Research Report

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

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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 (RDCL) inverter and the quasi resonant DC link (QRDCL) 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 was configured identically and drive the same induction motor under the same operating conditions when the test data is collected.

An insightful explanation of the experimental results is also provided to help understand the mechanisms of bearing currents and shaft voltages produced in 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 on the solutions to the bearing current and shaft voltage problems.

I. INTRODUCTION

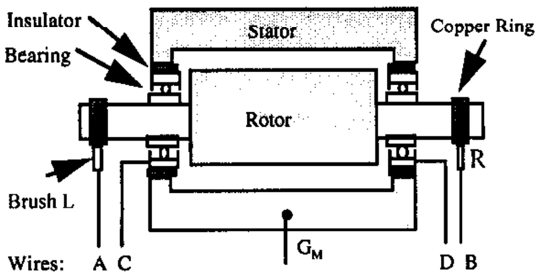
It has long been recognized that bearing damage can be caused by bearing currents and shaft voltages resulted from non-symmetry effects, homopolar flux effect or electrostatic discharge (ESD) effect in electric machines [1,2]. The evidence gathered in [3,4] proved that the use of PWM inverters can also 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 resulted from switching effect of inverters have also been established [7,8]. Thus far, only hard switched 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 the bearing currents and shaft voltages, a comparative study of soft switching inverters vs. 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 are tested: the Resonant DC Link (RDCL) inverter [9,10] and the Quasi Resonant DC Link (QRDCL) inverter [11,12]. The test results are compared to those obtained using the conventional hard switching inverter. To ensure objective comparisons between the soft and hard switching inverters, all inverters are instrumented identically and drive the same induction motor under the same operating conditions when the test data is collected.

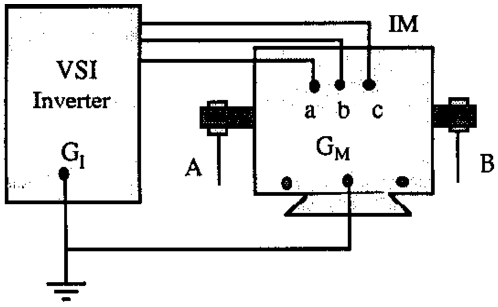
An insightful explanation of the experimental results is also provided to help understand the mechanisms of bearing currents and shaft voltages produced in the inverter drives. Consistency between the bearing current theory and the experimental results are demonstrated. Conclusions are then drawn regarding the effectiveness of the soft switching technologies as a solutions to the bearing current and shaft voltage problems.

II. MEASUREMENT SETUP

The purpose of this experiment is to quantify the bearing currents and shaft voltages of an induction motor which appear 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 insulation 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 induction motor with 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.



a) Motor modification for bearing current measurement

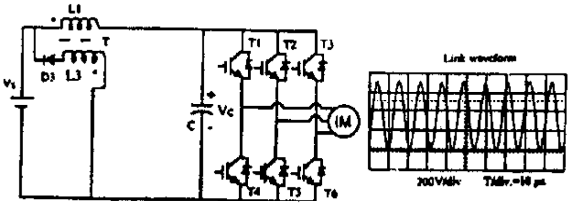


b) Connection and Grounding of the Inverter-Motor System

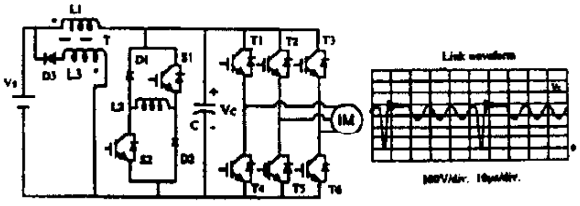
Figure 1. Test setup

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

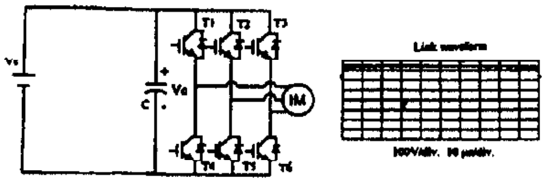
During the experiment, all inverters were operated as a voltage source inverter (VSI) with a simple constant volts/hertz control. For comparison purposes, all inverters are also required to operate under the same load conditions which include motor speed, voltage and current. No particular modulation scheme can be specified since different soft switching topologies may require different modulation techniques. However, 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 to investigate the influences of link frequency and clamp factor on the bearing currents and shaft voltages. The inverter topologies and the corresponding DC link waveforms are shown in Figure 2.



a) Resonant DC Link (RDCL) Inverter



b) Quasi Resonant DC Link (QRDCL) Inverter



c) Hard Switching Inverter

Figure 2. Three inverter topologies under test

It should be mentioned that the induction motor used has been tested to ensure that no other sources of bearing currents or shaft voltages within the motor itself, such as those due to the non-symmetry, homopolar flux or ESD effect. Therefore, all bearing currents and shaft voltages measured will be considered to result solely from the switching effect of inverters.

