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Induction Motor Bearing Currents and Shaft Voltages 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 common mode voltages produced in all types of converters. A hypothesis is then proposed to explain the bearing current problem in inverter-motor drives. Particularly, the common mode voltages produced by PWM switching excite the parasitic capacitances and generate common mode coupling currents in bearings. The hypothesis is verified by experimental measurement of common mode shaft voltages and bearing currents in a specially modified induction motor. Solutions are then proposed to suppress the bearing currents and shaft voltages.

Keywords: power converter, inverter, PWM modulation, power electronics, Induction motor, motor drive, bearing current, shaft voltage, common mode current, common mode voltage, capacitve coupling.

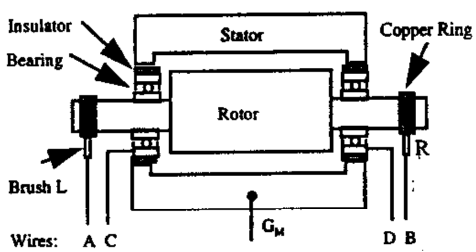
1. Introduction

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].

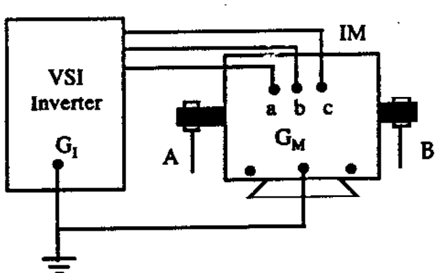
More recently, advances in power electronics have widened the scope of application of induction motors dramatically. In particular, PWM inverters with their high switching frequencies have made it possible for variable frequency drive systems to possess good spectra, low acoustic noise and more efficient 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]. 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.

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 the inverter switching frequency. As the switching frequencies of a converter are pushed up to increasingly higher values due to device improvements, a phenomenon of capacitive coupling associated with common mode voltages becomes considerable. Based on those findings, this paper proposes a reasonable hypothesis for bearing current and shaft voltage generation, and presents a detailed analysis of the mechanisms of shaft voltages and bearing currents in PWM inverter drive systems.

In order to verify the theory, an experimental setup as shown in Figure 1 is used to quantify the bearing currents and shaft voltages of an induction motor when it is driven by a PWM inverter. While the shaft voltage can be readily obtained by measuring the voltage between the rotor shaft and the stator case, it is impossible to observe the current in the bearings of an ordinary induction machine. To overcome this problem, a thin layer of insulator has been inserted between each bearing and its stator housing to block the electrical contact between them (Figure 1a). Two wires C and D connected to the bearing outer races are then used to bypass the insulators and to collect the currents of the bearings. Brushes R and L are also installed to make contact with the rotating shaft and pick up the shaft voltages through wires A and B. The brushes are also necessary for collecting the circulating type bearing currents as will be explained later. The specifications of the inverter and induction motor with above modifications are included in Appendix.



a) Motor modification



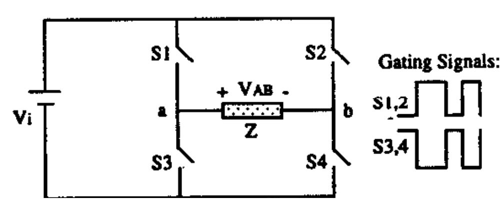
b) Inverter-motor system configuration

Figure 1. Test Setup

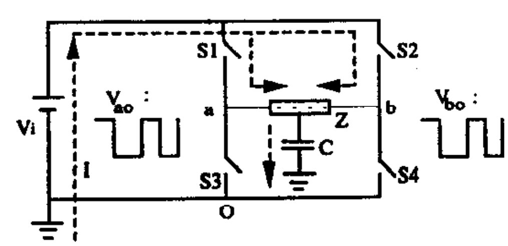
Finally, it is necessary to point out that only bearing currents caused purely by inverter switching will be considered in this paper. The induction motor used in the experiments has also been tested to ensure that it doesn't contain other types of bearing currents or shaft voltages, such as those caused by the classical rotor eccentricities, etc.

