Bearing Currents and Shaft Voltages of an Induction Motor Under Hard- and Soft-Switching Inverter Excitation

Shaotang Chen, *Member, IEEE*, and Thomas A. Lipo, *Fellow, IEEE*

***Abstract*—Bearing currents and shaft voltages of an induction motor are measured under hard- and soft-switching inverter excitation. The objective is to investigate whether the soft-switching technologies can provide solutions for reducing the bearing currents and shaft voltages. Two of the prevailing soft-switching inverters, the resonant dc-link inverter and the quasi-resonant dc-link inverter, are tested. The results are compared with those obtained using the conventional hard-switching inverter. To ensure objective comparisons between the soft- and hard-switching inverters, all inverters were configured identically and drove the same induction motor under the same operating conditions when the test data were collected. An insightful explanation of the experimental results is also provided to help understand the mechanisms of bearing currents and shaft voltages produced in the inverter drives. Consistency between the bearing current theory and the experimental results has been demonstrated. Conclusions are then drawn regarding the effectiveness of the soft-switching technologies as a solution to the bearing current and shaft voltage problems.**

***Index Terms*— Bearing currents, common-mode currents, common-mode voltages, hard switching, induction machine, induction motor, power converter, pulsewidth modulation inverter, quasi-resonant dc-link converter, resonant dc-link converter, shaft voltages, soft switching.**

I. Introduction

IT HAS LONG been recognized that bearing damage can be caused by bearing currents and shaft voltages resulting from dissymmetry effect, homopolar flux effect, or electrostatic discharge (ESD) effect in electric machines [1], [2]. The evidence gathered in [3] and [4] proved that the use of pulsewidth modulation (PWM) inverters can also introduce different types of bearing currents and shaft voltages. Analyses in [5]–[8] have further identified that common-mode voltages and currents in a PWM inverter are responsible for the shaft voltages and bearing currents. Models of the bearing currents and shaft voltages resulting from switching effects of inverters have also been established [7], [8]. Thus far, only hard-switching inverters have been investigated in detail and the inherent rapid dv/dt of such inverters pointed to as the fundamental cause for bearing damage.

To investigate whether soft-switching technologies can provide solutions for reducing bearing currents and shaft voltages, a comparative study of soft-switching inverters versus the hard-switching inverter is performed in this paper based on experimental measurement of bearing currents and shaft voltages generated by each of the inverters to be compared. Two of the prevailing soft-switching inverter topologies, the resonant dc-link (RDCL) inverter [9], [10] and the quasi-resonant dc-link (QRDCL) inverter [11], [12], are tested and compared with the conventional hard-switching inverter under the same conditions. An insightful explanation of the experimental results is also provided to help understand the mechanisms of bearing currents and shaft voltages produced in the inverter drives. Consistency between the bearing current theory and the experimental results is demonstrated. Conclusions are then drawn regarding the effectiveness of the soft-switching technologies as a solution to the bearing current and shaft voltage problems.

II. Measurement Setup

The purpose of the experiment is to quantify the bearing currents and shaft voltages of an induction motor when it is driven by each of the inverters to be tested. 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 [Fig. 1(a)]. 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 induction motor with the above modifications has a name plate as shown in Table I. It will be used throughout this investigation as the load for each of the inverters to be tested.

The wiring between the test inverter and the motor follows the standards for industrial applications of inverter drives. As shown in Fig. 1(b), the three-phase cable which connects the inverter to the motor is placed inside a grounded hollow metal

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S. Chen is with the Electrical and Electronics Department, GM Research and Development Center, Warren, MI 48090 USA.

T. A. Lipo is with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706 USA.

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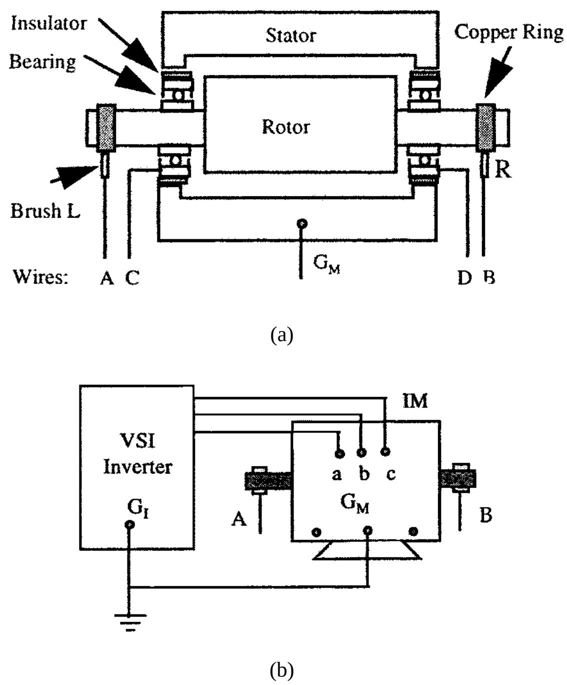


