Minimizing Electric Bearing Currents in Adjustable Speed Drive Systems

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***Abstract* - Electrical bearing currents have become of increasing interest in recent years due in part to the introduction of high speed switching technology employed in state of the art Adjustable Speed Drives (ASDs). High rates of change of ASD output voltage (dv/dt's), will cause transient currents to flow from motor windings to ground through stray capacitances. Under certain circumstances, these currents can flow though motor or gearbox/machinery bearings, and if large enough in amplitude, lead to reduced bearing life.**

This paper offers a view from an <u>industrial environment</u> perspective, of the most common reasons that damaging electrical bearing currents can occur in an ASD-fed motor or in connected machinery, and how installation practices can affect the generation of bearing currents. Technology is discussed that facilitates easy measurements of the common mode current, which can be used to quantify the risk a particular installation may have, as well as offer measurable proof of bearing current reduction after the implementation of corrective measures. Practical suggestions are given to optimize installation practices, which if followed, can reduce or eliminate the major risks of electrical bearing damage.

NOMENCLATURE	
AC	Alternating current
ACCS	Air cored current sensor
ASD	Adjustable speed drive
CMC	Common mode current
CML	Common mode loop
CMV	Common mode voltage
DC	Direct current
EMC	Electromagnetic compatibility
GTO	Gate turn-off thyristor
HF	High frequency
IEC	International Electrotechnical Commission
IGBT	Insulated gate bipolar transistor
NEC	National Electric Code ®
PWM	Pulse width modulation.
PE	Protective earth (safety ground)
rms	Root mean square.
SCR	Silicon controlled rectifier

I. INTRODUCTION

During recent years, an increase in bearing failures has been seen in ASD-fed electric motors, as well as in gearboxes, and other connected machinery, caused by electric current flow through such bearings.

Damage due to bearing current has sometimes been called "bearing fluting" due to the rhythmic pattern usually seen on the bearing's races. [1] Although all motor bearings may have some current flow, the existence of excessive levels of bearing current has often lead to bearing failures relatively soon after start-up, within one to six months.

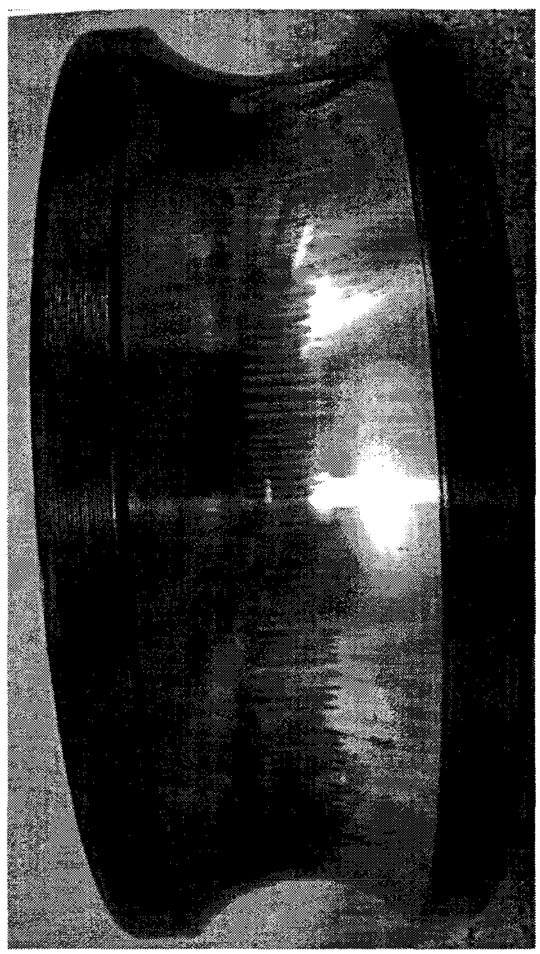

Fig. 1. Fluted Motor Bearing Race.

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Explanation of these failures has not generally been straight forward, or with conclusive results that lead to simple preventative recommendations to stop future bearing current failures. Without definitive prevention methods, engineering and maintenance personnel have had to overcome the obstacle of first gaining enough understanding of bearing failures to know where to focus their efforts. Or in other words, to find exactly which problem(s) needs to be solved.

Any of the affected items, whether it be the motor, gearbox, or drive controller, is a product of sophisticated manufacturing techniques, and normally carries a rather favorable Mean Time Between Failure (MTBF) rate. How is it possible that these items when combined together become the source of seemingly unpredictable bearing problems?

The answer becomes clearer when the "*installed system*" is looked upon as a whole. Not only is it important to understand the inter-relationships between a drive controller, a connected motor, and a gearbox or machine, but a global perspective of ASD operating experiences leads solidly to the importance of certain needed installation practices.

The theories presented here will focus on bearing currents in ASDs of the voltage source Pulse Width Modulated (PWM) type, for use with AC induction motors, although the concepts are applicable to various types AC and DC drive systems.

II. ROOT CAUSES OF ALL BEARING CURRENT

A. Motor Magnetic Asymmetry

It has been known for many years [2] that even with a sinusoidal 60 Hz power supply feeding an AC induction motor, that an asymmetric flux distribution inside the motor can lead to an induced voltage from end to end of the shaft. Such a voltage drop can lead to current through both motor bearings if the bearings' breakover voltage is exceeded. Modern motor design and manufacturing practices have nearly eliminated bearing failures from this type of "low frequency" bearing current. In some large motor frame sizes, an insulated bearing on the non-driven end of the shaft may be employed to stop such bearing current.

B. Power Supply Asymmetry Resulting in Common Mode Voltage Source

A typical three phase sinusoidal power source, under normal operating circumstances, is balanced and symmetrical. That is, the vector sum of the three phase voltages always equals zero. Thus it is normal that the "neutral" is at zero volts with respect to the system safety ground of the particular installation. In fact, if the power supply is WYE connected, the neutral voltage can be easily measured. This is not the case with any PWM solid state "switched" three phase power supply. While the voltages may be balanced in peak amplitude, it is impossible to achieve perfect balance between phases instantaneously, when pulses of different widths are produced. Fig. 2 shows each of three phase voltages of a typical three phase PWM power supply and the average of the three or neutral point voltage. The neutral voltage is clearly not zero and its presence can be defined as a common mode voltage (CMV) source. Sometimes called a zero-sequence voltage, it is proportional to the DC bus voltage, and has a frequency equal to the inverter switching frequency.

The CMV source appears as a potential between the aggregate inverter output and ground. It will act to force currents through stray impedances present between anything connected to the inverter phases, such as the

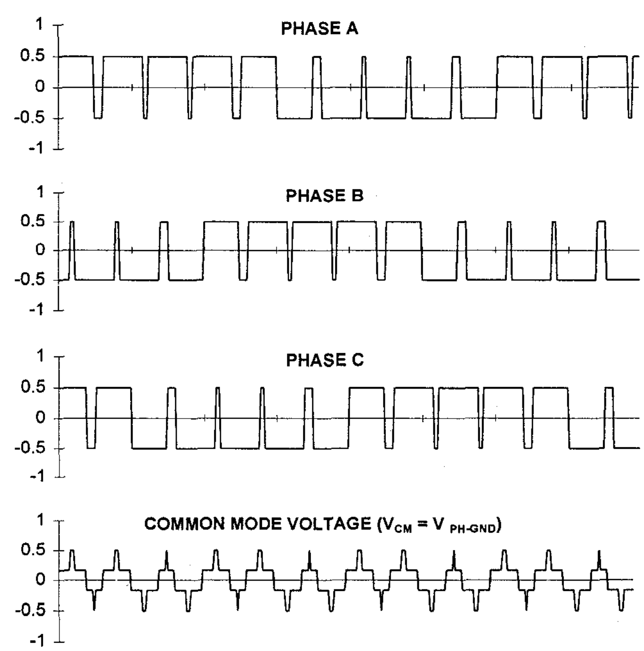

Fig. 2. PWM Inverter Output Phase Voltages and Common Mode Voltage.

motor cables and the motor windings, and ground. Such currents are called Common Mode Current (CMC).