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

III. TEST RESULTS

1. 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 Figure 3. In this figure, 'o' represents the negative DC bus, 'a' the phase 'a' motor input terminal and 'N' the motor neutral point. Figure 3 shows all common mode voltage and current paths in a typical inverter-motor system although only phase 'a' winding is depicted. The common mode voltage internal impedance Z_{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 designed as Cwr and those between the winding and the stator by capacitances Cws. The three common mode voltage sources Vao, Vbo and Vco in a three-phase inverter provide electrical charge via parasitic capacitive coupling 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.

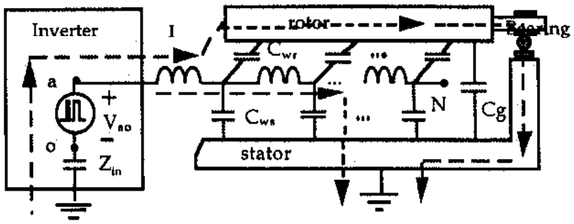


Figure 3. Common mode voltages and currents in an inverter-motor system

In this experiment, to obtain the desirable shaft voltage reading 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 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 shorted-circuited by connecting wires C and D to the motor stator case.

The measurement results for the shaft voltages in all three test inverters are plotted together in Figure 4 for comparison. 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 [6,7] 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. 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.

Figure 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 common mode voltage waveforms when measured at neutral point. By referring to Figure 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 Cwr (winding to rotor capacitance) and the airgap capacitor Cg. As the amplitude of the common mode voltage at neutral point is proportional to the amplitude of the dc link voltage, the neutral voltage with the QRDCL is about 1.2 times of that with the hard switching inverter, while the neutral voltage with the RDCL is about 2.1 time of that with the hard switching inverter. This relationship is very close to that found in the measured shaft voltages.

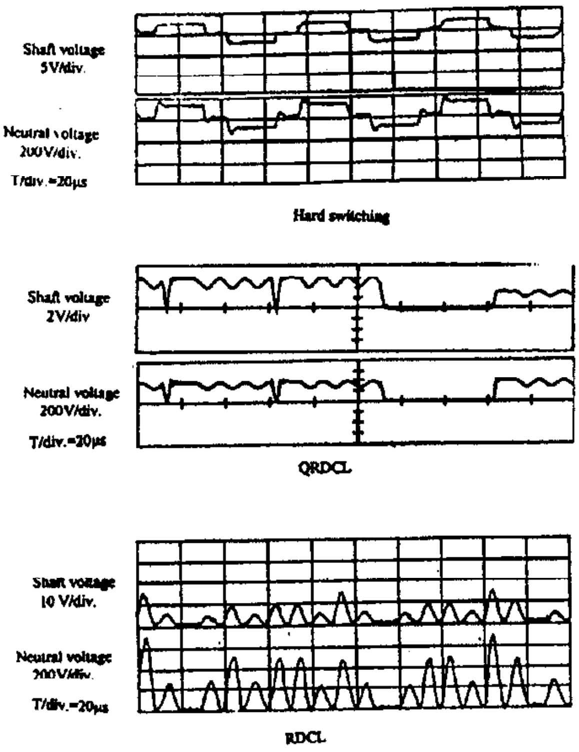


Figure 4. Comparison of shaft voltages

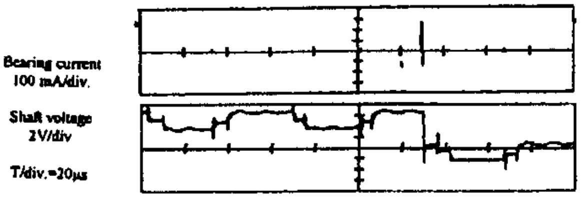
2. Bearing Currents

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 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 current. Therefore, this experiment study evaluates all three mechanisms of bearing currents independently.