2. Common Mode Voltages and Currents in an Inverter-Motor System

A typical inverter design methodology is based on the differential mode operation, which can be illustrated by the simple example of a single bridge DC to AC converter as shown in Figure 2a. In this philosophy, 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 (Figure 2b) 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 potentials of terminals a and b relative to the a reference point, such as the negative DC bus O, 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 reference point, 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 reference point is what is normally termed common mode voltages. The current through the capacitor is the common mode current.



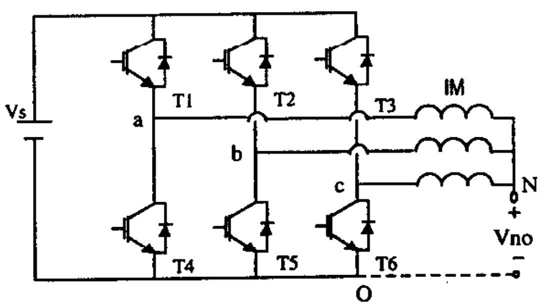
a) Differential mode - inverter function



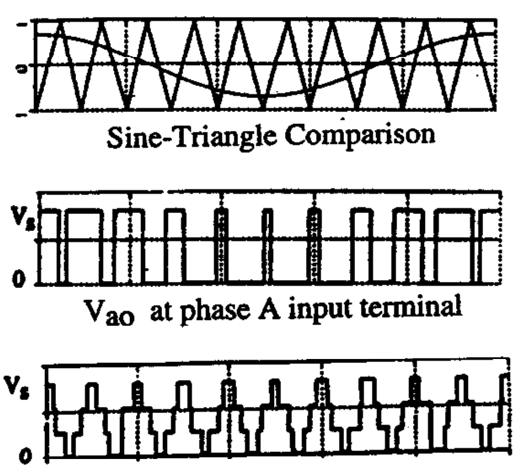
b) Common mode voltage and current generator

Figure 2. A Single Bridge DC to AC Converter

In a three-phase PWM inverter-motor system as shown in Figure 3, the common mode voltages relative to the negative dc bus O 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 the sine-triangle modulation is given in Fig. 3b). It is, therefore, evident that high frequency common mode voltage pulses exist at every point along the motor stator windings.



a) A PWM inverter-motor system



Sine-Triangle Comparison

V_{ao} at phase A input terminal

V_{NO} at neutral point

b) Common mode voltage waveforms

Figure 3. Common Mode Voltages in a Three-Phase Motor-Inverter System

Assuming no parasitic coupling, an induction machine will only experience the differential mode voltages, i.e., line to line voltages, and will behave as that with an ordinary three phase sinusoidal AC supply, except that some differential mode switching harmonic current will also exist. However, once the PWM switching frequencies of an inverter are 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 between the windings and the state iron. Similarly, there is a parasitic capacitive coupling effect between the stator windings and the rotor iron even though it is much smaller.

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. Figure 4 shows such a machine with the capacitors representing parasitic coupling from the stator windings to the stator and rotor respectively. 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 can be illustrated using Figure 4. This figure identifies all common mode voltage and current paths in a typical inverter-motor system although only phase 'a' winding is depicted. In this figure, 'o' represents the negative DC bus, 'a' the phase 'a' motor input terminal and 'N' the motor neutral point. The common mode voltage internal impedance Zin is the impedance between the negative DC bus and the earth ground which consists mainly of the parasitic capacitances between the negative DC bus and the earth ground. The parasitic capacitances between the phase windings and the rotor are represented by capacitances designated as Cwr and those between the windings and the stator by capacitances Cws. The motor airgap has a capacitance indicated by Cg.