Fig. 1. Test setup. (a) Motor modification for bearing current measurement. (b) Connection and grounding for the inverter–motor system.

TABLE I
NAME PLATE OF THE INDUCTION MOTOR USED AS THE LOAD

Volts	230
Amps	9
HP	3
RPM	1165
Frame	213T
Duty	Cont.
Bearings	FRT. 206SFF EXT. 207SFF

conduit. The conduit with its two ends tied, respectively, via terminals G_M and G_I to the cases of the motor and the inverter serves as the system ground.

During the experiment, all inverters were operated as voltage-source inverters (VSI's) with a simple constant volts/hertz control. For comparison purposes, all inverters are also required to operate under the same load conditions, which include motor speed, voltage, and current. No particular modulation scheme can be specified, since different soft-switching topologies may require different modulation techniques. In the test, the hard-switching inverter employs a sinusoidal PWM modulation with a 15-kHz switching frequency, and both of the soft-switching inverters are operated using the delta modulation which makes the dc link resonate at a fixed frequency. The two resonant inverters have very different link frequencies: 100 kHz for the RDCL and 20 kHz for the QRDCL. They also have different voltage clamp factors: 2.1 for the RDCL and 1.2 for the QRDCL. The differences will help investigate the influences of link frequency and clamp factor on bearing currents and shaft voltages. The inverter topologies and the corresponding dc-link waveforms are shown in Fig. 2.

It should be mentioned that the induction motor used has been tested to ensure that there are no other sources of bearing currents or shaft voltages within the motor itself, such as those due to the nonsymmetry, homopolar flux, or ESD effect. Therefore, all bearing currents and shaft voltages measured will be considered as being caused by the switching effect of inverters.