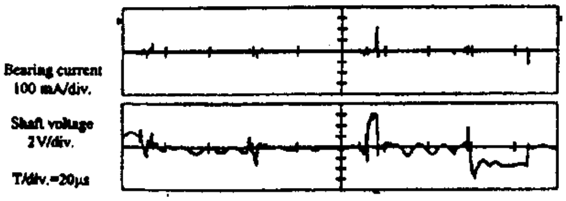
a. Bearing current due to discharge of air gap capacitor

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 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 micro seconds.

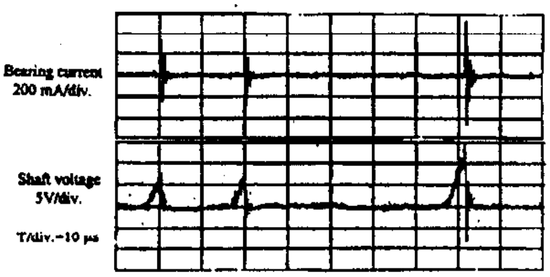
Plots of bearing currents and shaft voltages shown in Figure 5 clearly demonstrate the discharge phenomenon. The shaft voltage drops abruptly while a bearing current spike is produced. The RDCL inverter is seen to produce a discharge current of about 520 mA which is almost twice of that with the hard 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.



Hard swiching



QRDCL



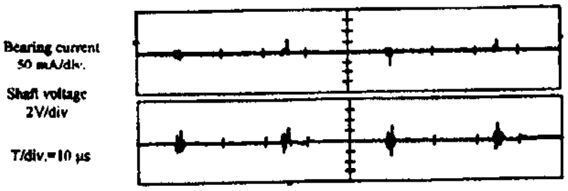
RDCL

Figure 5. Comparison of bearing currents due to discharge of airgap capacitor

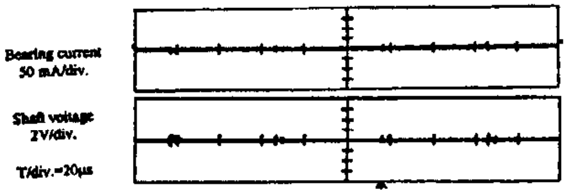
b. Bearing current due to dv/dt in common mode voltages

From the bearing current circuit shown in Figure 3, 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. In the hard switching inverter. the dv/dt of common mode 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 Cwr.

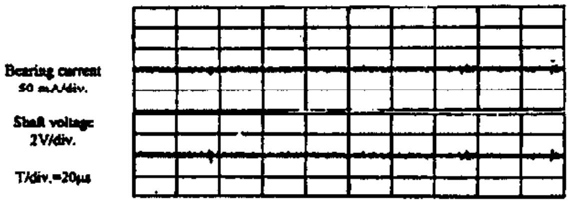
When the motor running at a very low speed, less than 2 HZ in the test, bearing current due to dv/dt begins to occur and the shaft voltage disappears. An explanation for this phenomenon is that the bearing balls are in good contact with the races at low speeds, providing a short circuit in the bearings which enable the dv/dt related bearing currents and disable the discharge phenomenon. The dv/dt related bearing currents for all three test inverters were measured and recorded in Figure 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.



Hard swiching



QRDCL



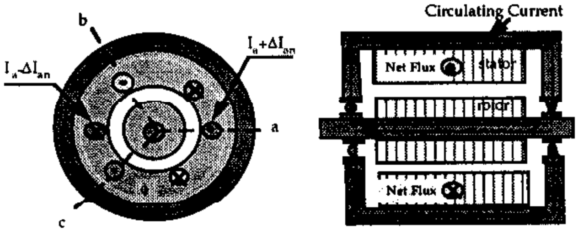
RDCL

Figure 6. Comparison of bearing currents due to dv/dt of common mode voltages

c. 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 can not be explained using Figure 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 Figure 7a, 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 7b. 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 current flow is the so called the circulating type bearing current [8].

