shaft and to the coupled equipment. This shaft current will flow at every dv/dt transition of the common mode voltage.

What is described above relates to current flow due to a dv/dt action. Voltage buildup on the motor shaft is also important in determining potential bearing current damage. The voltage that exists from shaft to frame also occurs across the bearing. A pulse of bearing current can result when this voltage becomes high enough to cause dielectric breakdown of the lubricant film between bearing balls and the bearing races. Also, with a shaft to ground voltage, when the bearing balls make contact to the inner and outer races a current will flow through the bearings. The magnitude of the shaft voltage generated in an inverter driven motor is a function of the ratios of capacitances in the motor and bearing equivalent circuit.
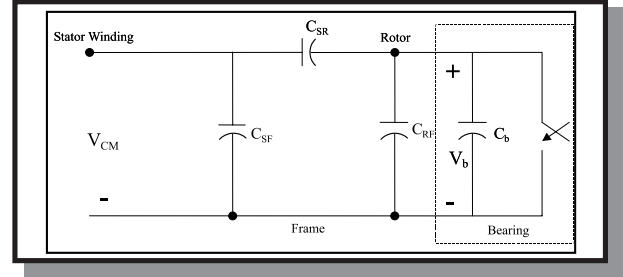

Figure A3-1: Simplified common mode circuit model of a motor.

The capacitive circuit model for a motor and bearing is given in Figure A3-1. Where:

Vcm = Common mode voltage at the stator winding

Vb = Voltage across the bearing

Csf = Capacitance from the stator winding to the stator frame

Csr = Capacitance from the stator winding to the rotor

Crf = Capacitance from the rotor to the frame (across the air gap)

Cb = Capacitance of the bearing

The bearing is modeled as a capacitance in parallel with a switch (a more thorough discussion of bearing electrical behavior is given in the next Appendix). The switch is open when the bearing is non-conducting and closed when current flows either from a dielectric breakdown of the lubricant or ball to race quasi-contact. With this switch open, the bearing voltage can be found from the voltage divider created by the capacitances:

Vb = Vcm * (Csr)/(Csr+Cb+Crf)   (6)

The relative magnitudes of the capacitive circuit elements in Equation (6) are a function of air gap length and other critical motor dimensions that are optimized to provide desired motor efficiency or insulation system life. Dramatic changes in the ratio of bearing voltage to common mode voltage are difficult to attain through simple motor dimension changes without adversely affecting motor performance. For this reason, add on features such as insulated bearings, shaft grounding brushes and/or electrostatic shielding are required to reduce the impact of the shaft voltage buildup and the resulting discharge on motor bearing life.

Appendix 4: Rolling Bearing Electrical Behaviors

Bearings in most cases are not designed to carry electric current. They are, however, called upon to do so in motor drive applications in which they are unintentionally subject to various sources of electric potential, as discussed in this article. The current through a motor bearing depends mainly on the magnitude of the shaft voltage and bearing impedance in the corresponding frequency range. The bearing impedance, in turn, depends on the lubricant properties, bearing geometry, bearing temperature, load, operating speed, and others.

According to electric contact theory, surface contact can be made in three ways. 1. Metal to metal contact – electric current flows with negligible resistance. 2. Quasi-metallic contact – surfaces are separated by a molecular layer of oxides and the electric current flows through with little resistance ($0.3 \sim 0.5\Omega$) by the quantum-mechanical tunneling effect. 3. Contact through a layer of relatively thick film – resistance will be normally high depending on the lubricant film thickness and resistivity. The rolling element-to-race contact in a stationary bearing is of quasi-metallic type, and the relatively large contact area can carry a strong current without any damage. In a rotating bearing, the rolling elements and race are separated, at most times, by a layer of lubricant; since, for example, the average lubricant film thickness is calculated to be $0.1 \sim 2$ mm for a roller bearing based on elastohydrodynamic theory. The actual contact area in a rotating bearing, however, will depend largely on the surface roughness and is comprised primarily of 'asperity contact' which may be estimated by the Herzian point contact theory.

It has been demonstrated that the AC impedance of parallel metal-lubricant interfaces may be described by three parallel R-C circuits in a series connection. One of the R-C circuits represents the bulk lubricant behavior, while the other two describe the metal-lubricant interfacial electrochemical interaction. This approach can be adapted to study rolling bearing and lubricant electrical behavior. The bearing capacitance can be calculated using the contact width and minimum film thickness based on particular bearing geometry, and lubricant dielectric constant. The bearing resistance can be calculated at the same time using lubricant resistivity. Recent research however has indicated that the resistivity of typical commercial lubricants used in motor bearings is highly unstable under the stress of an applied electric field. An electric field exists in the lubricant whenever a voltage appears across the lubricant film (or from shaft to ground in a motor). Some lubricants may 'recoup' their resistivity after the electric field is switched off, while others may not recover their resistivity after a long time. These changes in resistivity with applied voltage level and running time may be attributable to the nature of impurities and types of additives in the lubricant, besides its structure, density and compressibility.

Based on this analysis, the general electrical behavior of a rolling bearing may be described by an equivalent circuit shown at right. In this model, Z_{inner} and Z_{outer} are parallel R-C circuits representing inner and outer rolling-race interfaces, respectively. Z_o and Z_i represent the bulk lubricant and interfaces, respectively. R_{ir}, R_{or} and R_{ball} are metal resistances of inner and outer races, and balls/rollers, respectively. Bearing balls may momentarily contact the races at the asperity contacts thus effectively short the bearing. This random behavior is described by a switch-like nonlinear resistor $Z_{contact}$.

Essentially, the bearing acts like a resistive-capacitive (R-C) circuit when a voltage is applied across it. In a rotating bearing, the location of the bearing balls and resistive state of the bearing lubricant causes the bearing resistance and capacitance to change with time. The random contact of the bearings balls to the races as well as the highly unpredictable resistance behavior of the bearing grease make reliable prediction of bearing current difficult, even if the shaft to frame voltage is known.
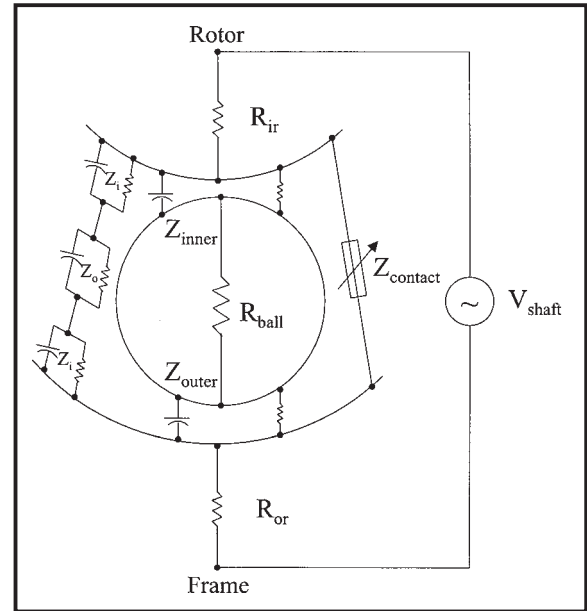

Figure A4-1: General electrical behavior of a rolling

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