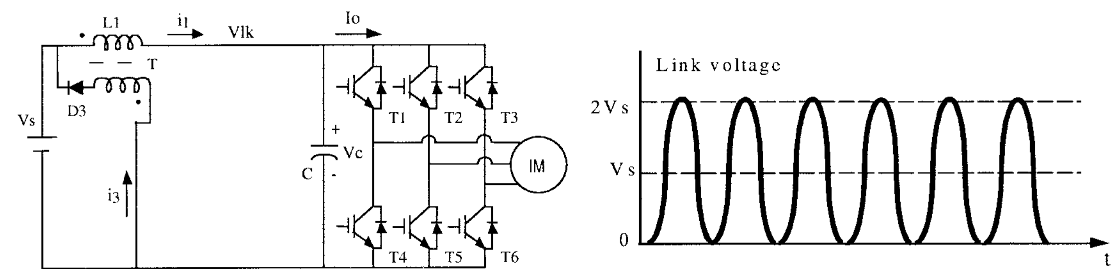
III. TEST RESULTS

A. Shaft Voltages

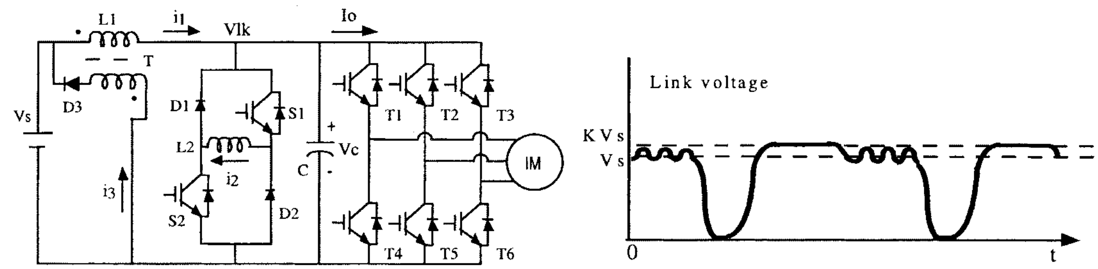
The shaft voltage is taken as the voltage measured between the motor shaft and the stator case. Since it appears across the inner race and the outer race of the motor bearings, the shaft voltage has long been used as an index for potential bearing damage problems. Some industrial regulations have established allowable shaft voltages for electric motors. In a motor drive system, the shaft voltage can be generated by inverter switching, as is explained in Fig. 3. In this figure, "o" represents the negative dc bus, "a" the phase "a" motor input terminal, and "N" the motor neutral point. Fig. 3 shows all common-mode voltage and current paths in a typical inverter–motor system, although only the phase "a" winding is depicted. The common-mode voltage internal impedance $Z_{\rm in}$ 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 winding and the rotor are represented by capacitances designated as $C_{\rm wr}$ and those between the winding and the stator by capacitances $C_{\rm ws}$. The three common-mode voltage sources V_{ao}, V_{bo}, and V_{co} in a three-phase inverter provide electrical charge via parasitic capacitive coupling $C_{\rm wr}$ to the rotor. The charge is stored in the airgap capacitor C_g if no discharge path through the bearings is available. Thus, the shaft voltage is actually the voltage across the equivalent motor airgap capacitor.

In this experiment, 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 motor. However, with a motor running at a 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 motor has been found when the motor is operated above 55 Hz. Therefore, all shaft voltage measurements presented here are performed at 55 Hz with both insulation layers short circuited by connecting wires *C* and *D* to the motor stator case.

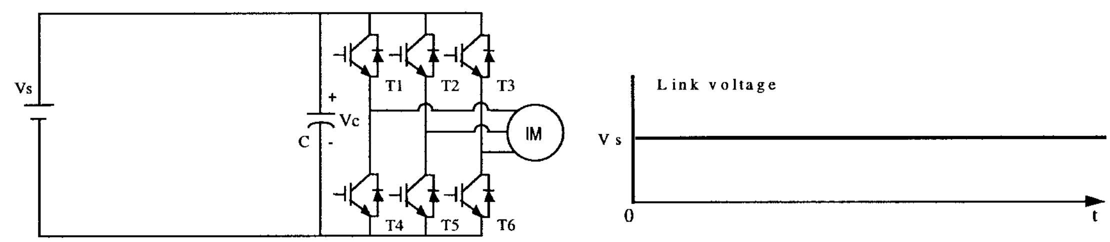
The measurement results of the shaft voltages in all three test inverters are plotted together in Fig. 4 for comparison. To help in understanding the correlation between the shaft



(a)



(b)



(c)

Fig. 2. Three inverter topologies under test. (a) RDCL inverter. (b) QRDCL inverter. (c) Hard-switching inverter.

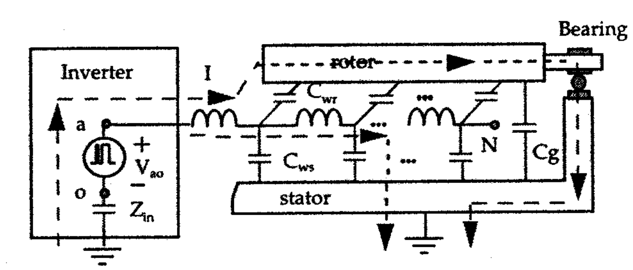
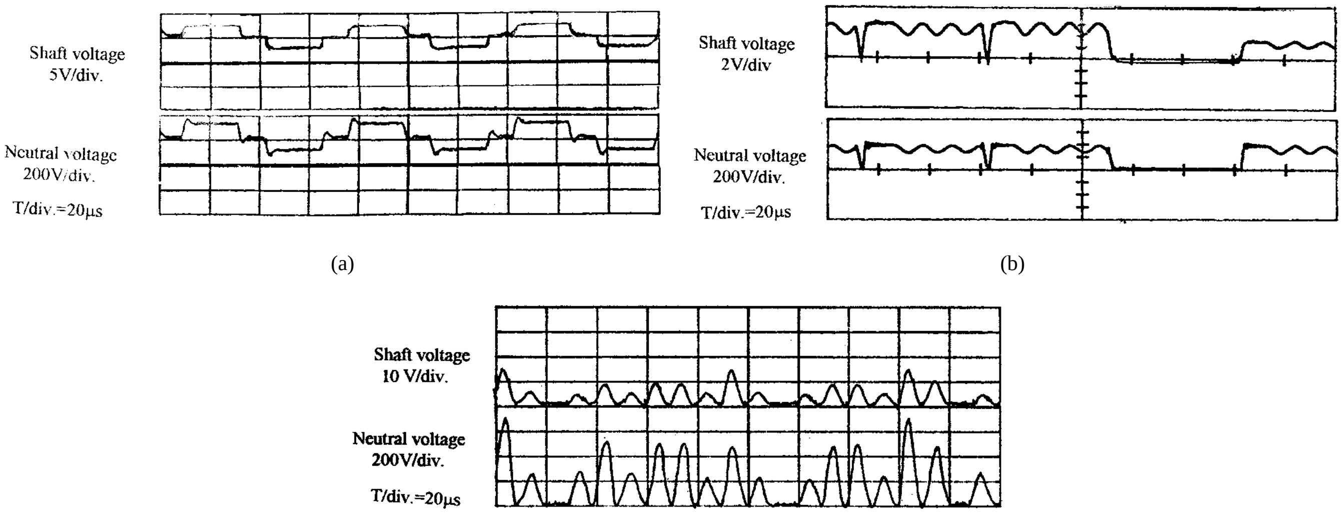


