Source of Induction Motor Bearing Currents Caused by PWM Inverters

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Abstract - **The recent increase of bearing damage in induction machines driven by transistorized inverters has spurred activity on possible causes related to PWM inverters. This paper looks into a typical power conversion system from this perspective. It identifies the existence of the common mode voltages produced in all types of converters. A hypothesis is then proposed to explain the bearing current problem. In particular, it is shown that in an inverter-motor system the common mode voltages generated by a PWM inverter, which are attributed to PWM switching harmonics, couple through parasitic capacitances from stator windings to the rotor body and then returns through the motor bearings to the commonly grounded stator case as a closed loop circuit. The hypothesis is verified by experimental measurement of common mode coupling currents and true bearing currents in a specially modified induction motor. Solutions are then provided to suppress the bearing currents.**

1. Introduction

Bearing currents, or shaft currents, which usually flow from the shaft of an electric machine through its bearings have existed ever since the invention of electric machines [1]. It has long been recognized that the causes for this problem are usually related to the rotor eccentricity, homopolar flux effects, or electrostatic discharge (ESD) in electric machines [2,3].

More recently advances in power electronics has widened the scope of application of induction motors dramatically. In particular, PWM inverters with their high switching frequencies have made it possible for variable frequency drive systems to possess good spectra, low acoustic noise and more efficient electromagnetic power conversion. However, the PWM inverter has also been suspected to be related to the increase of bearing failures observed in variable speed drive systems [3,4]. Whether an inverter can, in fact, cause damaging bearing currents must remain an unresolved mystery before an acceptable theory and more solid evidence is available. In addition, effective solutions to the recent increase of bearing damage will remain difficult unless the exact bearing failure mechanism is well understood.

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In this paper, power converters are reviewed from a totally different perspective than the traditional viewpoint of energy conversion. It has been found that the converter itself is a common mode voltage generator. The common mode voltage is usually at a high voltage level and with a frequency equal to inverter switching frequency. As the switching frequencies of a converter are pushed up to increasingly higher values due to device improvements, the parasitic coupling of common mode voltage becomes a dominant side effect in addition to harmonics and other commonly recognized unwanted byproducts of pulse width modulation.

Therefore, a reasonable hypothesis of motor bearing currents generated by PWM inverters can be proposed based on the common mode voltages and high frequency coupling through parasitic capacitances. The focus of this paper is then to identify the source of the common mode voltages in a three phase PWM inverter and to define the major parasitic coupling paths in an induction machine which lead to bearing current generation. Two major parasitic coupling paths are found: the stator windings to the stator iron and stator windings to the rotor iron. The common mode voltage model together with the coupling path model are combined to give a satisfactory explanation of the currents flowing in the machine bearings as well as in the grounding cables. An experimental measurement is then performed on a modified induction machine to verify the existence of considerable parasitic coupling effects caused by the common mode voltages of an inverter. Bearing currents caused by inverters are also observed through experiment. Based on these findings, several solutions to reduce bearing current are provided. As the common mode voltages are also the cause of motor and inverter grounding currents which produce major EMI emission in the inverter-motor systems, the theory and solutions can also be applied to EMI and grounding current generation and reduction.

2. Converters As Common Mode Voltage And Current Generators

It is well known that a power electronic converter must be specifically designed for a particular type of energy conversion such as from DC to DC, AC to DC, or DC to AC. A designer of converters is usually concerned with the output parameters to satisfy certain specifications. In

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most converter topologies, the useful output voltages or currents are generated as a result of what can be termed the differential mode.

A typical converter design methodology can be illustrated by the simple example of a single bridge DC to AC converter as shown in Fig. 1. If the gating signals to switches S1 and S2 are kept the same (gating signals to S3 and S4 are inverted), no output voltage will be generated between terminals a and b. Such an inverter would, of course, be considered useless in terms of energy conversion. Even in this case of zero real power conversion, however, if one observes the voltage potential of terminals a and b relative to the a grounding point, O, as shown in Fig 1b) respectively, it is evident that the converter is actually generating pulses at points a and b. Furthermore, if a parasitic capacitor is assumed to exist from the midpoint of the load to the ground, a current will clearly flow into the load and the capacitor, as is indicated by the arrows. The voltages of terminals a and b relative to the ground is what is normally termed common mode voltages. The current through the capacitor is the common mode current.