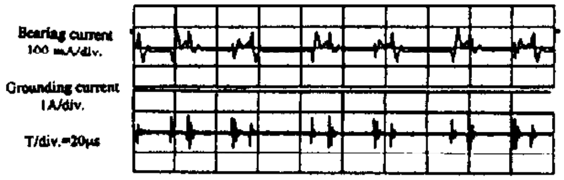


a) Cross section of an induction motor for determining flux linkage caused by common mode currents

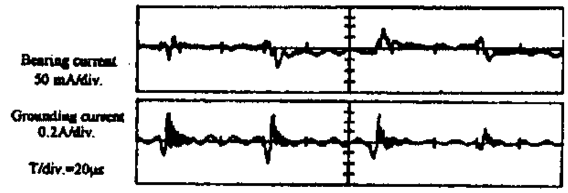
b) Path of circulating bearing currents

Figure 7. Cause of circulating bearing current

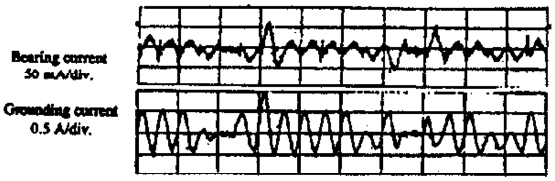
For the induction motor used in the test, no circulating bearing current can be found when both bearings are in normal contact with the stator. This means that the EMF in the loop seems to be unable to overcome the bearing impedances to produce a detectable circulating current. However, to evaluate its 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 8. The total common mode current is measured by adding all three phase input currents and is labeled as ground current in Figure 8.



Hard switching



QRDCL



RDCL

Figure 8. Comparison of circulating type bearing currents

From Figure 8, a comparison shows that all test inverters generate considerable ground currents as well as circulating bearing currents. 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 that with the hard switching inverter.

IV. CONCLUSIONS

The bearing currents and shaft voltages of an induction motor are measured under the excitations of hard switching and soft switching inverters. 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, in 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 that resulted from the hard switching inverter. These results has 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.

REFERENCES

[1] F. Punga and W. Hess, "Bearing Currents" (in German), Elektrotechnik und Maschinenbau, Vol. 25, pp. 615-618, Aug., 1907.

[2] J. Boyd and H. N. Kaufman, "The Causes and Control of Electrical Currents in Bearings", Lubricating Engineering, Jan., 1958, pp. 28-35.

[3] I. Kerszenbaum, "Shaft Currents in Electric Machines Fed by Solid State Drives", IEEE Conf. Proc. Industrial and Commercial Power System Tech. Conf., 1992, pp. 71-79.

[4] J. Erdman, R. J. Kerkman, D. Schlegel, and G. Skibinski, "Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages", IEEE Proc. of 10th Annual Applied Power Electronics Conference and Exhibition (APEC), 1995, Dallas, TX, Vol. 1, pp. 24-33.

[5] S. Chen, "Bearing Current, EMI and Soft Switching in Induction Motor Drives", Ph.D. Dissertation, University of Wisconsin-Madison, 1995.

[6] S. Chen, T. A. Lipo and D. Fitzgerald, "Source of Induction Motor Bearing Currents Caused by PWM Inverters", IEEE Transactions on Energy Conversion, Vol. 11, No. 1, March, 1996, pp. 25-32.

[7] S. Chen, T. A. Lipo and D. Fitzgerald, "Modeling of Motor Bearing Current in PWM Inverter Drives", IEEE Transactions on Industry Applications, Vol. 32, No. 6, November/December 1996, pp. 1365-1370.

[8] S. Chen, T. A. Lipo and D. W. Novotny, "Circulating Type Motor Bearing Current in Inverter Drives", Conference Records of the IEEE IAS Annual Meeting, 1996. Vol. 1, pp. 162-167.

[9] D. M. Divan, "The Resonant DC Link Inverter - A New Concept in Static Power Conversion", IEEE-IAS Annual Meeting Conf. Rec., 1986, pp. 648-656.

[10] G. Skibinski, " The Design and Implementation of a Passive Clamp Resonant DC Link Inverter for High Power Application", Ph.D. Dissertation, University of Wisconsin-Madison, 1992.

[11] S. Chen, T. A. Lipo, "A Passively Clamped Quasi-Resonant DC Link Inverter", IEEE-IAS Annual Meeting Record, 1994, Vol. 2, pp. 841-848.

[12] S. Chen, B. J. Cardoso Filho and T. A. Lipo, "Design and Implementation of a Passively Clamped Quasi Resonant DC Link Inverter", IEEE-IAS Annual Meeting Record, 1995, Vol. 2, pp. 2387-2392.