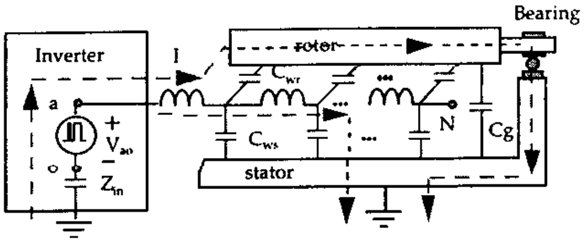


Figure 4. Common mode voltages and currents in an inverter-motor system

3. Shaft Voltages

The shaft voltage is the voltage between the motor shaft and the stator case. Since it appears across the inner race and the outer race of the motor bearings, the shaft voltage has long been used as an index for potential bearing damage problems. Some industrial regulations have established allowable shaft voltages for electric motors. In a motor drive system, the shaft voltage generated by inverter switching can be explained by refering to Figure 4. The three common mode voltage sources Vao, Vbo and Vco in a three-phase inverter provide electrical charge via parasitic capacitive coupling Cwr to the rotor. The charge is stored in the airgap capacitor Cg if no discharge path through the bearings is available. Thus, the shaft voltage is actually the voltage across the equivalent motor airgap capacitor. Since the capacitors Cwr and Cg form a voltage divider of V_{NO}, it is obvious that the shaft voltage will look similar in waveform to V_{NO}.

This principle can be verified by a simple experiment. In order to obtain the desirable shaft voltage readings it may be necessary to block the discharge paths of the bearings during measurement. This can be easily done by activating the bearing insulation of the modified test motor. However, with a motor running at certain high speed, the rotating bearings can exhibit a very high impedance and it may not be actually required to add the insulation layers for shaft voltage measurement. In fact, as is observed in the experiment, even with the insulation layers bypassed by the bearing wires, C and D, no discharge of the shaft voltage in the test motor has been found when the motor is operated above 55 Hz. Therefore, a shaft voltage measurement is performed at 55 Hz with both insulation layers shorted-circuited by connecting wires C and D to the motor stator case.

The measurement shaft voltage is plotted in Figure 5. To help in understanding the correlation between the shaft voltages and the common mode voltages, the motor neutral point voltage relative to the negative DC bus is also included. As has been proven in [6] the motor neutral voltage can be treated as the average common mode voltage generated by a three-phase inverter, i.e., (Vao+Vbo+Vco)/3. The average common mode voltage is the signature of any inverter which contains information of dv/dt, link voltage waveform and switching pattern. In fact, it is a replica of the dc link voltage waveform with the amplitude modulated by inverter switching. By the principle of superposition, the total effect of all three common mode voltages of an inverter can always be viewed as related to this average voltage only.

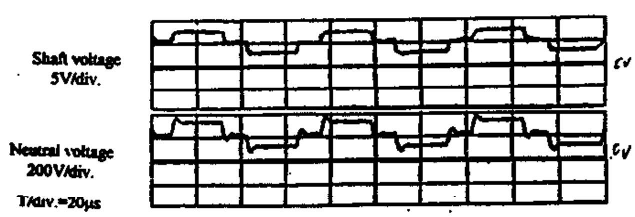


Figure 5. Measured shaft voltage

4. Bearing Currents

Although it can be proven that all bearing currents originate from only one single source resulting from the sum of common mode voltages of an inverter, the process of bearing current generation is far more complicated.

There are at least three mechanisms of bearing current generation discovered so far. Each mechanism may or may occur, depending on the bearing electrical characteristics. Conversely, several of these mechanisms may exist at the same time. Fortunately, under the laboratory conditions it is possible to isolate each mechanism and measure the corresponding bearing currents. Therefore, All three mechanisms of bearing currents will be analyzed independently.

4.1 Bearing current due to discharge of air gap capacitor[5,6]

The shaft voltage represents the energy or electric charges stored in the airgap capacitor of the motor. This energy will not be sustained long in an ordinary motor in which insulation of the bearings is not used mainly due to safety concerns. The shaft voltage will discharge to its only load - the bearings and produce a bearing current spike. This occurs when bearings exhibit a high internal impedance for a certain period and then suddenly become short-circuited with a low impedance by touching the bearing race or lubricating film breakdown.

In experiment, by shorting both bearing insulators in the test setup, it is seen that capacitor discharge seems to be the dominant phenomenon when the motor is supplied with a frequency in the range of 2 Hz to 55 Hz. Since motors are mostly operated in this frequency range, the discharge mechanism has been believed to be the major cause of bearing damage. The power or intensity of the energy dumped to the bearings is also the largest among all three mechanisms because this discharge usually happens within only a few microseconds.

Plots of bearing currents and shaft voltages shown in Figure 6 clearly demonstrate the discharge phenomenon. The shaft voltage drops abruptly while a bearing current spike is produced. Since the energy dump from the airgap capacitor is proportional to the square of the shaft voltage, the higher the shaft voltage, the worse the potential bearing damage problem will be.