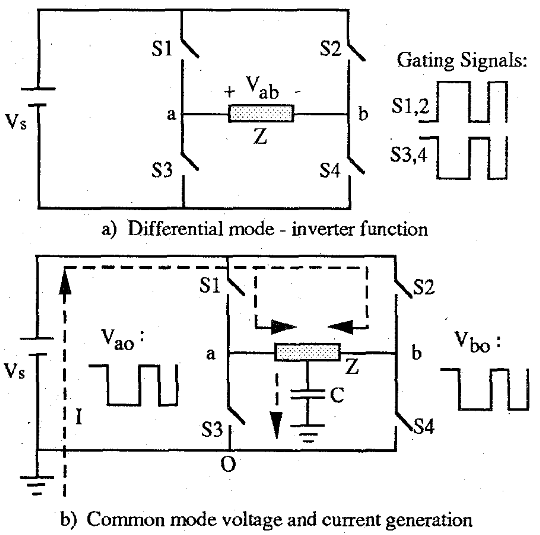


Fig. 1 A Single Bridge DC to AC Converter

The resulting common mode voltage can thus be defined as a voltage potential relative to a common reference point, usually the negative DC bus O or the earth. Common mode currents are the result of these common mode voltages. In a realistic inverter, grounding of a DC bus such as illustrated in Fig. 1 is never permitted. However, it is a convenient point from which to measure common mode voltages. One can still argue that a parasitic capacitance always exists from the DC bus to the Earth, or that the Earth connection to DC bus can be switched through rectifier and AC source. Generally, common mode voltages have certain internal impedance which depends on the system grounding configuration.

It is generally true in any converter-load system that common mode voltages will exist everywhere in any of these circuits connected to the output of converter switches. The mechanism by which common mode currents flow, however, will depend on the common mode impedance of the system, circuit configuration and ground connections. Finally, it is important to note that although a common mode voltage is not visible from the normal differential output, common mode current does flow through the load. This current can also consume input power and may even cause damage to the load.

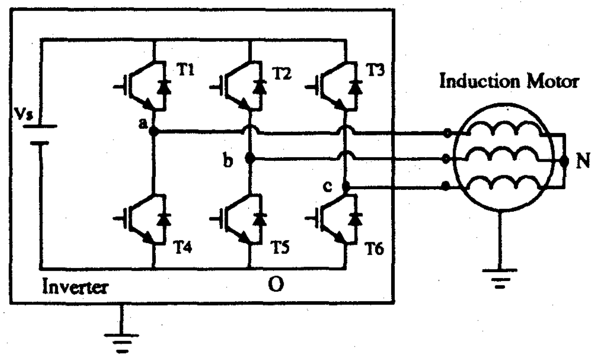
3. Motor Bearing Currents Caused by PWM Inverters

To distinguish between the bearing currents caused purely by inverter switching from those caused by other mechanisms such as the classical rotor eccentricities, etc., it is assumed here that no other types of bearing currents will exist in the electric machine model of our study which was readily confirmed by operating the motor on balanced three phase sinusoidal voltages. As any hypothesis of bearing currents caused by inverters is based on existence of common mode voltages and parasitic coupling capacitances, it is necessary to look at both of these two factors in an inverter-motor system.

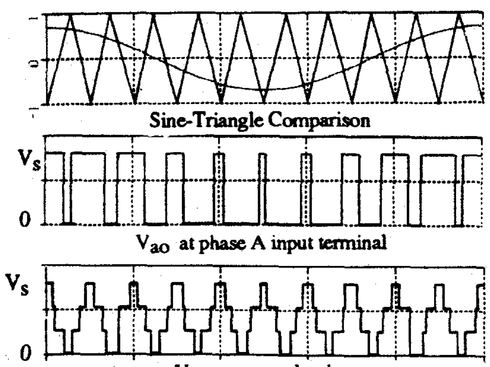
If, in a three-phase PWM inverter-motor system as shown in Fig. 2, one considers the common mode voltage relative to the negative dc bus O, the common mode voltages at the inputs of the three-phase windings will be V_{ao}, V_{bo}, and V_{co}, respectively. These common mode voltages have exactly the same switching pattern as the three gating signals of the upper-leg inverter switches except that their pulse amplitudes will be as high as the dc bus voltage V_s. At the motor neutral point, the common mode voltage will be equal to $(V_{ao}+V_{bo}+V_{co})/3$, assuming no parasitic coupling capacitances for the moment. A plot of common mode voltages in a motor phase winding for sine-triangle modulation is given in Fig. 2b). It is, therefore, evident that common mode voltage pulses exist at every point along the motor stator windings.

