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Reduction of Bearing Currents in Doubly Fed Induction Generators

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***Abstract* - Bearing currents have been identified as a major cause of electrical machine failure when operating from a solid-state pulse-width modulated inverter. This is because at frequencies corresponding to the switching time of the inverter semiconductors, charges accumulating in the parasitic capacitances between the stator and rotor create voltages across the bearings of the machine that eventually discharge and damage the bearings. It is to be anticipated that generators as well as motors would be susceptible to bearing failure in this way, particularly in wind turbine applications where a frequency converter is often used to convert the power produced by the variable speed turbine to AC electrical power at a constant line frequency. This paper presents a novel approach to reducing bearing currents in doubly fed operation wound rotor induction machines where the rotor is controlled by a back-to-back rectifier/ inverter system. The approach used is to constrain the inverter PWM strategy to reduce overall common mode voltages across the rectifier/inverter system, and thus significantly reduce bearing discharge currents. It is shown that the common mode voltage can be almost completely eliminated, at the price of a reduction in voltage gain of the rotor supply to 57% of the supply voltage. However, since the wind generator is never required to operate at more than plus or minus 30% above or below synchronous speed. this limitation is of little consequence in variable speed wind turbine applications.**

I. Introduction

Bearing currents have been identified as a major cause of electrical machine failure when operating from a solid-state pulse-width modulated inverter. At frequencies corresponding to the switching time of the inverter semiconductors, the machine appears as a capacitive load made up of stator turn to turn, stator turn to stator frame and stator turn to rotor frame capacitances. This last capacitance causes charge to accumulate on the rotor, resulting in a voltage appearing across the bearings of the machine. Voltages of more than a few volts lead to breakdown of the lubrication film, which then produces a current flow through the bearings [1]. The resulting degradation of the bearing has been defined as electrostatic discharge machining or EDM [2].

This problem has been dealt with using a variety of methods including shaft grounding brushes, conductive lubricant, Faraday shields, insulated bearings and ceramic bearings. Cost and/or maintenance issues have prevented these strategies from being widely accepted. Electrical solutions are also possible, including terminal voltage filtering or changing to an even number of phase loads. However, once again cost enters the picture. Finally, modification of the pulse width modulation algorithm has been shown to be useful [3], in particular for motors with an even number of actual [4] or effective [5] phases or for three phase motors fed by multilevel inverters [6]. Added cost and/or derating of the inverter switches is usually the price to pay for such approaches.

It would be expected that generators as well as motors would be susceptible to bearing failure in this way, but since far fewer generators operate in conjunction with a power converter, the problem is much less recognized. However, one important exception is wind turbine applications, where a frequency converter is often used to convert the power produced by the variable speed turbine to AC electrical power at a constant line frequency. Both squirrel cage singly fed induction machines and doubly fed induction machine have encountered problems in the field with particular problems encountered in doubly fed generator applications [7].

II. Wind Turbine Configuration

Figure 1 shows the circuit arrangement of the doubly fed induction machine system typically utilized for wind turbine applications. The quantity C_{sr} corresponds to the parasitic

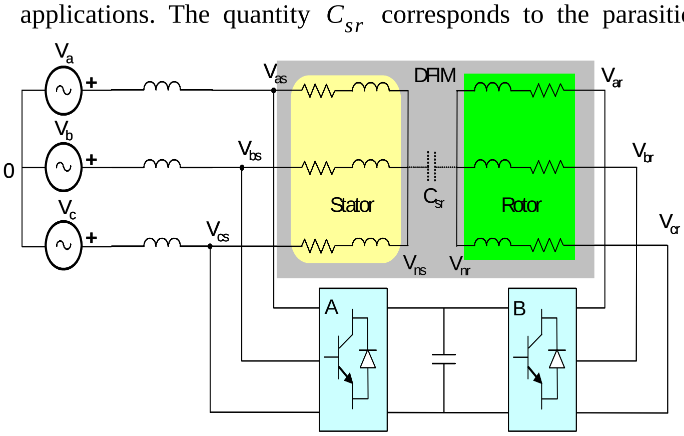


Figure 1: Doubly fed induction generator arrangement for wind power applications.