Fig. 3. Common-mode voltages and currents in an inverter–motor system.

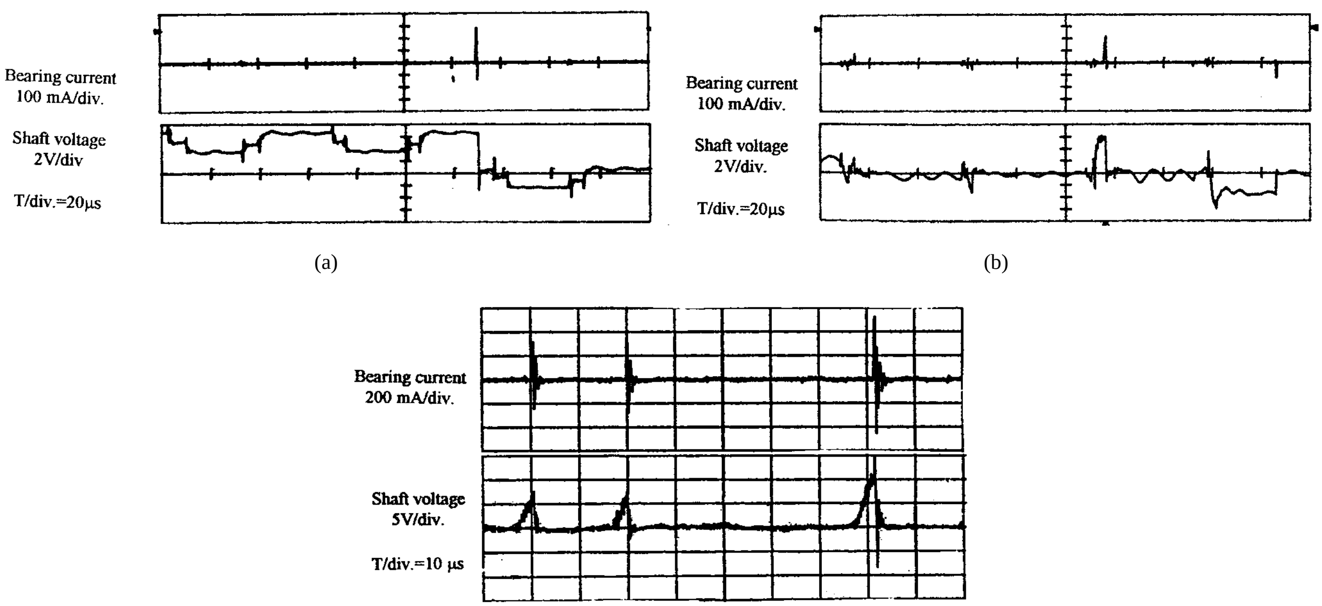
voltages and the common-mode voltages, the motor neutral point voltage relative to the negative dc bus is also included. As has been proven in [6] and [7], the motor neutral voltage can be treated as the average common-mode voltage generated by a three-phase inverter, i.e., $(V_{ao}+V_{bo}+V_{co})/3$. 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. This explains why the neutral voltage has played such a significant role in helping discover the relationship between the common-mode voltages and the shaft voltages.