Assuming no parasitic coupling, an induction machine will only experience the differential mode voltages, i.e., line to line voltages, and will behave as an ordinary three phase sinusoidal AC supply, except that some differential mode switching harmonic current will also exist. However, once the switching speed of an inverter is pushed up beyond a certain level, parasitic coupling begins to appear as a dominant factor. In an induction motor particularly, the uniform distribution of windings along the stator surface greatly enhances the possibility of considerable parasitic capacitive coupling. As reported previously in a study of the high frequency losses of induction machine [5], above certain frequency level, machine windings begin to behave capacitively with a large level of high frequency current circulating inside the machine.

While it is difficult to accept that the stator windings have substantial parasitic capacitive coupling to the stator, by a simple measurement the stator winding capacitance relative to stator case using a LCR meter, it is readily determined that roughly 5-10 nF exists between stator winding to stator case in a typical 1-50 kW motor, over a frequency range from 1 to 500 kHz (frequency range of the meter).

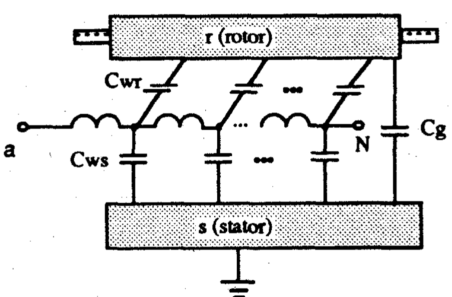


a) A PWM inverter-motor system

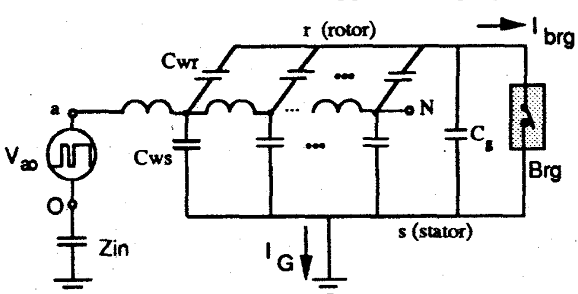


b) Common mode voltages in motor windings

Fig. 2 Common Mode Voltage in a Three-Phase Motor-Inverter System



a) Induction machine showing parasitic coupling



b) Per phase equivalent circuit

Fig. 3 Equivalent circuit for Bearing Currents in an Inverter-Machine System

Another parasitic coupling path, which is usually difficult to visualize but critical to the proposed bearing current generation theory, is that of capacitive coupling from the stator windings to the rotor iron. The coupling capacitance is usually very small, in the range of 10-50 pF. However, it is found that even such a small capacitance can actually cause detrimental bearing damage.

By identifying these two important parasitic coupling paths, it is now possible to propose an induction machine model for high frequency common mode voltage excitation. Fig. 3a) shows such a machine with the capacitors C_{ws} and C_{wr} representing parasitic coupling from stator windings to stator and rotor respectively. If the motor stator and rotor are electrically insulated, there is an airgap capacitance C_g between the rotor and stator laminations which is also included in Fig. 3.

Finally, by combining the machine model with common mode voltage excitation from the inverter, a per phase model of bearing current generation in an inverter-motor system is shown in Fig. 3b). In the model, V_{ao} represents the common mode voltage relative to the inverter negative DC bus, Z_{in} the common mode internal impedance which is mainly the parasitic coupling capacitance from negative DC bus to the grounded inverter case. The bearings are modeled as a switch Brg which may be turned on and off randomly due to rotating bearing electrical behavior. The bearing currents are thus the currents from stator windings to the rotor and then back through Brg to the earth ground. The grounding currents are the sum of bearing currents and coupling currents from windings to stator.

4. Experimental Measurement of Bearing Currents

A special modification to an ordinary induction machine has been made for experimental verification of the parasitic coupling effect of common mode voltage inside a squirrel cage induction machine. Such a modification also has made it possible to perform measurement of true bearing, or shaft, voltage and current. Fig. 4 depicts an idealized representation of this machine.