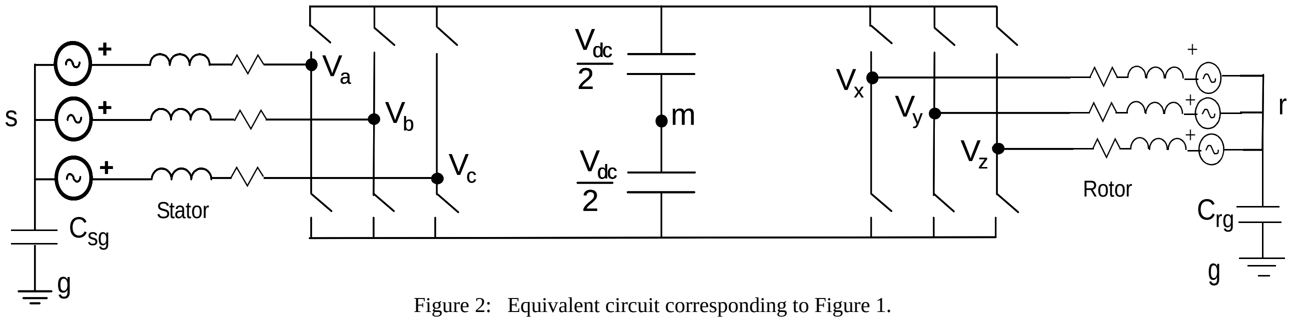


Figure 2: Equivalent circuit corresponding to Figure 1.

capacitance between the stator and rotor that provides the mechanism by which bearing currents are produced.

III. COMMON MODE VOLTAGE ELIMINATION

Figure 2 shows the equivalent circuit for this arrangement, identifying key voltage quantities for purposes of analysis. The voltage generators in the stator and rotor circuits represent the voltages induced in the stator and rotor as a result of the rate of change of the air gap flux linkages. The capacitance C_{sg} represents the capacitance of the stator windings with respect to the stator frame which is assumed to be grounded. Current flowing in this capacitance flows directly to ground and not in the motor bearing. The capacitance C_{rg} represents the capacitance between the rotor windings with respect to the stator frame and thus includes the bearing capacitance and accounts for the bearing current.

It can be observed that even though the circuit is grounded, if the voltage potentials of points s and r fluctuate in identical fashion then the current flow in the loop containing the ground point g is identically zero so that the ground current can be effectively eliminated if this condition can be reached. Analysis of this circuit shows that the voltage between the two neutral points is given by

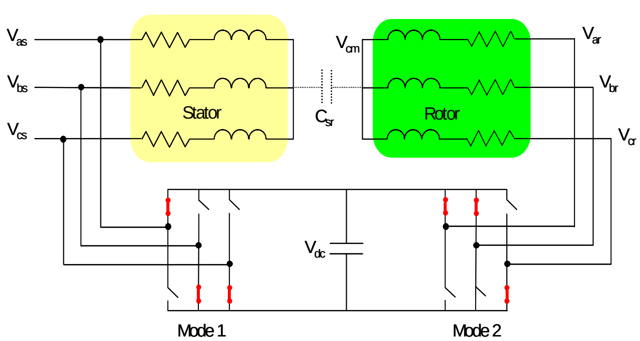
$$v_{rs} = v_{mr} - v_{ms} = \frac{(v_{xr} + v_{yr} + v_{zr})}{3} - \frac{(v_{as} + v_{bs} + v_{cs})}{3} \quad (1)$$

Equation (1) suggests that if the two terms on the right hand side can be made equal then the common mode voltage v_{rs} can be forced to zero.

It is well known that there are 8 switching states for a conventional three phase bridge converter, two of which correspond to the zero state [8]. The table included in Figure 3 shows that when the switch states of the machine side converter and the line side converter systems are both odd or even, or when the zero states are the same, the common mode voltage v_{rs} becomes zero.