Extensive motor cable studies [3] have shown that in a typical PWM drive system, three distinct frequencies, and their harmonics, are present in the spectrum of CMC that returns back to the inverter:

- The base operating frequency of the power being delivered to the motor stator.
  Typically between 10 and 100 Hz in most applications, this portion of CMC is not a result of power supply characteristics, but motor cable asymmetry usually related to single ground wire construction.
- The frequency of the PWM carrier.
  Usually in the range of 800 - 3500 Hz in most coordinated system drive applications, this is the fundamental frequency of the CMV. The biggest percentage of CMC in this frequency range returns to the inverter without passing through motor bearings due to the high impedance at this relatively low frequency.
- Common mode path resonant frequencies triggered by inverter switching.
  Although typically in the range of 50 kHz -1 MHz, these are limited by the effective frequency of the switching time or dv/dt of the PWM pulses. Depending upon the particular inverter switching device in use, these can cover a spectrum range up to 300 kHz for some Gate Turn Off devices (GTO), and up to 5 MHz for the smaller Insulated Gate Bipolar Transistors or IGBT's. **This component is considered to be the most critical of the total CMC, and is the basic origin, of nearly ALL bearing current problems in ASD systems.**

C. *Fast Power Supply Switching Speeds Cause Voltage Transients (dv/dt)*

As can be seen in Fig. 2, the CMV waveform contains very fast rise/fall times, each of which is caused from the switching of an inverter power device. Present state of the art technology, which incorporates IGBTs, has brought switching times 20 times faster than considered typical ten years ago. These switching speeds cause dv/dt's that initiate high frequency currents that flow through stray capacitances naturally formed between current carrying

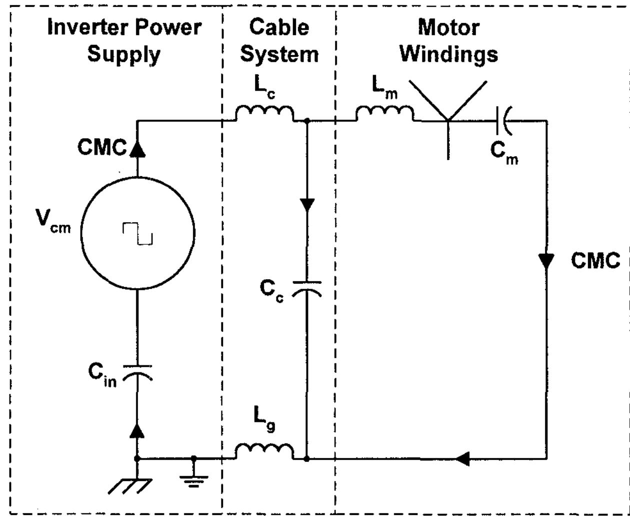

Fig. 3. Simplified Common Mode Loop of PWM Inverter ASD and Induction Motor

conductors and "grounds" in the drive system. A "stray" capacitance is created any time two conductive components are separated by an insulator. For example, a bus bar insulated from a metallic cabinet by a glastic support has capacitance to the cabinet frame; or in a motor, a winding turn insulated from the frame by an enamel coating and slot insulation, has a value of capacitance to the motor's frame.

Such currents are a part of the total CMC, and follow a path called the common mode loop (CML).

Fig. 3 shows the ASD, as an inverter power supply that acts as a CMV source (V_{cm}). CMC flows through the common mode cable and motor inductances, L_c L_m, and through the stray capacitances between the motor windings and motor frame, combined to be C_m. From the motor frame, it proceeds through the factory ground circuit which has the inductance L_g. L_g is also "fed" CMC from the stray cable capacitance C_c. The inverter frame is connected to the factory ground and couples the CMC "ground" currents through stray inverter to frame capacitances, lumped as C_{in}, back to the CMV source.

In reality, multiple CMLs will be formed in any drive system, the number depending upon **the drive system architecture,** and **the installation techniques** used.

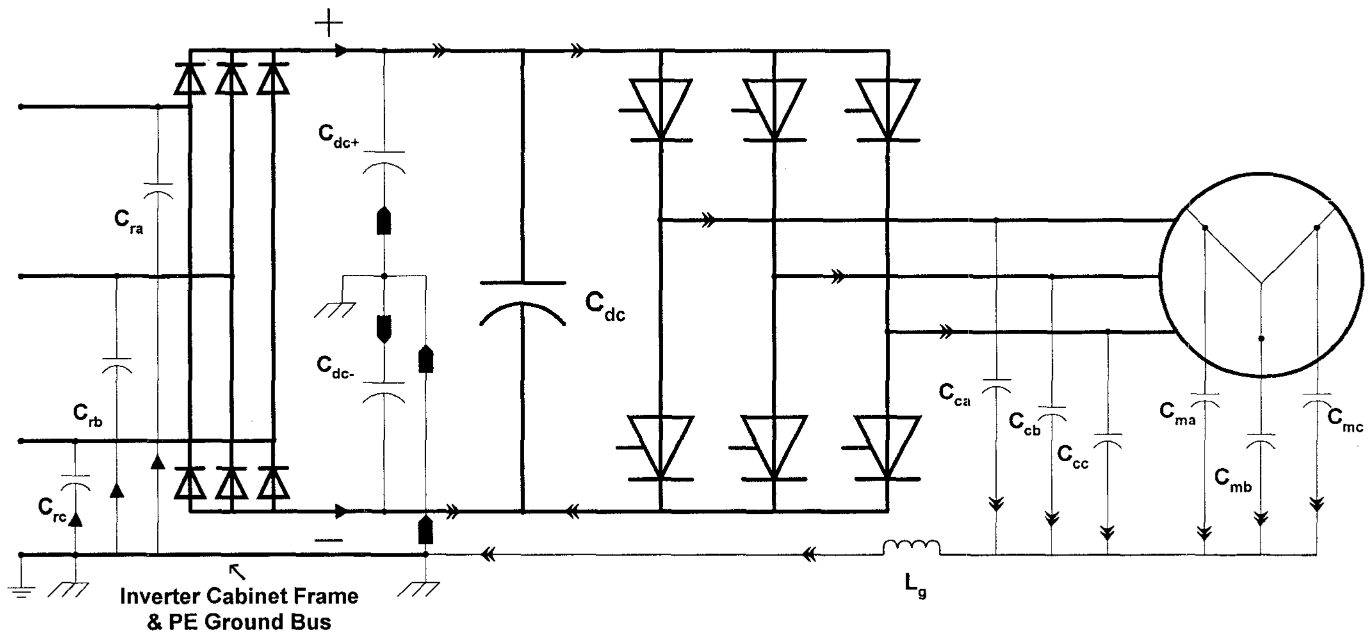

Fig. 4 "Differential" View of Basic PWM Inverter ASD Common Mode Current Paths

Fig. 4 shows the "differential" equivalent of a basic CML. Note by the double arrows, that the CMC leaves from each of the inverter output terminals, and flows through stray capacitances to ground between each of the motor cables, (C_{ca}, C_{cb}, C_{cc}), and each of the motor phases (C_{ma}, C_{mb}, C_{mc}), back to the inverter frame. Once conducted to the inverter frame, two main routes are possible for it to return to the DC bus capacitors:

➠ Through capacitances C_{dc+} and C_{dc-}. These represent the lumped stray capacitances present between the DC bus + and DC bus - to inverter frame, respectively. Included are the capacitances formed between any DC bus bars, the DC bus capacitor bank, as well as, the power semiconductors, and the metallic frame. This path is predominant for CMC in common bus *system* ASD applications, due to the long physical length of the DC bus and the resulting larger values of capacitance formed.