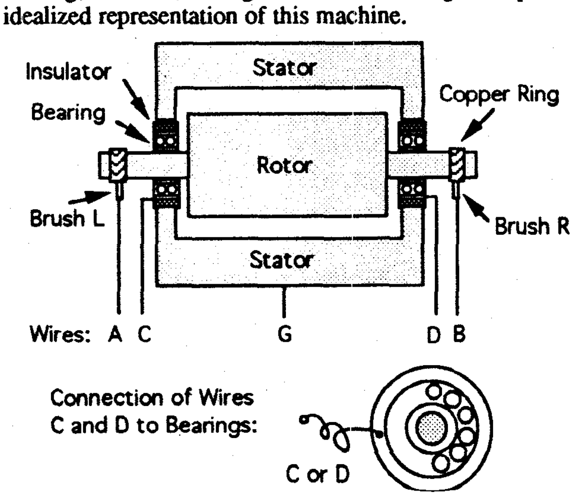


Fig. 4 Modified Induction Machine for Bearing Current Measurement

In this modified motor, insulation material is inserted between the outer races of bearings and the stator case, which ensures electrical isolation of the stator and rotor. Brushes are used to connect wires A and B to left and right ends, respectively, of the motor shaft, while wires C and D are connected to the outer races of bearings. It is obvious that by securely connecting wires C and D to the stator case, the machine will simulate a realistic motor without insulated bearings. Hence, almost all bearing currents will now flow into wires C and D, providing a means to measure the true bearing currents. In addition, cable G is connected to the grounding terminal G of the motor stator case.

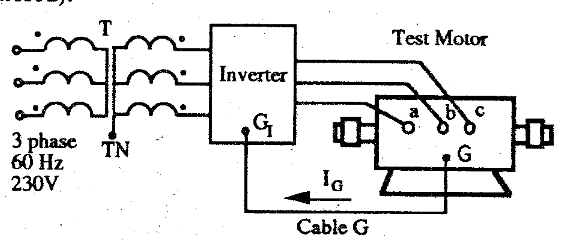
A. Verification of Two Main Coupling Paths

The overall experimental inverter-motor system connection is shown in Fig. 5. The inverter and motor data are included in the Appendix. An isolation transformer is used to decouple the system from the Earth. The platform upon which the motor and inverter is situated is also insulated. Therefore, all the measurement results presented here will represent the case of minimum coupling. In an actual application, the inverter case, motor case and perhaps even the neutral of the isolation transformer or AC power supply are all connected to the Earth, which in general will greatly enhance the coupling effect. Thus all the coupling currents would be expected to increase considerably from the values observed in this test.

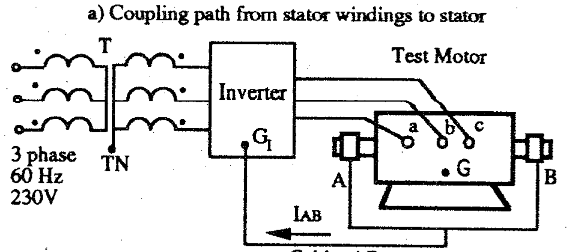
The two main paths of parasitic capacitive coupling can be verified through the following experiments:

a. Parasitic coupling from stator windings to stator

The setup in this case is to connect only cable G of the test motor to the inverter case (grounding terminal G_I) as shown in Fig. 5a). Since the rotor is isolated from the stator, one expects to observe only coupling current from the stator windings to stator case flowing in the cable G (The insulation capacitance between stator and bearings is ignored).



a) Coupling path from stator windings to stator



b) Coupling path from windings to rotor

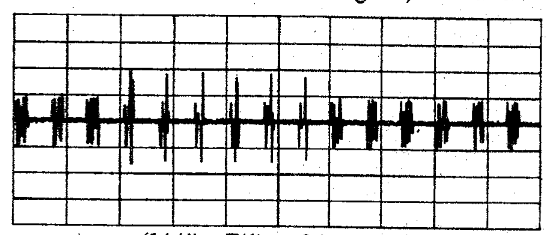
Fig. 5 Setup for Measurement of Two Major Capacitive Coupling Paths

With the motor running at 60 Hz, the current in cable G was recorded as shown in Fig. 6a). It was found that even in this relatively conservative test system without grounding to the Earth, the parasitic coupling current, I_G, from stator windings to stator has a peak value of 2 A. When cable G is also connected the real Earth, it was observed that additional common mode currents will flow to the Earth and return through transformer parasitic capacitor to the inverter input. Thus, the total common mode coupling currents are further increased.