The approach presented in this paper is to constrain the switching of both converters so that the total common mode voltage is always zero. The primary rectifier bridge is switched using conventional SVM as shown in Figure 3. Depending upon the selection of the switching state of the rectifier bridge the rotor inverter bridge is controlled by a constrained switching scheme that uses three active space vectors at any one time (displaced by 120°) without any zero states. The permissible active state vectors are illustrated in Figure 4. This strategy ensures that the bridge maintains a constant common mode voltage during its switching sequence, and is selected to cancel the common mode voltage of the rectifier bridge and hence maintain zero common mode voltage overall.

Figure 5 shows the available space vector states for conventional SCVM (the usual hexagon bounded operating locus) [8] and the constrained space vector options available to the rotor inverter (triangular bounded operating locus). It should be noted particularly that the use of constrained SVM for the rotor inverter reduces the available voltage gain from $V_{dc}/\sqrt{3}$ to $V_{dc}/3$. However, while such a large penalty is clearly undesirable in general, when a doubly fed machine is operated in conjunction with a wind turbine, the per unit speed variation about synchronous speed is only about 0.2 to 0.3 per unit. Thus, the reduced voltage gain created by using the



Inverter / Rectifier	Space Vector 1, 3, 5	Space Vector 2, 4, 6	Space Vector 7	Space Vector 0
Space Vector 1, 3, 5	0	$+V_{dc}/3$	$+2V_{dc}/3$	$-V_{dc}/3$
Space Vector 2, 4, 6	$-V_{dc}/3$	0	$+V_{dc}/3$	$-2V_{dc}/3$
Space Vector 7	$-2V_{dc}/3$	$-V_{dc}/3$	0	$-V_{dc}$
Space Vector 0	$+V_{dc}/3$	$+2V_{dc}/3$	$+V_{dc}$	0

Figure 3: Top: Illustrating production of space vector 1 (left hand bridge) and space vector 2 (right hand bridge). Bottom: Table of space vector states of the line and load side converter and resulting common mode voltage v_s.

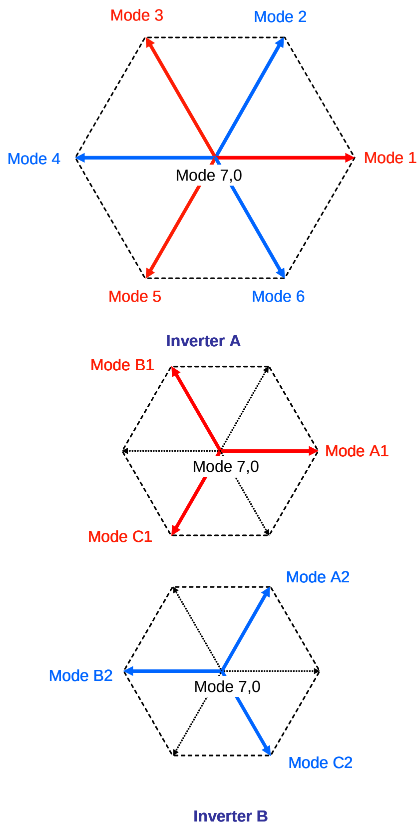


Figure 4: Upper: Available vector states for line side rectifier Lower: Vector states permitted (blue or red) depending upon the selected state of the input rectifier.

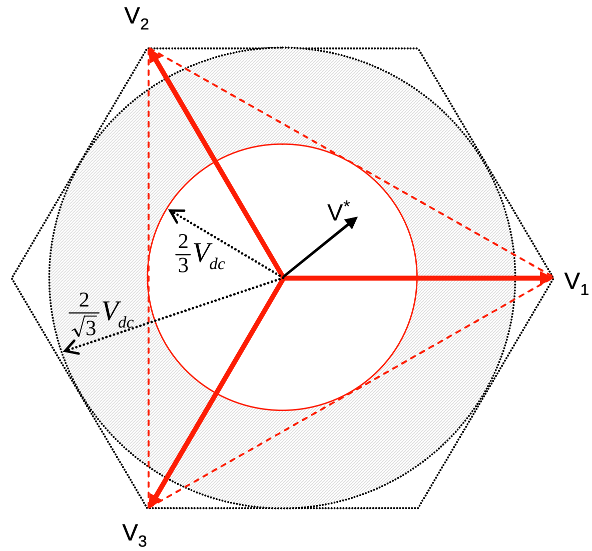


Figure 5: Space vector operating space for conventional SVM and constrained SVM to eliminate overall common mode.

constrained SV operating strategy is still more than sufficient to operate the wind turbine without any voltage penalty.