► It is also possible for CMC to flow through the phase-to-ground stray capacitances of the AC input supply, (C_{ra}, C_{rb}, C_{rc}), and proceed through the AC to DC rectifier in route to the DC bus capacitors. In "stand alone" ASD applications, CMC is more likely to follow this path due to the lack of substantial values of C_{dc+} and C_{dc-}.

All CMLs have some common factors:

- They "start" at the source of the CMV, the inverter itself, at the bank of DC bus filter capacitors which are extremely "stiff" in their ability to produce quite large current flows at very high pulse frequencies.

- For ***all*** components of CMC, the "destination" of these high frequency currents is the inverter frame, in route back to the DC bus capacitors through stray capacitive couplings.

In should be emphasized, that CMC is NOT naturally seeking the building structure, the ground grid below the building surface, or any 60 Hz power transformer and associated ground. CMC will flow however, though these or whatever else form the lowest inductance paths that are available, as routes towards *returning to the DC bus capacitors, via the inverter frame.*

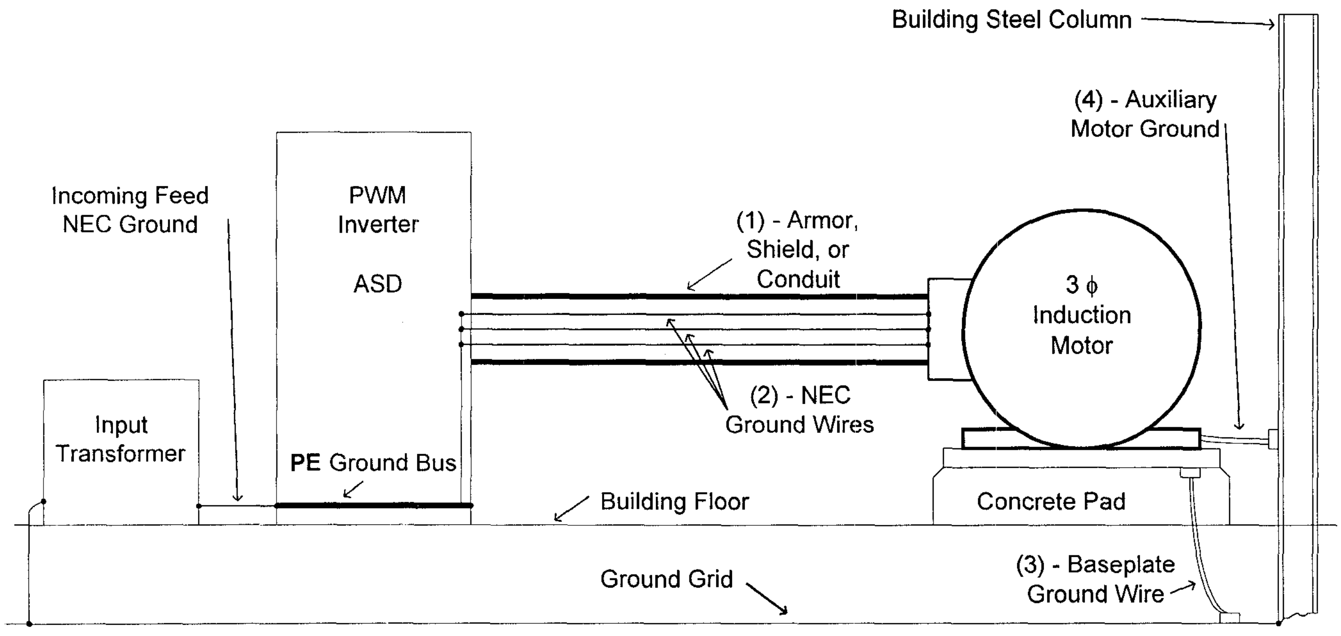

Fig. 5 Building View Showing the Four Normal Paths for CMC to Return to the ASD.

III. SPECIFIC EFFECTS OF STRAY CAPACITIVE CURRENTS

Stray capacitive currents flowing in the ASD circuit can lead to voltage drops that can be impressed across the motor or machinery bearings. Dependent upon the electrical and mechanical architecture of the equipment, bearing voltage can be generated in **three different ways.**

A. High Motor Frame Voltage Due to CMC Return Path Circuit Inductance

As inverter switching causes dv/dt's across cable and motor stray capacitances C_c, and C_m, the return path for the current is conducted from the motor frame, back to the inverter frame (in route to the DC bus capacitors), through four *normal* paths (See Fig. 5):

1. Directly via the motor cable's shield, armor, or conduit connection from the motor terminal box to the inverter frame entrance, (if existing).
2. Directly via the motor cable NEC ground conductor(s) connected at the motor terminal box and at the inverter safety ground (PE) bus. (The PE bus is electrically connected to the inverter frame.)
3. Indirectly from a *more or less* undefined *electrical connection* between the motor's frame, to a grounded base plate, (if existing), to building steel, continuing to the drive system incoming transformer's ground, through the NEC ground conductors of the three phase incoming power supply feeder, and finally back to the inverter's PE bus.
4. Indirectly from an *auxiliary ground* connection between the motor's frame to building steel, continuing to the drive system's incoming transformer's ground, through the NEC ground conductors of the three phase incoming power supply feeder and finally back to the inverter's PE bus, (in route to the DC bus capacitors).

Unfortunately, any of these routes contain inductance, some much more than others. CMC flow through such inductance, will cause a voltage drop that raises the motor frame above zero volts ground potential. Called "Motor Frame Voltage", it is really a portion of the inverter's CMV. (V_{MF} in Fig. 6a & 6b.) The CMC will seek the path or paths of least impedance. If a high amount of inductance is present in the *direct* paths, (1 & 2), the motor frame voltage will cause some of the CMC to be diverted into an indirect path, (such as 3 or 4 if existing), which flows through the building.

Additionally, if the value of such inductance (L_g in Fig. 6a & 6b), is large enough, the reactance at the upper range of typical CMC frequencies, (50 kHz to 1 MHz), can support substantial voltage drops, of over 100 volts between the motor frame and the inverter frame. In such a case, an *abnormal* indirect path may also be formed in parallel to the *normal* paths. If the motor shaft is connected through a ***metallic coupling, to a gearbox or other driven machinery that is solidly grounded and near the same***

ground potential as the inverter frame, then a high probability will exist for shaft currents to flow, due to the ***shaft's effectively superior ground.*** Sometimes called "shaft grounding current", ***it may flow through the bearings of the motor, the machine bearings or both.***

Fig. 6 shows two possible machinery configurations which, in the presence of high motor frame voltage, form *undesirable* paths for CMC to be drained from the motor and cable stray capacitances C_m and C_c.

- In certain instances, the motor shaft may be connected to machinery that is massive in size and has a substantial low inductance path to either the building structure or the ground grid. This can also be true for liquid pumping applications, in which the fluid may provide a low impedance path to ground for the shaft. In such situations, a portion of the CMV or "motor frame voltage", will be impressed across ***the motor bearing(s).*** (See Fig. 6a.) High frequency pulses of CMC will flow ***through the motor bearing(s) if un-insulated, the shaft,*** and into the associated machinery, back to building steel, continuing to the drive system incoming transformer's ground, through the NEC ground conductors of the three phase incoming power supply feeder, and finally back to the inverter's PE bus, (in route to the DC bus capacitors).