b. Parasitic coupling from stator windings to rotor

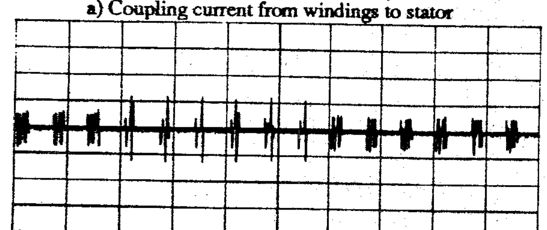
This parasitic coupling is measured by connecting only wires A and B together, then through cable AB to the inverter case, G_I, as is indicated in Fig. 5b). The parasitic coupling current, I_{AB}, from the stator windings to the rotor is recorded as Fig. 6b). It can be seen that this coupling is also considerable with a peak current as large as 1.2 A. Although a large potion of the coupling current is believed to flow via the airgap capacitance, it does suggest that coupling effect can not be ignored in inverter drives.

These two experiments strongly support our argument of the existence of two major coupling paths in an induction motor. It also gives an impression of how serious the problems of the common mode voltages generated by a PWM inverter can be. It is important to point out that when the motor and inverter case are both connected to the Earth, both of the common mode coupling currents will increase considerably because the equivalent internal impedance Z_{in} as shown in Fig. 3b) is smaller.



(1A/div., T/div. = 0.1 msec.)

a) Coupling current from windings to stator



(1A/div., T/div. = 0.1 msec.)

b) Coupling current from windings to rotor

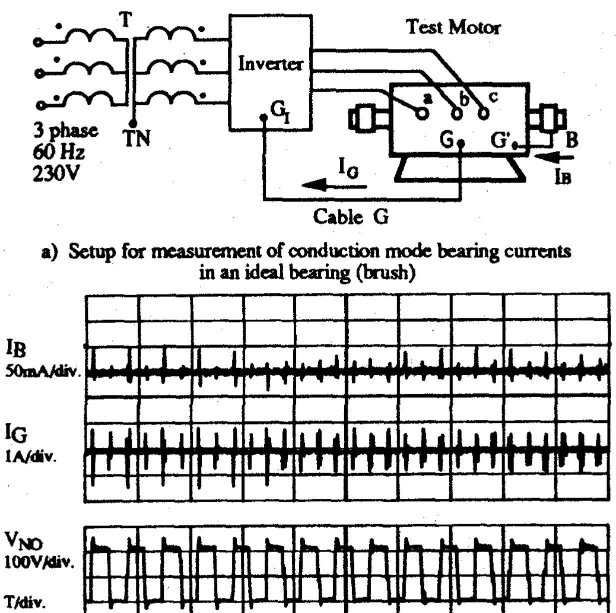
Fig. 6 Coupling Current from Stator Windings to Stator and Rotors

B. Verification of Bearing Currents

Another important experiment is to verify the existence of bearing currents caused by PWM inverters. In general, the electrical properties of a rotating bearing were found to be more complicated than expected. At different operating conditions, a bearing/race may exhibit randomly good conductivity, no conductivity, or values between. Several experiments were designed to reveal the various characteristics of bearing currents. Two basic types of bearing currents are found to exist: what we have termed the conduction mode bearing current and the discharge mode bearing current.

a. Conduction mode bearing current

The conduction mode bearing current is referred to the current flowing in bearings which exhibit continuously good conductivity during certain period of time. The experimental setup for conduction mode bearing current measurement is shown in Fig. 7, which shows that the brush wire B is connected to the grounding terminal G' of the motor stator case. The location of G' is chosen to ensure that the wire connection is as short as possible so that minimum leakage inductance in the wire can be achieved. This configuration allows one to test the current from shaft to stator case through a simulated ideal bearing with continuous conduction path and very low impedance. As the bearings are insulated and bearing wires C and D are not connected to the stator, it can be assumed that no current flows inside the bearings. Thus, the current flowing in wire B will represent all common mode current coupling from stator winding to rotor and then returning to the stator case. This type of bearing current in the case of continuously conductive bearings is termed the conduction mode bearing current. Although, in a realistic bearing, both components of the conduction mode and the discharge mode bearing currents exist, this measurement provides information concerning the maximum conduction mode bearing current if bearings exhibit good conductivity.