Figure 6 shows the simulated and actual measured common mode voltage for a wind turbine system operating with conventional SVM for both the rectifier and inverter. An 800 hp, 480 V, 60 Hz, 6 pole doubly fed machine, as is commonly employed in a wind turbine application, has been simulated. The line side converter (inverter) is switched at 8 kHz while the rotor side converter (rectifier) is switched at 1 kHz. The dc link voltage is 750 V.

Common mode voltages from rotor neutral measured with respect to ground are in excess of 700-800 volts are clearly in evidence in Figure 6, illustrating the severity of the common mode bearing current problem for this application. Furthermore, the good agreement achieved between the simulation and measurement confirms that the common mode effect has been properly simulated, so that the performance of the proposed mitigation strategy can now be investigated with confidence using simulation.

Figure 7 shows the improvement in common mode voltage that can be achieved when the constrained SV strategy has been implemented. If ideal switching is assumed, the common

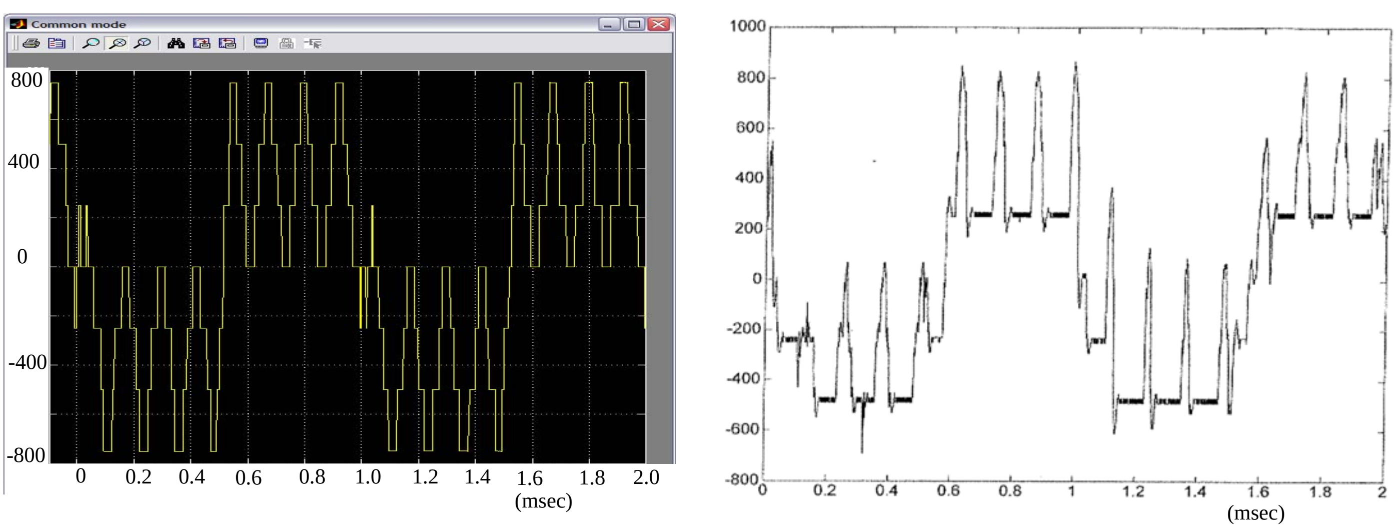


Figure 6: Simulated (left) and measured (right) common mode voltage v_{ms} using conventional PWM modulation for a doubly fed wind generation system.