- If the machinery connected to the motor shaft is less substantial, possibly just a gearbox whose frame may be solidly grounded (perhaps through oil or water piping), but its shafting "floating" from the ground, then the motor frame voltage will be dropped across ***the bearings of the motor and the gearbox.*** (See Fig. 6b.) Again, high frequency pulses of CMC will flow ***through the motor bearing(s) and shaft, through the gearbox shaft and bearings,*** back to building steel, continuing to the drive system incoming transformer's ground, through the NEC ground conductors of the three phase incoming power supply feeder, and finally back to the inverter's PE bus, (in route to the DC bus capacitors).

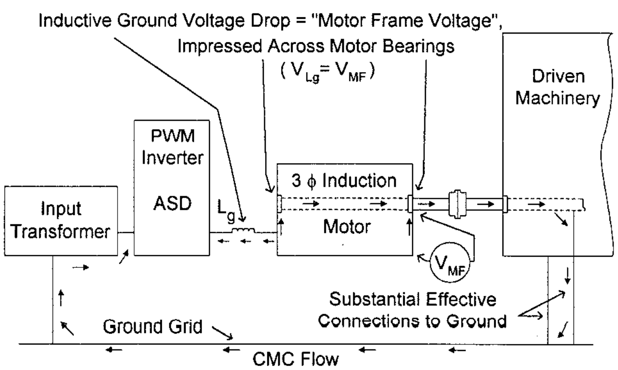

Fig. 6a Example of "Shaft Grounding Current" Resulting from High Motor Frame Voltage with *Superior* Machine Grounding.

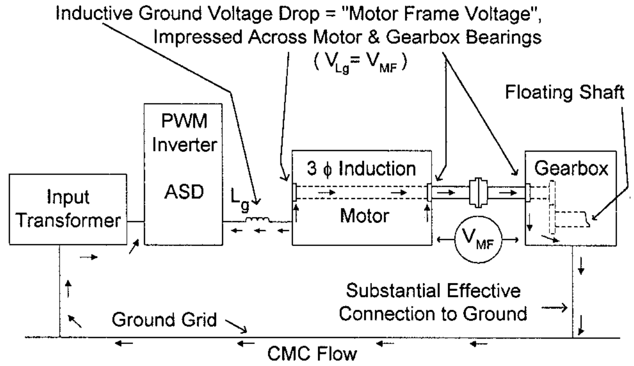

Fig. 6b Example of "Shaft Grounding Current" Resulting from High Motor Frame Voltage with *Superior* Gearbox Frame Grounding.

Bearing current caused from high frame voltage is not seen in belt driven applications, or those with insulated couplings, in which the motor shaft has no electrical connection to driven machinery or building structure.

B. HF Axial Shaft Voltage

Of the motor's stray capacitance C_m, the largest component is formed between the stator windings and the motor frame. Called C_{ws}, this capacitance is distributed around the circumference and length of the stator.

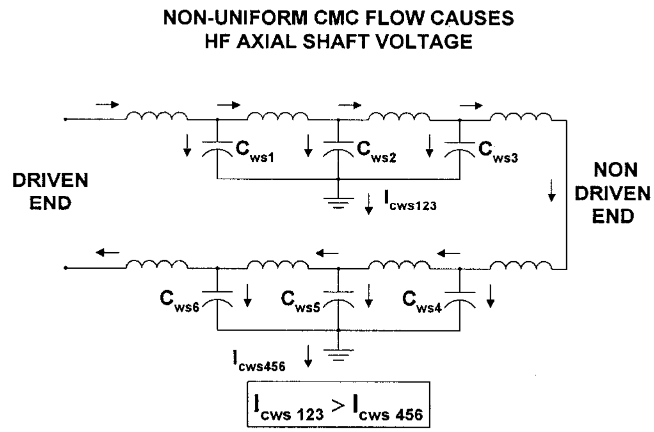

Fig. 7 One Turn Drawing of Motor Winding Showing Non-uniform HF Current Distribution

Research at the ABB Motors OY and the Tampere University of Technology in Tampere, Finland, [4-5], finds that the CMC that "leaks" through C_{ws} does so in a non-uniform manner. That is, in each distributed increment of C_{ws} , less current flows than in the increment before. (See Fig. 7.) This means that the HF component of CMC entering the coil is greater than the HF component that exits it. This effect will produce a magnetic flux that will circulate in the stator laminations, which will induce an axial voltage between shaft ends. If the voltage becomes large enough, a high frequency circulating current can flow, internal to the motor, through the shaft and both bearings. The HF axial shaft voltage can be thought of as the resultant of a transformer effect, in which CMC flowing in the stator frame acts as a primary, and induces the circulating current into the rotor circuit or secondary. (See Fig. 8.)

Although the circulating current has only been measured on medium sized induction motor frames with shaft heights of 12.5 inches (315 mm) and larger, it is considered to be the most damaging with typical peak values of 4 to 5 amps.

C. Coupling of Inverter CMV into Bearing Capacitance

In addition to C_{ws}, other stray capacitances are present inside the motor [6-7]. (See Fig. 9.) For instance, capacitance C_{wr} exists between the stator windings and the rotor itself. C_{ag} is the capacitance of the motor's airgap, between the stator iron and that of the rotor. Additionally, the bearings themselves have stray capacitance under certain operating circumstances, C_{mb}.

The existence of C_{wr} effectively couples the stator windings to the rotor iron, which is also connected to the shaft and the bearings' inner races. From the CML in Fig. 9, it can be seen that a fast change, or dv/dt in the CMV from the inverter can not only result in currents in C_{ws}, but also through C_{wr}, into the bearings.

The magnitude of current flow into the bearings is determined by the physical state of the bearing which can change drastically. For instance, the presence of C_{mb} is only sustained as long as the balls of a bearing are covered in oil or grease that has dielectric properties, and are in a non-conducting state. In such a situation, with each ASD switching transient, a portion of the CMV will be *charged* into the motor bearings according to the values of a capacitive voltage divider consisting of C_{in}, C_{wr}, and the parallel combination of C_{ag} and C_{mb}.

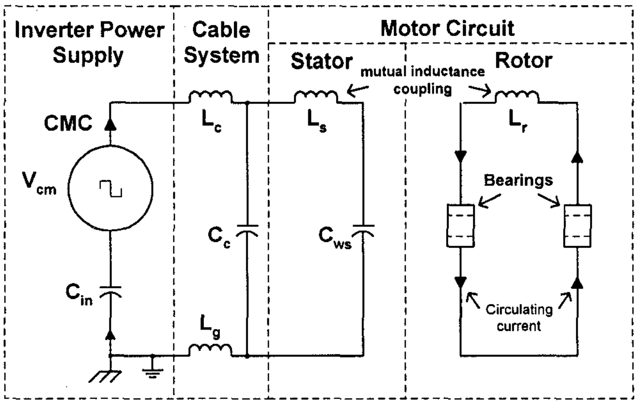

Fig. 8 Common Mode Transformer effect Causing HF Circulating Current

C_{mb} can be short-circuited if the bearing voltage exceeds the threshold of its breakover value or if a "high spot" on a ball breaks through the oil film and allows the ball to contact both bearing races. In either situation, the bearing's capacitance, and that of the airgap, C_{ag}, may discharge with a larger amount of current, in the hundreds of mA, and cause metal transfer between the ball and races. This is known as electric discharge machining or EDM.

It is also possible for C_{mb} to be bypassed if the motor shaft is connected to machinery with a good effective connection to building ground, as the shaft can drain current way from C_{wr}. Accordingly, bearing damage due to the coupling effect of capacitance C_{wr} is thought to be the most predominant in applications in which the shaft is floating with respect to ground, as with belted loads, or those with insulated couplings.