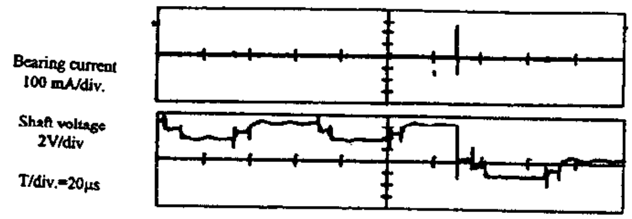


Figure 6. Measured bearing currents due to discharge of airgap capacitor

4.2 Bearing current due to dv/dt in common mode voltages [5,6]

From the bearing current circuit shown in Figure 4, it can be seen that bearings are connected in two different paths: one in parallel with the airgap capacitor; another in series with the parasitic capacitors between the windings and the rotor. If the effective bearing impedance becomes very small, the airgap capacitor will be short-circuited by the bearings and all currents in winding parasitic capacitors (Cwr's) will flow into the bearings. The sum of all parasitic coupling currents in Cwr becomes the bearing current. This bearing current is produced only when there is a dv/dt in the common mode voltages or, equivalently, the neutral voltage. Assuming zero bearing impedance, the bearing current will be proportional to the dv/dt of the common mode voltages and the parasitic capacitance Cwr.

When the motor running at a very low speed, less than 2 HZ in the test, bearing current due to dv/dt begins to occur in the experiment and the shaft voltage disappears. An explanation for this phenomenon is that the bearing balls are in good contact with the races at low speeds, providing a short circuit in the bearings which enables the dv/dt related bearing currents and disables the discharge phenomenon. The dv/dt related bearing currents were measured and recorded in Figure 7. It is seen that bearing current consists of short pulses of about 50 mA in peak. The pulses were seen to be in synchronization with the step change in the neutral voltage, indicating the correspondence to PWM switching instants.

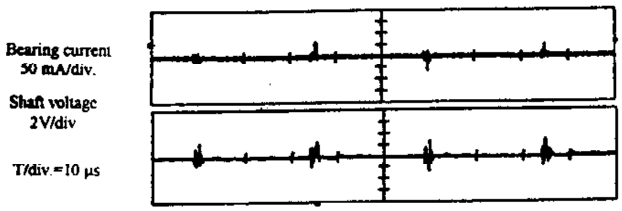
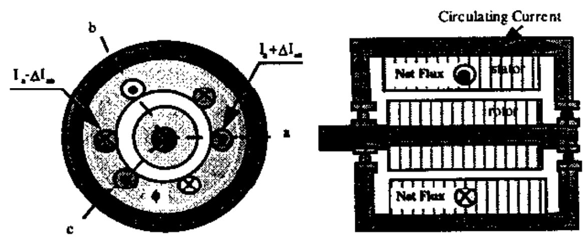


Figure 7. Measured bearing currents due to dv/dt of common mode voltages

4.3 Circulating bearing current due to magnetic flux resulting from common mode currents [7]

The above two mechanisms of bearing current generation are directly related to the common mode voltages. The resulting bearing currents flow unidirectionally from the shaft via bearings to the stator. A third mechanism of bearing current generation is a more complicated process. This mechanism causes a bearing current to circulate in the conductive loop formed by the shaft, the bearings and the stator case. Since the current does not source directly from the common mode voltages, it can not be explained using Figure 4. However, by analyzing the effect of common mode currents in a drive system, this new type of bearing current can be recognized.

As common mode voltages produce coupling currents to the rotor, they also supply much higher coupling currents to the stator since the winding capacitance to the stator is much larger than that to the rotor. All common mode currents come from the three motor input terminals and they never flow back to the terminals. Therefore, the sum of all three phase currents supplied to the motor must not be zero but equal to the total common mode current. By drawing a Gaussian plane ϕ in the cross section of a motor as shown in Figure 8a, it can be seen that the enclosed current is equal to the total common mode current. Therefore, a net flux enclosing the motor shaft must be produced. Consequently, a back EMF will be induced in the conductive loop formed by the shaft, the bearings and the stator enclosure as shown in Figure 8b. The EMF is usually very small, in the milli-volt range, and its contribution to the shaft voltage can be ignored (as was done in the previous shaft voltage measurement). However, when the impedance of this loop is sufficiently low, a circulating current will pass through the bearings. This becomes the circulating type bearing current caused by inverter [7].