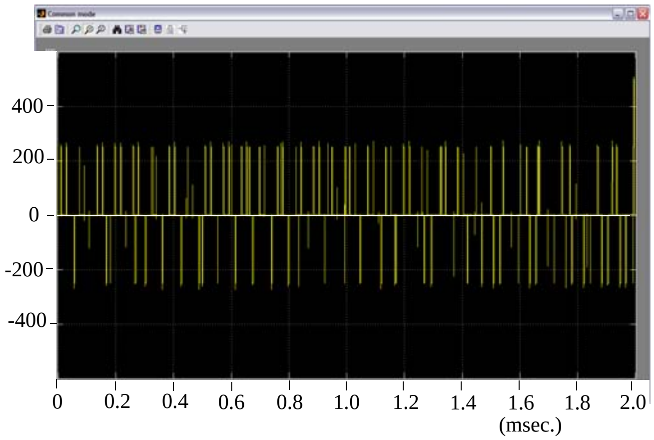


Figure 7 Common mode voltage using modified pulse width modulation, blanking time - 1.0 μsec.

mode voltage is completely eliminated, but in practice small common voltage spikes may remain because of deadtime in the inverter phase leg switching process. This residual effect can be minimized by optimizing the deadtime depending upon the switching conditions and the device temperature, or even completely removed by use of a modified inverter [9].

To fully eliminate the common mode it is, in principle, necessary to coordinate the zero states such that they occur synchronously. However, since the line side rectifier operates at line voltage and the inverter requires only a small fraction of the line voltage as it operates at slip frequency and at a different switching frequency, such synchronous operation is generally impractical. The problem can be eliminated by simply avoiding the use of the zero states. Figure 8 shows a typical example how the required inverter output voltage can be achieved without the use of the zero states. It can be noted that the penalty for this strategy is an increase in the switching frequency of 33%. The resulting current is shown in Figure 9, where it can be seen that a small amount of harmonics is still present in the rotor side current. However, this is of little consequence for a wind turbine application, and produces only a very small amount of additional losses. In general, only the line side current is required to be sinusoidal to satisfy IEEE Standards. Since the line side current is the sum of the stator current (which remains sinusoidal) and the line side rotor current (which corresponds only to slip power and is switched at a much higher pulse frequency) the line side current is relatively unaffected by the modified switching strategy.