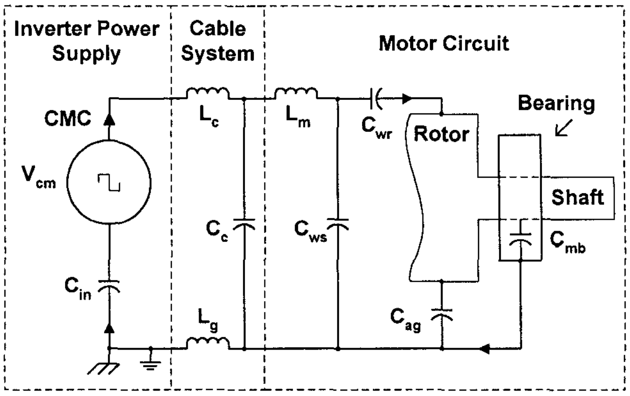

Fig. 9 Common Mode Loop of ASD Showing Stator, Rotor, & Bearing Stray Capacitances.

IV. MEASUREMENT OF THE COMMON MODE CURRENT (CMC)

When a bearing failure occurs, in addition to replacement of the affected bearing, it is usually desired to take corrective measures to avert similar occurrences in the future. Although a "fluting" pattern on its races may indicate damage due to electrical current, the particular origin of the bearing current must be determined to arrive at appropriate remedial procedures. Accordingly, an analysis can be performed on the installed architecture of the ASD system to identify the CMLs that bearing currents follow.

Field measurements can be taken to verify the existence of suspected CMLs. This can be difficult considering that CMC can flow in unusual places, such as a rotating shaft. In electrical terms, it contains short duration pulses with fast rise times.

In order to simplify such measurements, a flexible air-cored current sensor (ACCS) was developed. (See Fig. 10.) It can be positioned around objects, such as motor cables, motor shafts, and other paths for CMC, such as water or oil pipes, and can be opened during readings. Dimensionally, it was made approximately 20 inches in diameter, and is capable of measuring signals up to 1 MHz in frequency. Additionally, a hand held HF RMS converter was designed for use with the ACCS, to allow simple <u>*relative*</u> field measurements. The ACCS can also be connected to an oscilloscope for more detailed waveform analysis including peak current and pulse frequency measurements.

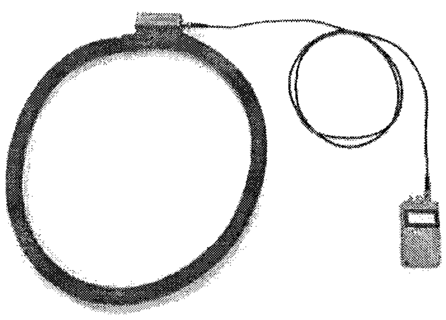

Fig. 10 Air Cored Current Sensor and RMS Converter.

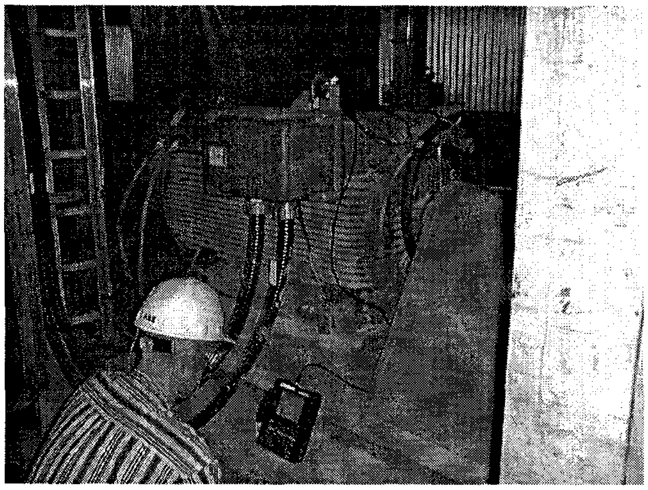

Fig. 11 Actual Shaft Current Measurement in an ASD System.

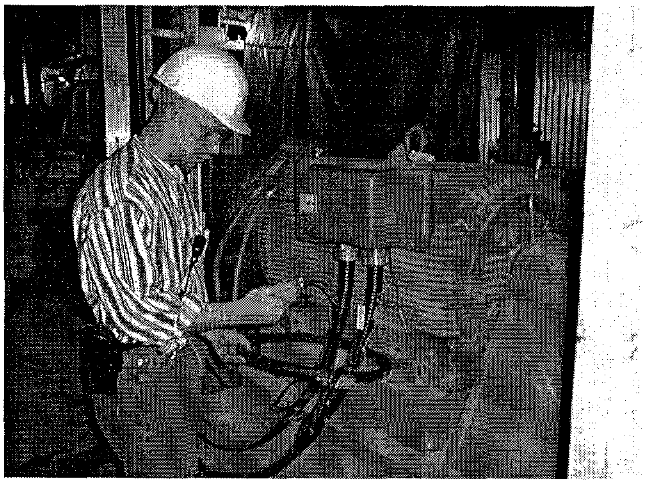

Fig. 12 Actual CMC "Cable Sum" Measurement in an ASD System.

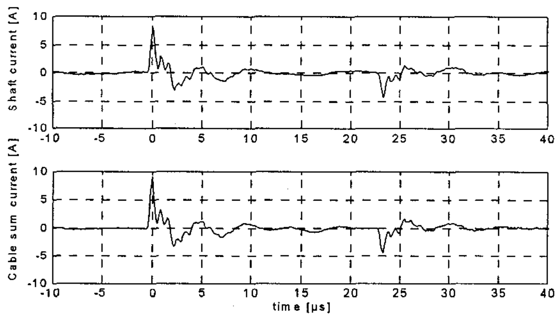

Fig. 13 Actual Shaft Current and "Cable Sum" Current Waveforms in an ASD System.

MEASUREMENT POINTS FOR HF CURRENTS

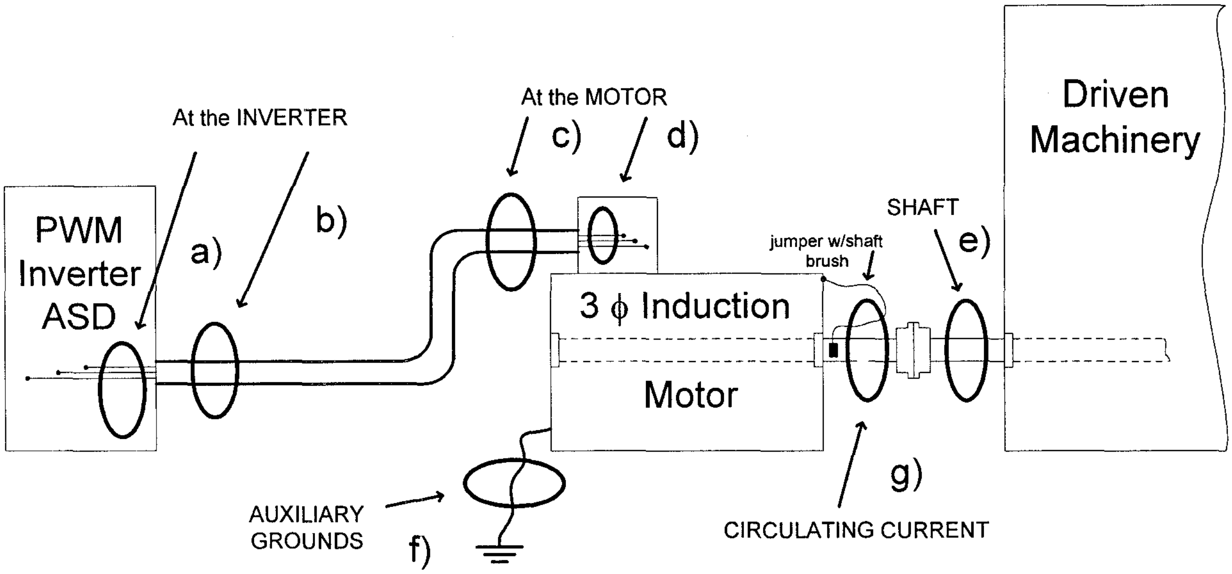

Fig. 14 High Frequency Current Measurement Locations in an ASD System.