a) Setup for measurement of conduction mode bearing currents in an ideal bearing (brush)

b) Measurement results

Fig. 7 Conduction Mode Bearing Current in a Simulated Conductive Bearing (Brush)

For the inverter-motor system connection with least coupling as shown in Fig. 7a), the plot in Fig. 7b) shows the currents in brush wire B and cable G, as well as the motor neutral voltage relative to negative DC bus, V_{NO}. It is seen that the conduction mode bearing current is about 50 to 60 mA peak value. This is equivalent to stating that the parasitic coupling capacitance C_{wr} from stator windings to rotor is actually very small. By correlating to motor neutral voltage relative to negative DC bus, V_{NO}, which shows all PWM switching states in the inverter, the relationship between PWM switching and the bearing current as well as common mode current in the cable G can be clearly identified. It is noted that the conduction mode bearing current is characterized by its occurrences in synchronization with the edges of common mode voltage pulses. Therefore, conduction mode bearing current is dv/dt related.

For measurement of true bearing currents in the isolated inverter-motor system of Fig. 7, wire D, instead of wire B, is connected to G'. Measurement shows that only conduction mode bearing current is observable. The peak bearing current, I_{brg}, in this case was about 50 mA with the same waveform as I_B in Fig. 7b). In this special test system configuration without connection to earth ground, the internal impedance of common mode voltages is so high that the airgap capacitor can not be charged up enough to produce discharge mode bearing current. However, as will be shown next, the discharge mode bearing current will appear in addition to conduction mode bearing current as the coupling effect of the system is increased.

b. Discharge mode bearing current

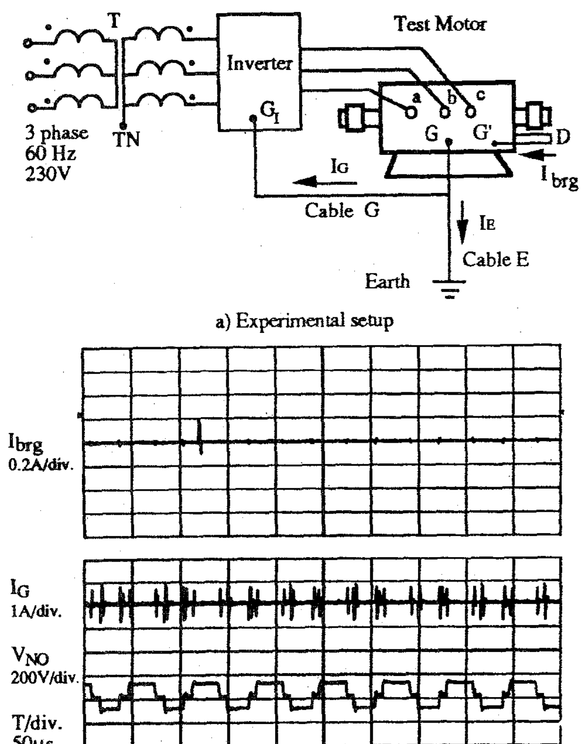
As shown in Fig. 8, an additional connection is made by connecting motor case G to the earth ground to increase the coupling effect (which is closer to the practical situation). Measurement of bearing current I_{brg} shows that at different motor speeds, different types of bearing currents dominate. With inverter output frequencies as low as several hertz and the test motor running at low speed, it is seen that only conduction mode bearing current appears with a peak value of about 60 mA. The shaft voltage which is the voltage between the shaft and the stator is measured to be almost zero. It is obvious that the at low shaft speed, the bearing balls are in good contact with races and the airgap capacitor is short-circuited by the bearings.

However, as inverter output frequency increases to certain level, large bearing current spikes begin to appear which have an amplitude considerably larger than the maximum conduction mode current. Fig. 8b) is a measured trace of such a current waveform when the motor running at 35 Hz. It is seen that the spikes are now as high as 200 mA.

Since the spikes are always preceded by a very small conduction mode current, it is evident that it occurs only after bearings exhibit high resistance or low conductivity for a certain period. In addition, the occurrence of current spikes is not necessarily in synchronization with the edges of the common mode voltage pulses. On the contrary, it is dv/dt independent. The largest spike current usually occurs sometime during the interval of highest level of common voltage in motor neutral point.

The same phenomenon was also observed in another modified large motor with 460V input and 15 HP output operating under the same condition. For the large motor, the current spikes have a peak amplitude as high as 2A. The chance of their appearance is also much more frequent.