a) Motor cross section showing common mode flux linkage

b) Path of circulating type bearing currents

Figure 8. Principle of circulating bearing current

For the specific induction motor used in the test, no circulating bearing current can be found when both bearings are in normal contact with the stator. This means that the EMF in the loop seems to be unable to overcome the bearing impedances to produce a detectable circulating current. However, to evaluate its potential existence, the two brushes L and R are connected to the stator to bypass the bearings, providing low impedance paths between both ends of the shaft and the stator case. The current in the brush is then measured and considered as the potential circulating bearing current. Since this current is correlated with the total common mode current, it is shown together with the corresponding total common mode current in Figure 9. The total common mode current is measured by adding all three phase input currents and is labeled as ground current in Figure 9.

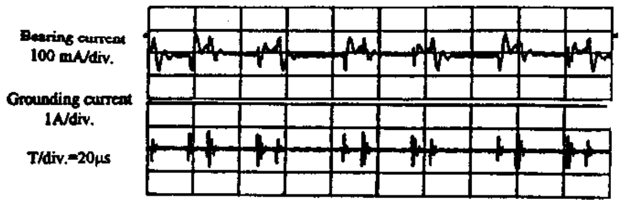


Figure 9. Measured circulating type bearing currents

5. Solutions

The question is whether it is possible to eliminate common mode voltages or bearing currents by changing the PWM 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.

Suppression methods can be used to reduce the bearing current amplitude. This is based on the fact that bearing currents will decrease with the common mode impedance. Theoretically, it is possible to increase the common mode impedance by inserting a three-phase common mode filter/choke between the inverter output and the motor input to reduce the bearing current amplitude.

To actually eliminate the bearing current, deviation methods can be very effective. The methods are also well-known to the classical bearing current problem caused by rotor eccentricity and other phenomena. A brush from rotor to stator will always function to deviate the bearing currents to the brush and thus protect the bearings. Conductive bearing lubrication may be applied to avoid the actual installation of brushes. However, based on the bearing current theory, it seems that an optimal solution to both circulating and non-circulating bearing currents seems to be the combination of brush installation and bearing insulation. In fact, a combination resulting in minimum current ratings in the brush is to use one brush connecting one end of the shaft to the stator and, at the same time, to insulate the bearing which locates on the other end of the shaft.

Another promising method is the concept of common mode voltage cancellation. This idea is based on the fact that common mode voltages input to the motor are the origin of all common mode currents and, thus, all bearing currents as well as common mode EMI's. If the total effect of the common mode voltages can be eliminated, both of the bearing currents and EMI will be reduced. A technique of common cancellation has been proposed in [4]. This concept has recently gained more and more attentions as is evidenced by reference [8].

6. Conclusions

This paper proposes a theory for the motor bearing currents and shaft voltages caused by a PWM inverter. The theory is based on recognition of high frequency common mode voltages produced in converters and the parasitic capacitive coupling effect inside the motor-drive systems. The theory states that:

1) When the motor bearings exhibit high impedance, the common mode voltages will charge the motor airgap capacitor and produce a shaft voltage.
2) The shaft voltage will discharge to the bearings if the bearing impedance become low suddenly due to ball-race contact or lubricating film breakdown. The bearing currents related to capacitor discharge produce the largest current spikes and seems to be the dominant mechanism accounting for bearing damage.
3) When the bearings exhibit continuously low impedance such as when running at very low speeds, the airgap capacitor will be short-circuited and no shaft voltage can build-up. The currents in bearings will become dv/dt related pulses with small amplitudes corresponding to each PWM switching.

4) A large amount of common mode grounding current in the drive system will caused a non-zero net flux surrounding the motor shaft. This flux will induce a back EMF and result in a circulating type bearing current in the closed–loop formed by the shaft, the bearings and the stator case.

In addition, bearing current and shaft voltage measurements have also been carried out to verify the theory, and several solutions have been suggested to solve the bearing damage problem.

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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