Several different measurements can be taken in a particular installation, (See Fig. 14):

a) Inside inverter cabinet
By placing the ACCS around all three ASD output phase leads, the total CMC flowing can be measured. This can be used to compare the effects of remedies, such as ASD output filters.

b) Outside of inverter cabinet
With the ACCS around the phase leads, ground wires and shield, armor, or conduit, the component of CMC can be measured that is flowing from the motor and motor cable stray capacitances through *indirect* paths such as the motor shaft, and the auxiliary grounds via the building structure.

c) Outside motor terminal box
A measurement around the complete "feeder" to the motor will show the CMC, returning only from the motor, *indirectly* via the shaft and auxiliary grounds. A reading of zero mA here shows that the shield, armor or conduit connections are proper and that no HF CMC is "leaking" into the building structure.

d) Inside motor terminal box
Although sometimes difficult to perform, a reading around the phase conductors inside the motor terminal box will show only the CMC flowing through the motor stray capacitances in either *direct* or *indirect* routes back to the inverter.

e) Shaft current
Needless to say, shaft current should be very near zero otherwise risk is present to motor bearings, and those of the driven load.

f) Auxiliary ground currents
Although many auxiliary grounds may be present between the motor frame and the building, the summation of measurements should equal the CMCc, outside the motor terminal box, minus any shaft currents CMCe.

g) Circulating currents
In order to measure the HF circulating currents internal to the motor, a short jumper wire and shaft brush is needed. The jumper is fastened to the motor frame on one end, and temporarily put in contact with the shaft with the brush end. By placing the ACCS around both the jumper and the shaft, any shaft current is subtracted from the current reading resulting in the measurement of the circulating current.

New and existing drive installations can have baseline CMC readings taken to ensure proper installation practices have been followed. If bearing problems have occurred, readings can be used to quantify the CMC before and after corrective measures.

V. GOOD INSTALLATION PRACTICES CAN REDUCE THE RISK OF BEARING CURRENT

Any motor, regardless of frame size, may be subject to bearing currents if its shaft is connected to machinery that is at a different ground potential than the motor frame. It is the CMC flow through ground circuit inductance that causes high motor frame voltage pulses, resulting in shaft grounding currents. In order to eliminate motor frame voltage, it is necessary that grounding practices maintain all circuit components effectively grounded at the high frequencies encountered with today's state of the art ASD's.

The National Electric Code, (NEC), [8] Article 100 Definitions states for the term "Effectively Grounded": ***Intentionally connected to earth through a ground connection of sufficiently low impedance and having current carrying capacity to prevent the buildup of voltages that may result in undue hazards to connected equipment or to persons.***

Unfortunately, many standard equipment grounding practices only meet the intent of the NEC in a *low frequency "60 Hz"* sense. The most common method used to ground a motor (in the U.S.), is through the use of a ground wire bundled along with the main phase conductors. Such a wire's inductance build-up can result in large voltage drops with typical amounts of CMC flow.

An ASD can be effectively grounded at the high CMC frequencies if the installation standards implement three practices:

1. **Define a short, low impedance path for CMC to return back to the inverter.**
   Considering that the HF CMC leaves the ASD through the three output conductors leading to the motor, the closest possible HF return path would be a shield made from either **armor**, or **conduit** around these conductors that has a low transfer impedance at the frequencies encountered. Fig. 15 shows a graph of transfer impedance vs. frequency for different shielding types. Note the favorable characteristic of tubular copper where the impedance decreases with frequency due to "skin effect". [9] It is also desirable that the cable's shielding media be in close proximity to the phase conductors, as the mutual inductance between them will reduce the effective path inductance.

Perhaps one of the best and easiest ways to achieve such properties is through the use of a cable surrounded by continuously corrugated aluminum armor. Not only will it provide excellent shielding properties, but its welded construction provides an impervious seal against moisture and other chemicals, as well as physical protection.

Some caution is warranted regarding the use of conduit. Theoretically, aluminum or steel conduit can provide a satisfactory shielding effect. Yet because conduit is normally thought of as merely providing *mechanical* protection for cables, practical problems can develop causing discontinuity and a **poor** HF ground. Motor cables may "leave" an ASD cabinet in conduit but after a short distance may switch to:

- Cable tray
- Interlocked flexible conduit
- A "pull box" that may be painted and add impedance at input and output connections.

Also, in some cases where conduit is brought to the bottom of a drive cabinet, it is **not always connected** to the cabinet, thus open-circuiting the shortest and most important HF path for CMC.

Conduit will only minimize HF ground voltages if care is taken to ensure that continuous connections are made from the motor frame all the way to the inverter cabinet, with 360° connections at both ends.

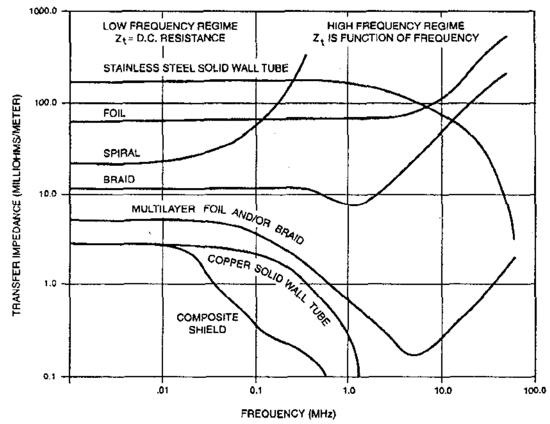

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Fig. 15 Graph of Transfer Impedance vs. Frequency for Different Shielding Media.

Considering that CMC flows in a series loop, the shielding effect from an armor, or conduit is only as good as the end connections made at the motor connection box and the inverter frame. It is important that end connections be made with low inductance and resistance. By using connectors that have contact with 360° of the shielding media's circumference, the low transfer impedance characteristics of the shield can be extended to the motor and inverter. Several types of connectors are commercially available that provide good HF electrical connections. (See Fig. 16.)

An important environmental benefit is gained from shielding the motor cables. By providing the lowest impedance path for HF currents, the majority of CMC will be effectively confined to within the shield. The result will be a cleaner electrical environment of the whole building, by reducing HF conducted emissions into the factory ground system! The concept of shielding the motor cables is not new for countries in the European Union (EU) where people must follow stiff Electro-Magnetic Compatibility (EMC) standards as required by law. Shielded motor cables are typically used that have a transfer impedance of no more than 100 milliohms/meter at 100 MHz.

2. **Employ Auxiliary High Frequency Bonding Connections for Potential Equalization**

In most instances, providing a shielding means for the motor cables will reduce the motor frame voltage to a low enough value to eliminate shaft current. However, extremely long runs of cabling systems can result in some inductance build-up and subsequent voltage drop. In addition, quality control of shield, armor or conduit connections will always be of interest as people sometimes make mistakes when tightening and terminating cable components. Such practical realities can be compensated by adding HF bonding connections between the motor frame and known ground reference points, in an effort to equalize the potential of affected items. The term HF bonding, as used in this paper, denotes methods to "Effectively Ground" drive system components ", (per NEC Article 100), in a manner that attempts to minimize conductor inductance build up, by maximizing "skin effect" for pulse currents in the vicinity of 5 Mhz. Such HF bonding connections can be made up from braided straps or strips of copper 2-4 inches in width. Flat conductors will provide a lower inductance path than round wires, which can develop 1 μH per 3 feet of length. If round wires must be used, multiple parallel conductors should be employed at different locations to reduce the inductance.