The large bearing current spikes are the so called discharge mode bearing current. Discharge mode bearing current usually happens after bearings lose conductivity for a short period of time and then suddenly become conductive. The sudden change of bearing conductivity from poor to good is called conductivity switching in this paper. Conductivity switching is inherent with rotating bearings which has been observed to exist also in electric machines with shaft voltages induced by homopolar flux. It is usually caused by lubricant film breakdown or by the contact of the bearing balls with the races.



a) Experimental setup

b) Measurement results

Fig. 8 Discharge Mode Bearing Current in a Real Bearing

c. Mechanisms for discharge mode bearing current

The mechanisms for current spikes is easily observed in a maximum coupling configuration for common mode voltages. By connecting cable G in Fig. 7 directly to the negative DC bus, O, of the inverter instead of to its case, it is possible to bypass all the parasitic capacitance outside of the test motor. Thus, the minimum internal impedance of common mode voltages is achieved. In this case, maximum bearing current spikes in the test motor, with a peak as high as 500 mA were observed, and a larger number of these large pulses again occur as is shown in Fig. 9.

To confirm the bearing conductivity switching, the brush voltage relative to the negative dc bus, V_{BO}, which is also the voltage across airgap capacitor, is plotted in Fig. 10. Based on these traces, it seen that whenever the bearing loses conductivity, the common mode voltage, which can be represented by the motor neutral voltage relative to the negative DC bus, V_{NO}, causes the airgap capacitor C_g to charge up and down to a certain voltage level. Occasionally the bearings become conductive or short-circuited and the airgap capacitor immediately discharges to the bearings, causing a much larger bearing current spike than the conduction mode bearing current. Due to its capacitor discharge mechanisms, the current spike is termed in this paper the discharge mode bearing current.

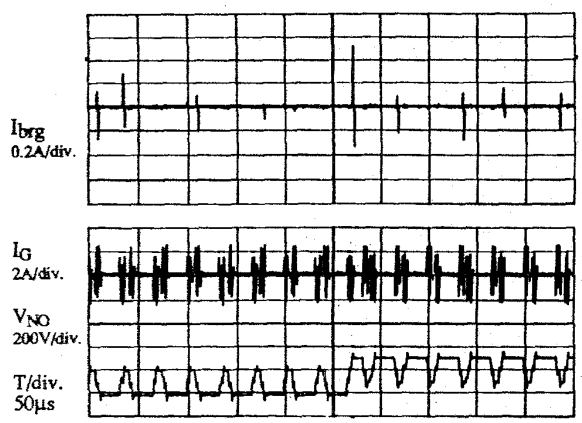


Fig. 9 Showing Discharge Mode Bearing Current Increase as Coupling Effect Increases

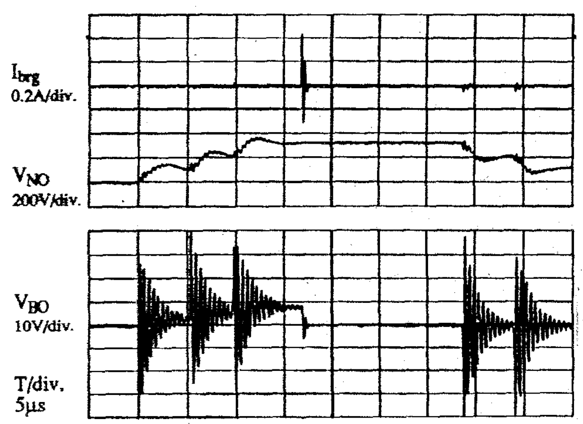


Fig. 10 Charge and Discharge of Bearing Capacitor by Common Mode Voltages

In summary, parasitic coupling and common mode voltages are the causes of bearing currents and their generation also depends on frequency of the bearing short-circuit or its conductivity switching. Although, there exist two types of bearing currents in bearings depending upon operating conditions, which will dominate is a random process since the bearing conductivity switching occurs randomly and depends upon the speed, temperature, lubrication type, and various other operating conditions. In general, however, it can be stated that a bearing behaves as a switch with certain internal conducting impedance which switches randomly.

As the discharge mode bearing current has large amplitude and it is also observed to exist in a wide range of motor shaft speed, it is this component that is the critical current that contributes to most bearing damage. As was observed, the bearing currents increase as coupling increases, so that bearing damage will also occur more often for a grounding configuration with largest coupling. Also, the bearing current problem can be expected to increase as the size of the machine increases as the capacitive charge accumulated on the rotor surface increases with rating faster than the bearing surface area.