Fig. 4 shows that both of the soft-switching inverters produce a shaft voltage comparable to that caused by the hard-switching inverter. The shaft voltage with the QRDCL inverter has a peak of about 7.5 V, which is quite close to the 7.5 V obtained with the hard-switching inverter. The shaft voltage with the RDCL inverter is twice that encountered with the hard-switching inverter. It is interesting to see that all shaft voltage waveforms are almost identical to the common-mode voltage waveforms measured at neutral point. By referring to Fig. 3, it is obvious that the shaft voltage must be proportional to the motor neutral voltage, since it is governed by the capacitor divider formed by the capacitor C_{wr} (winding to rotor capacitance) and the airgap capacitor C_g. As the amplitude of the common-mode voltage at neutral point is proportional to



(a) (b) (c)

Fig. 4. Comparison of shaft voltages. (a) Hard switching. (b) QRDCL. (c) RDCL.



(a) (b) (c)

Fig. 5. Comparison of bearing currents due to discharge of airgap capacitor. (a) Hard switching. (b) QRDCL. (c) RDCL.

the amplitude of the dc-link voltage, the neutral voltage with the QRDCL is about 1.2 times that with the hard-switching inverter, and the neutral voltage with the RDCL is about 2.1 times that with the hard-switching inverter. This relationship is very close to that found in the measured shaft voltages.

B. Bearing Currents

Although 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 thus far. Each mechanism may or may not 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, the experiment study evaluates all three mechanisms of bearing currents independently.

1) Bearing Current Due to Discharge of Airgap Capacitor; 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. 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. By bypassing both bearing insulators in the test setup, it is seen that capacitor

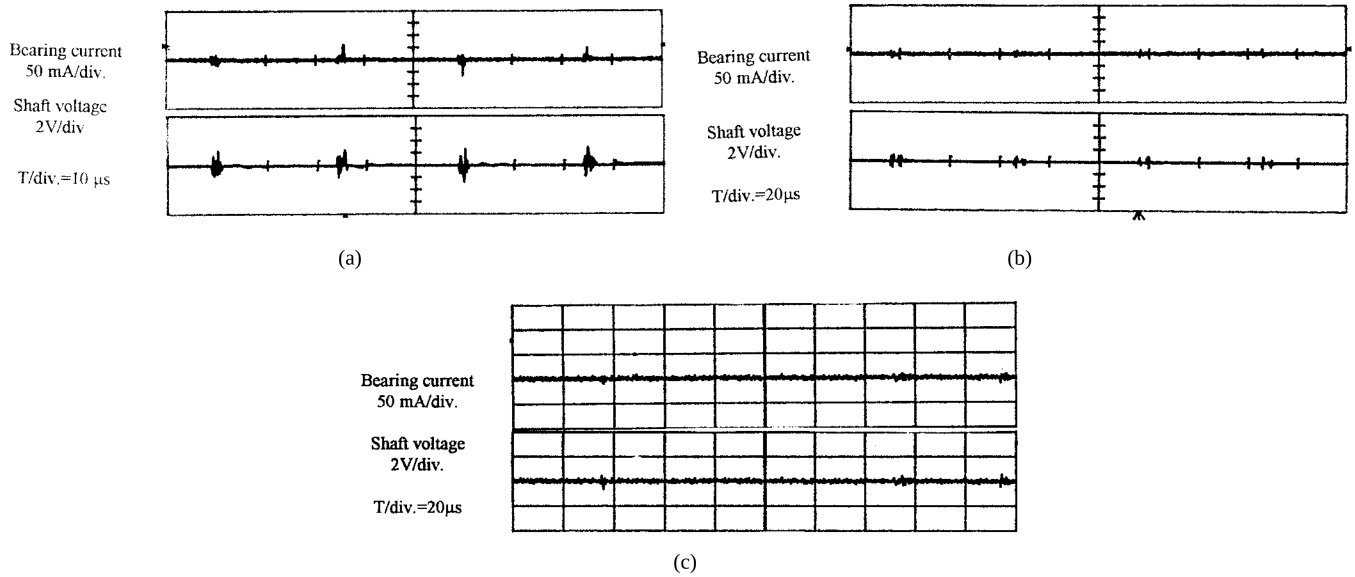


Fig. 6. Comparison of bearing currents due to dv/dt of common-mode voltages. (a) Hard switching. (b) QRDCL. (c) RDCL.