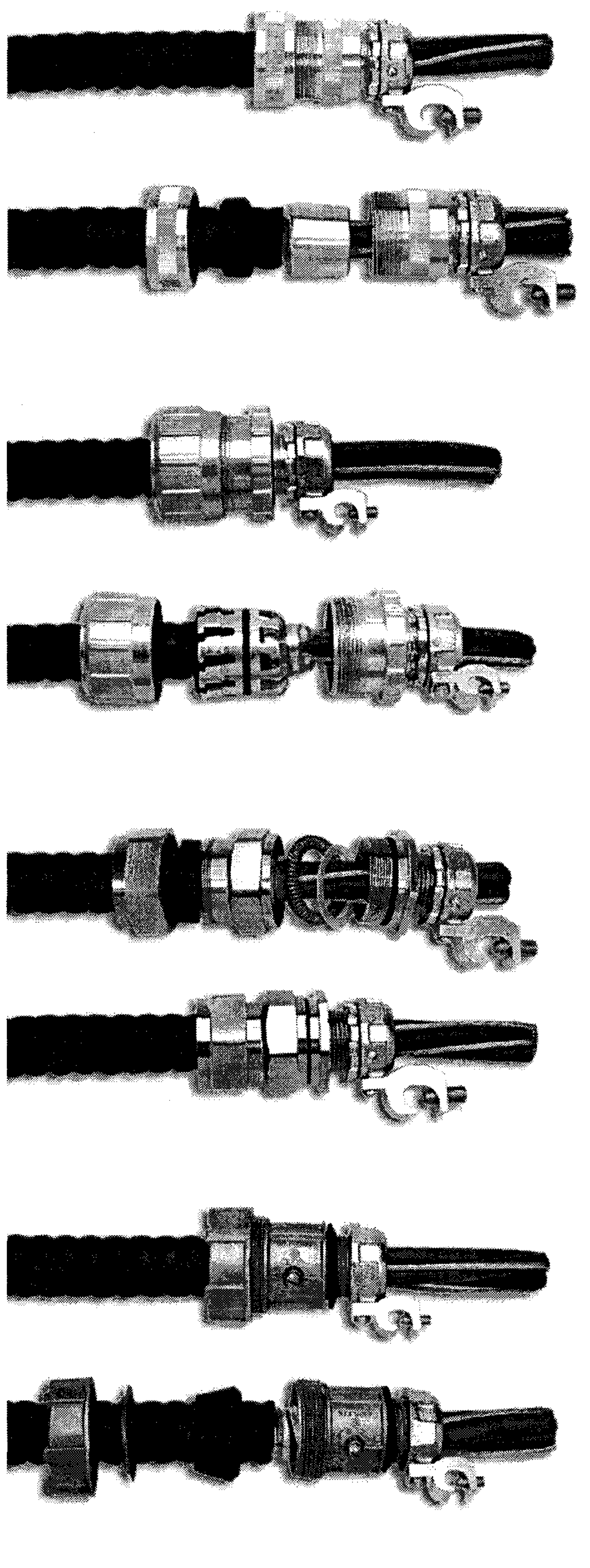

Fig. 16 Connectors for 360° Contact with Metal Clad Cable.

a. Inverter Frame to the "Sealing Sub-Floor" for Bottom Entry of Motor Cable Installations

Many modern ASD sub-stations are environmentally protected in terms of humidity and chemical contaminants, and may be supplied with conditioned air. For some installations, in which the motor cables enter the inverter cabinet from the bottom, metallic sheeting may used below the concrete floor to provide a seal to the room against incoming contaminants. It is possible that the motor cable shield, armor or conduit may be terminated at this point, which leaves it effectively disconnected from the cabinet.

In such cases, HF bonding straps can be connected between the sub-floor and PE ground bus to ensure a suitable HF connection for returning CMC to the inverter frame. (See Fig. 17.)

b. Motor Frame Connection to Gearbox or Connected Machinery

The best way to eliminate a voltage differential between the motor frame and a gearbox is to mount both of them on the same baseplate. This may not be possible for some gearboxes and various types of driven machinery. However, the same effect can be achieved if HF bonding straps are employed.

Keep in mind though, that if poor cabling practices cause a high frame voltage between a motor frame and ground, equalizing the potential between the motor frame and that of the gearbox, may shift the potential difference from the motor/gearbox bearings to other machinery bearings.

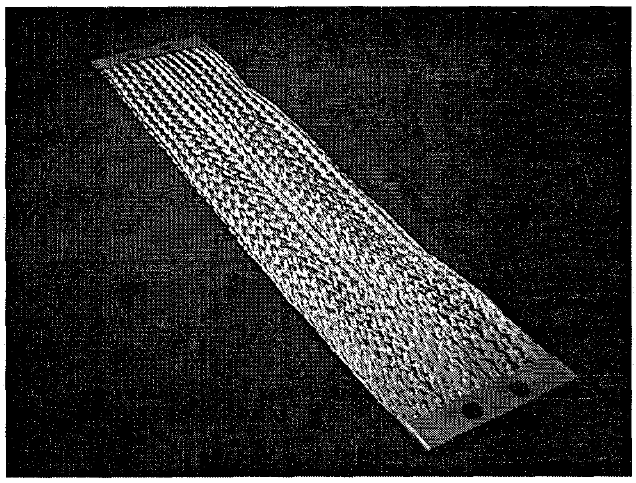

Fig. 17 HF Bonding Strap Suitable for Connecting Inverter Cabinet to Sub-Floor.

b. Motor Base Connection to Building Steel

Once upon a time, it was standard practice to ground a motor baseplate to building steel. It is doubtful whether this custom is consistently followed any more. Sometimes at new construction sites, a copper conductor can be seen stretching from nearby building steel, through the rebar of concrete forms, for eventual connection to the baseplate. On rebuilds, the existence of such a ground wire seems to be rare. **Nevertheless, a HF bonding strap should connect the motor baseplate to the nearest conductive building member, preferably a vertically oriented one that is cadwelded to the ground grid. Such a connection may make the difference between an *effectively grounded* motor frame, or one that merely is "*sitting on concrete*".**

c. Motor Frame Connection to Building Steel

In many established mills, the ground connection of a motor's baseplate may be in question or unknown. If an existing baseplate is to be used for a new motor installation, it is wise to **connect an auxiliary HF bonding connection from the motor frame to the nearest conductive building member, preferably a vertically oriented one that is cadwelded to the ground grid.**

d. Ensure Good HF Connection Between Motor Frame and the Motor Terminal Box

The majority of motor terminal boxes are of cast construction and are usually well connected to the motor frame by multiple screw type fasteners. It is important that the screws make good contact with the metallic inside surface of the terminal box to allow the HF currents to pass from the frame to the cable shield, armor or conduit. The design of some fabricated terminal boxes may involve multiple gaskets in between painted sheet metal and may offer a questionable HF connection. HF bonding straps can be connected between the terminal box and motor frame if there is any doubt.

3. Use symmetrical motor cables to minimize the magnitude of CMC.

The symmetry of the cable core configuration affects the magnitude of both the low and HF CMC. Although the *main* conductors of a three phase cable are symmetrical, many contain only a single ground wire placed on the side of two phase wires. Such a cable, will have additional ground current (CMC), flowing within it due to induction.