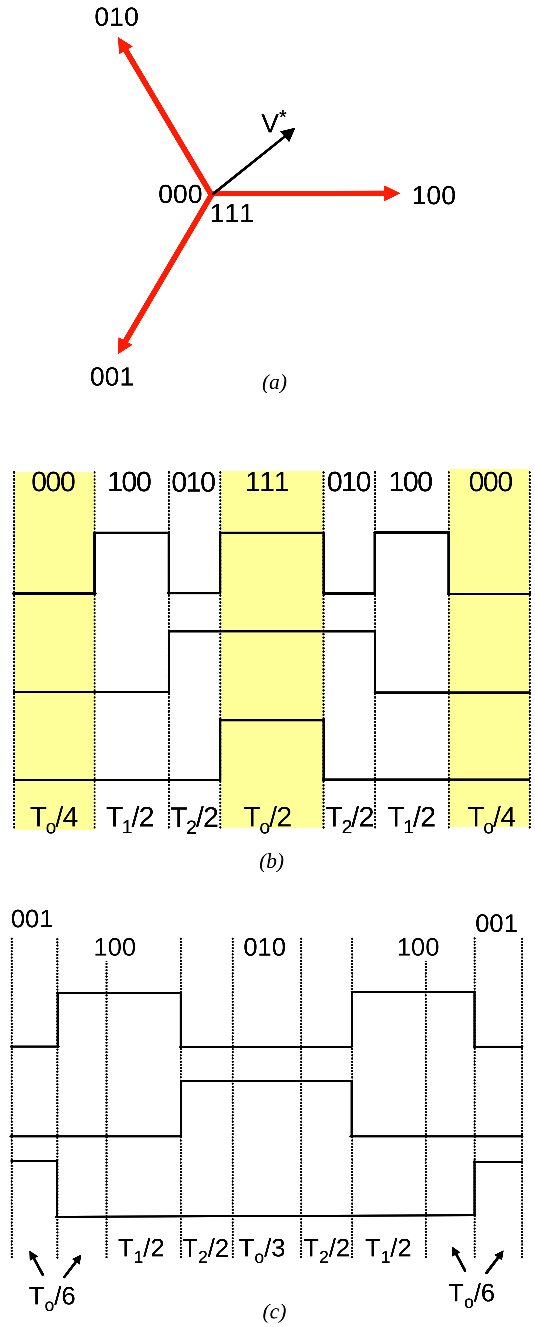


Figure 8(a) Illustrating creation of vector V* from three available active states (b) implemented using zero states, (c) implemented without using zero states.

IV. Effect of Coordinated SVM on Bearing Currents

Thus far it has been shown that the common mode voltage can be significantly reduced by proper selection of the rectifier and inverter switching states. The impact on the consequent bearing current can be examined by considering the bearing current model shown in Figure 10 in which the capacitance C_{rg} of Figure 2 is replaced by a more detailed representation which includes the effect of the bearing[10]. In this model, contact of the bearing onto the race is accounted for by a random number generator. Using typical parameters for the bearing, the current for a typical bearing contact scenario is shown in Figure 11. Again a 1 μsec switching delay for switching of the converters has been modeled. While the bearing current has not been completely eliminated, a dramatic reduction is clearly apparent.

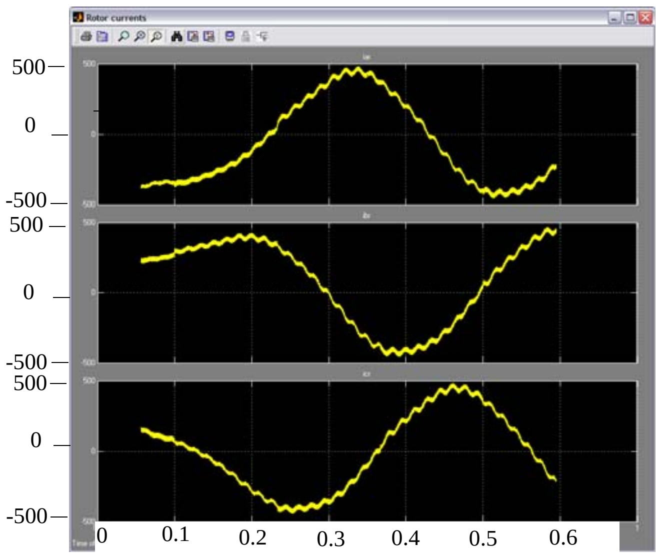


Figure 9 Three phase rotor currents when utilizing the switching strategy of Figure 8(c) (Transient produced by assuming zero initial conditions). Blanking time is 1.0 μsec.

V. Conclusion

Bearing currents have been a serious problem in the application of doubly fed induction motors for use in a variable speed wind turbine. This paper has demonstrated that the essential cause is the large excessive common mode voltage impressed on the rotor body by the switching of the power converter connected to the rotor circuits. It has been shown that this effect can be substantially reduced (ideally eliminated) by coordinated switching of the line and load side converters. This strategy ensures that the common mode voltage produced in both the stator and rotor circuits will be identical thus eliminating the common mode current. Implementation of this type of switching strategy is expected to help mitigate a potentially serious problem in the wind turbine industry.