discharge seems to be the dominant phenomenon when the motor is supplied with a frequency in the range of 2–55 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 Fig. 5 clearly demonstrate the discharge phenomenon. The shaft voltage drops abruptly while a bearing current spike is produced. The RDCL inverter is seen to produce a discharge current of about 520 mA, which is almost twice that with the hard-switching inverter. The peak discharge current of the QRDCL inverter is close to that with the hard-switching inverter, although it is slightly less. Assuming that the bearing short-circuit impedance remains constant, it is not difficult to determine that the above relationship is expected based on the amplitude of shaft voltage measured for each of the test inverters. Since the energy dump from the airgap capacitor is proportional to the square of the shaft voltage, the RDCL appears to be not favorable for driving a motor in terms of the potential bearing damage problem.

2) Bearing Current Due to dv/dt in Common-Mode Voltages: From the bearing current circuit shown in Fig. 3, it can be seen that bearings are connected in two different paths, one in parallel with the airgap capacitor and 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 ($C_{\rm wr}$'s) will flow into the bearings. The sum of all parasitic coupling currents in $C_{\rm wr}$ 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. In the hard-switching inverter, the dv/dt of common-mode

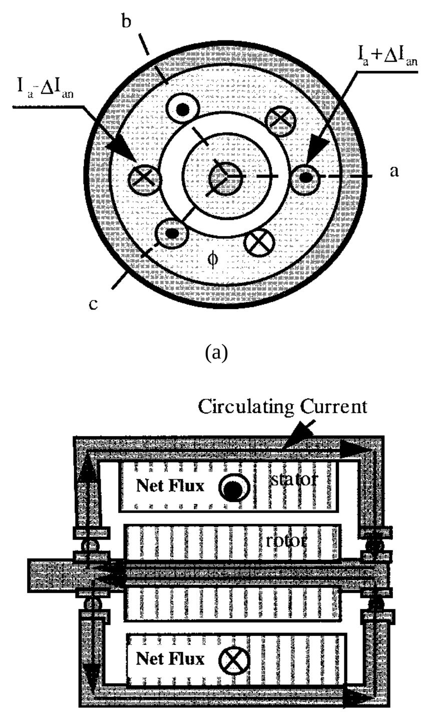
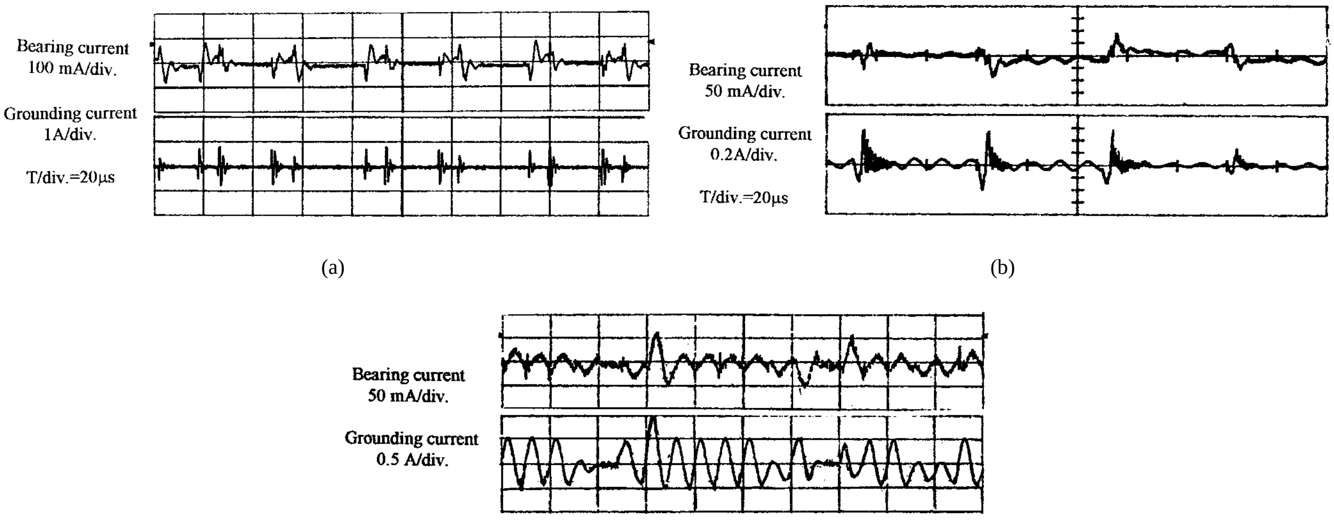