Faraday's law says that if a conductor is placed in a changing magnetic field, a voltage will be induced into the conductor. Each main motor "feed" conductor will have current flow within it, which will result in the presence of a magnetic field around each conductor. The sum of the three fluxes will cancel, if they are truly balanced, only at a point that is symmetrical to all three conductors. However, ***a single ground conductor asymmetrically placed, will be influenced differently by the changing fields of each main conductor*** and accordingly, will have current flow due to the induced voltage.

Current measurements, of single ground wires, have been taken with readings in excess of 15 amps RMS at the fundamental inverter output frequency. (Typically, 10 - 100 Hz.)

Accordingly, a three phase cable should have three main and three ground conductors placed symmetrically within its core to reduce the magnitude of CMC flow. (See Fig. 18.)

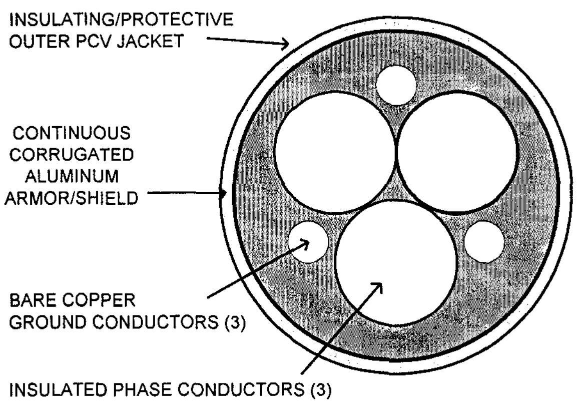

Fig. 18. Recommended Motor Cable with Symmetrical Core Configuration.

The extra ground wire ampacity can be an advantage for parallel feeds per NEC 250-95. [10]

A grounding bushing should be used on both ends of the motor cable to effectively connect the ground wires to the armor or conduit. This will reduce the current flow in the ground wires that exit the cable core leading to PE ground termination points. (See Fig. 19.)

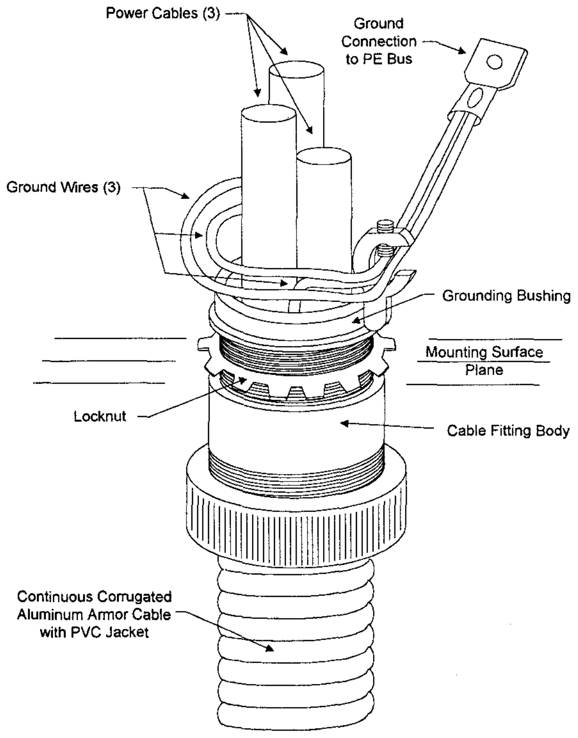

Fig. 19 View of Armor, Connector & Grounding Bushing.

VI. RECOMMENDATIONS TO MINIMIZE THE RISK OF BEARING CURRENTS

A. Equalize HF Ground Potential Between Motor Frame, Inverter Chassis, and Driven Machinery

1) Use Symmetric Motor Cables with Low Inductance Shield, Armor or Conduit

Type: MC metal-clad three phase type cable per NEC 334-1, UL approved
Sheath: Continuous corrugated aluminum - welded or seamless, with wall thickness as heavy as practical
Configuration: Three (3) phase conductors. Three (3) ground conductors.

2) Use Cable Connectors with 360° Connections to the Armor\Conduit at Both Ends of the Motor Cables
Several different types of connectors are available for metal-clad cable to connect the complete circumference of the armor to the inverter cabinet entry plate or motor connection box. (See Fig. 16.)

3) Employ Auxiliary High Frequency Bonding Connections for Potential Equalization
HF bonding connections should be made between the following items:
a) Inverter Frame and the "Sealing Sub-Floor" for Bottom Entry of Motor Cable Installations
b) Motor Frame and Gearbox or Connected Machinery
c) Motor Baseplate and Building Steel
d) Motor Frame and Building Steel
e) Motor Frame and the Motor Terminal Box

B. Specify Insulated Motor Bearing on Non-Driven End of Larger Motor Frame Sizes

Motors with a shaft height of 12.5 inches or larger. (NEMA frames 504, or IEC frames 315)

C. Reduce Rate of Power Supply Switching Voltage (dv/dt's)

Where bearing currents are known to exist, two types of inductive filters are commercially available, that will lower the dv/dt's endured by the motor, and reduce bearing current. (An inductor must be used that exhibits good HF characteristics, and is lossy, to help dampen transient oscillations that can occur with each ASD output pulse.)

1) Common Mode Chokes
Ferrite rings can be placed around all three ASD output conductors. The number, size, and inductance value will be dependent upon the operating voltage level of the DC bus, and the inductance present in the CML.

2) Three Phase Output Reactor
Three phase inductors are available, some with added resistors or resistor and capacitor combinations, in an effort to form a damped low pass filter. Ranges of 1 to 3% impedance are typically used.

D. Lower Power Supply Switching Frequency

Many PWM inverter ASDs include the ability to program the carrier frequency of the PWM waveform. Some units have a range from as low as 1 kHz, up to 10 kHz or more. In cases where bearing damage has occurred, some short term relief can be achieved by reducing the carrier to the 1 - 3 kHz range.
Although this type of adjustment may affect motor performance and does not change the dv/dt, it can greatly affect the number of pulses that are sent out of the ASD to the motor and cables. By lowering the carrier frequency, the number of bearing current "spikes" can be reduced.

VII. CONCLUSIONS

Electric bearing currents in ASD systems, are caused by shaft voltages, which can be generated in three different ways:

1. High Motor Frame Voltage
2. HF Axial Shaft Voltage
3. Coupling of Inverter CMV into Bearing Capacitance

All result from the ability of a PWM inverter to produce a voltage between its output and ground, sometimes called a common mode voltage. Fast rise times of this CMV, related to inverter switching speeds, cause transient currents to flow between circuit components and ground. These high frequency currents can flow through motor or machinery bearings.

Both the installation practices and the architecture of an ASD system play critical roles in determining the risk for any particular type of shaft voltage. When bearing damage occurs, an analysis can be performed on the particular ASD system's installed architecture. Such a study should focus on identification of the common mode loops that bearing currents follow, leading to the determination of the specific origin of the bearing damage. Field measurements of the common mode current can be used to verify proper installation techniques, as well as, quantify the existence of current flow in shafts and other components. Data gathered can also provide comparative data as proof of bearing current reduction after corrective measures have been implemented.

Preventative, as well as corrective measures should include the use of :

- Symmetric motor cables with shield of armor or conduit.
- Proper installation of motor cables & connectors.
- Equalize ground potentials with HF bonding.
- Insulated motor bearings on certain frame sizes
- Reduction of the inverter output dv/dt.
- Lowering of the PWM carrier frequency.

VIII. ACKNOWLEDGMENTS

The author wishes to express gratitude to Mr. John Bentley and the many people of ABB Industrial Systems Inc., ABB Industry OY, ABB Motors OY, and the Tampere University of Technology, who helped in making this paper possible through extensive research, sharing of global experiences, and providing critical review of the paper.

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