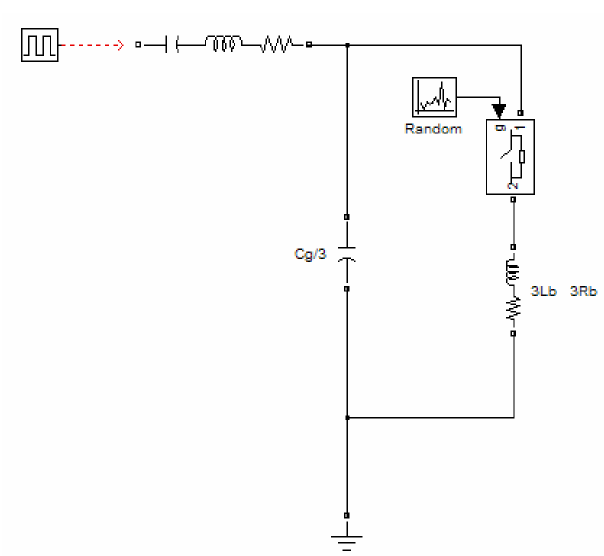
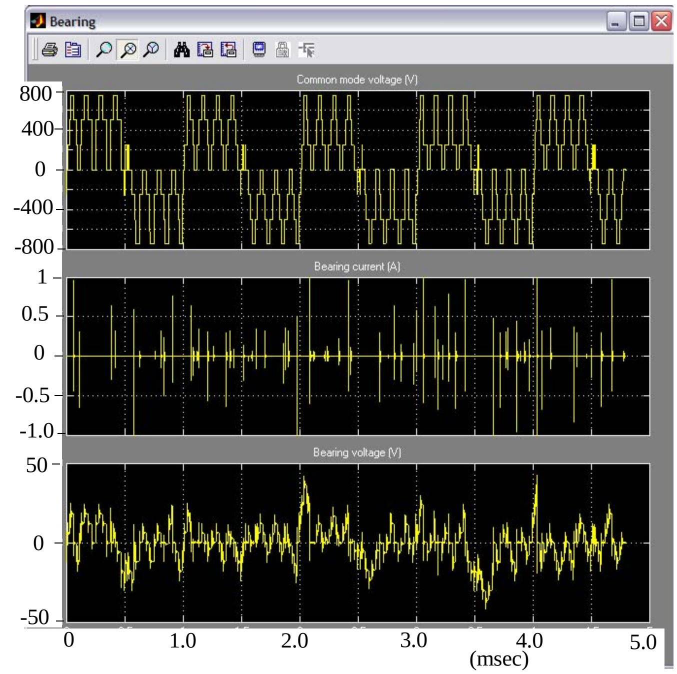
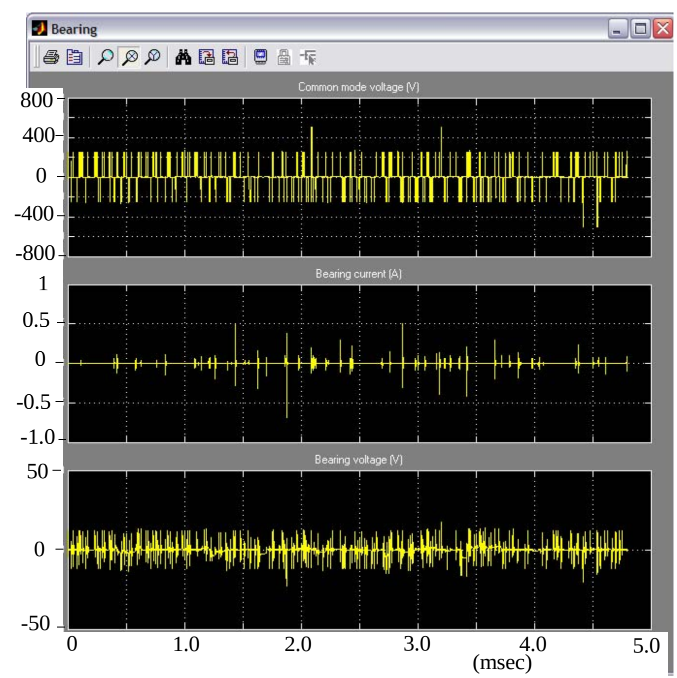


Figure 10 More Advanced Model for Bearing Current Investigation.



(a)



(b)

Figure 11: (a) Conventional space vector modulation, (V_{rg} = 28 V rms)
(b) Coordinated space vector modulation (V_{rg} = 4.5 V rms).
Traces: Top - Common mode voltage, Middle - Bearing Current, Bottom - Bearing Voltage

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