Fig. 7. Cause of circulating bearing current. (a) Cross section of an induction motor for determining flux linkage caused by common-mode currents. (b) Path of circulating bearing currents.

voltages is due to the inverter switching. In soft-switching inverters, the dv/dt is related to both inverter switching and the dc-link resonance and is dominated by the link resonance. Assuming zero bearing impedance, the bearing current will be proportional to the dv/dt of the common-mode voltages and the parasitic capacitance $C_{\rm wr}$.

When the motor is running at a very low speed, less than 2 Hz in the test, bearing current due to dv/dt begins to



(c)

Fig. 8. Comparison of circulating-type bearing currents. (a) Hard switching. (b) QRDCL. (c) RDCL.

occur, 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 for all three test inverters were measured and recorded in Fig. 6. It is seen that the hard-switching inverter has the highest bearing current, which consists of short pulses of about 50 mA in peak. The pulses are in synchronization with the step change in the neutral voltage, indicating the correspondence to PWM switching instants. Both of the soft-switching inverters provide almost zero dv/dt-related bearing currents owing to much lower dv/dt's in their common-mode voltages in comparison with the hard-switching inverter.

3) Circulating Bearing Current Due to Magnetic Flux Resulting from Common-Mode Currents: 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 cannot be explained using Fig. 3. 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 Fig. 7(a), 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 Fig. 7(b). The EMF is usually very small, in the millivolt 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 the inverter [8].

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 Fig. 8. The total common-mode current is measured by adding all three phase input currents and is labeled as ground current in Fig. 8.

From Fig. 8, a comparison shows that all test inverters generate considerable ground currents, as well as circulating bearing currents, given low impedances across the bearings. The amplitudes of circulating currents for all three inverters tested are comparable in amplitude. However, the duty cycles vary considerably. For the hard-switching inverter, the circulating bearing current has the lowest duty cycle. In both of the soft-switching inverters, the circulating bearing currents are continuous, since oscillations in the dc links contribute to the continuous flow of grounding currents. Therefore, the rms values of circulating bearing currents with the resonant link inverters are higher than those with the hard-switching inverter.

IV. Conclusion

The bearing currents and shaft voltages of an induction motor are measured under hard- and soft-switching inverter excitation. The results provide objective comparisons between the soft-switching and the hard-switching technologies in terms of their impacts on induction motors. Two resonant dc-link soft-switching inverters are tested and compared with the conventional hard-switching inverter. Based on the measurement data, the resonant link inverters overall do not provide significant advantages over the conventional hard-switching inverter. In particular, the induction motor receives equal or higher shaft voltages when it is excited by the resonant link inverters than by the hard-switching inverter. The levels of motor bearing currents produced by soft-switching inverters are also comparable to those caused by the hard-switching inverter. The results have been demonstrated to agree with theoretical analysis based on bearing current theory.

In summary, the comparative study based on both an experimental measurement and theoretical analysis suggests that soft-switching inverters, sometimes posed as a simple, problem-free replacement for hard-switching inverters, are not an inherent solution to the problems of bearing currents and shaft voltages caused by inverter switching.

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Shaotang Chen (S'93–M'96) received the B.Eng. and M.Eng. degrees from Central China University of Science and Technology, Wuhan, China, in 1983 and 1986, respectively, and the M.S. and Ph.D. degrees from the University of Wisconsin, Madison, in 1993 and 1995, respectively.

He was with Central China University of Science and Technology from 1986 to 1991. He is currently a Senior Research Engineer in the Electrical and Electronics Department, GM Research and Development Center, Warren, MI. His research interests are the control of electric machines, electric machine drives, and power electronics.

Thomas A. Lipo (M'64–SM'71–F'87), for a photograph and biography, see p. 97 of the January/February 1998 issue of this Transactions.