5. Solutions

The first question to be asked is whether it is possible to eliminate common mode voltages or bearing currents by a change in the modulation scheme? Unfortunately, the answer is no. As the common mode voltage can always be considered as a voltage relative to the negative DC bus, it is apparent that no switching pattern can completely avoid common mode voltage generation. However, several solutions can be applied to solve or reduce the bearing current problem. The solutions can be divided into two categories: suppression and deviation.

Suppression is aimed at reducing the bearing current amplitude. As was observed in the experiment, bearing current increases with the capacitive coupling effect. Therefore a three phase common mode choke inserted between inverter output and motor input can be used to reduce this coupling effect and thus the current amplitude. Other types of common mode filter can be also applied.

To actually eliminate the bearing current, deviation methods can be chosen. This method is also the well known solution to the classical bearing currents caused by rotor eccentricity and other problems. A brush from rotor to stator will always function to deviate the bearing current to the brush and thus protect the bearings. Other solutions using conductive bearing lubrication can also be applied to avoid the actual installation of brushes.

6. Conclusions

This paper proposes a model for the bearing currents caused by a PWM inverter. The theory is based on the identification of a high frequency common mode voltage produced by converters and the parasitic capacitive coupling existing inside the motor. Experiments have been performed on a specially modified motor to verify the existence of two major coupling paths for common mode voltages and currents in an induction machine. Bearing currents measurements have also been carried out. Thus, the existence of bearing currents has been predicted both theoretically and verified experimentally.

Based on the theory and experiments, several conclusions regarding bearing current generation can be made:

1) Given same motor configuration, since the common mode voltage has an amplitude proportional to the inverter DC bus voltage and contains all frequencies of the inverter switching harmonics, a motor driven by a modern high switching frequency inverter will have more serious bearing currents than previous inverters with either six step operation or relatively low frequency PWM. Also, large motors have much high bearing currents due to increase in DC bus voltage and capacitance from windings to rotor.

2) It is also found from the experiment that largest motor bearing currents usually occur at different shaft speeds for different motors. The conduction mode bearing current usually dominates at very low inverter output frequency or shaft speed, while the discharge mode bearing current is more commonly found in normal motor operation. However, amplitude of bearing currents varies considerably with motor and bearing types, shaft speed and temperature, as well as grounding system configuration.

3) As the common mode current flowing inside the motor is zero sequence, the current is limited essentially by the zero sequence inductance, which is usually equal to a value smaller than the stator leakage inductance. Therefore, motors with smaller leakage inductance will have more ground current and thus bearing currents.

In addition, the theory presented in this paper also helps to suggest several solutions to the bearing current problem. In particular a common mode choke/filter inserted between the inverter output and the motor input is found to be a cost effective solution.

Nomenclature

Brg	Model of electrical behavior of rotating Bearings
C_g	Capacitance between stator and rotor laminations
C_{wr}	Parasitic coupling capacitance from motor stator windings to rotor laminations (iron)
C_{ws}	Parasitic coupling capacitance from motor stator windings to stator laminations (iron)
G	Motor case grounding terminal
G'	Motor case grounding terminal close to bearings
G_I	Inverter case grounding terminal
I_B	Current flowing in Brush wire B
I_{brg}	Current flowing in the bearings or bearing wires C or D
I_E	Earth grounding current flowing from motor case to earth ground
I_G	Current flowing in the cable connected from motor case to inverter case
V_{ab}	Difference of voltage potentials between terminals a and b
V_{ao}	Common mode voltage at terminal a relative to negative DC bus O
V_{BO}	Bearing voltage measured from brush B to negative DC bus O

V_{NO}	Common mode at motor neutral relative to negative DC bus
V_S	Inverter DC bus voltage
Z_{in}	Common mode voltage internal impedance

Appendix: Test Motor and Inverter Specifications

Induction Motor:
Volts: 230
HP: 3
RPM: 1165
AMPS : 9
DUTY: CONT.
FRAME: 213T
BEARINGS: FRT. 206SFF, EXT. 207SFF

Inverter:
INPUT: 230 V, 60 Hz
OUTPUT: 230 V, 18 A, 2-60 Hz
HP: 5
DC Bus: 320 V
Modulation: 15 kHz Sine-Triangle PWM

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