Modeling of Motor Bearing Currents in PWM Inverter Drives

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

***Abstract*— Pulsewidth modulated (PWM) inverters have recently been found to be a major cause of motor bearing failures in inverter-motor drive systems. Specifically, all inverters generate common mode voltages relative to the earth ground. The voltages provide coupling or bearing currents through motor parasitic capacitances to the rotor iron which flow via the bearings to the grounded stator case.**

In this paper, a model of bearing currents caused by PWM inverter is proposed. The model is based on transmission line theory which uses an equivalent lumped parameter π-network to describe the parasitic coupling phenomenon. The model parameters are then identified by matching the calculated model outputs with those of experimental measurement. The validation of the method is demonstrated by the fact that the model can reproduce a variety of experimental results obtained on a test motor.

An application of this method also gives a motor grounding current model. As the conducted electromagnetic interference (EMI) in drive systems is related to the grounding currents, the grounding current model can be used for the analysis of conducted EMI in motor-drive systems.

***Index Terms*—Bearing current, bearing damage, bearing failures, induction motor, parasitic capacitive coupling, PWM inverter, shaft voltage, common mode voltage**

I. Introduction

RECENTLY, pulsewidth modulated (PWM) inverters have been found to be a major cause of motor bearing failures in inverter-motor drive systems [1]–[3]. In principle, all inverters generate common mode voltages relative to the earth ground which provide coupling currents through the motor parasitic capacitances to the rotor iron. As the coupling currents find their way via the motor bearings back to the grounded stator case, they form the so-called bearing currents [2], [3].

The principle of bearing current generation can be illustrated using Fig. 1. By taking the inverter negative dc bus, O, as a reference for common mode voltages, the common mode voltage at motor phase A input terminal is V_{AO}. The parasitic coupling capacitances from the motor windings to the stator and rotor irons are represented by C_{ws} and C_{wr}, respectively. There is also a capacitance C_g present across the bearings which mainly consists of the motor air gap capacitance. The bearings are approximated by a switch B which turns on and off randomly based on observation of electric behavior of motor rotating bearings [1], [2]. A closed-loop parasitic coupling circuit is formed if the coupling capacitance from the negative dc bus to the earth is also recognized. This capacitance is represented by an impedance Z_{in} which will be treated as the internal impedance of the common mode voltage source V_{AO}. Based on the above circuit, a bearing current I_{brg} is easily identified as the total current flowing into all C_{wr}'s and then via bearing model B back to the grounded stator. Similarly, for phases B and C, common mode voltages V_{BO} and V_{CO} also contribute to the bearing current.

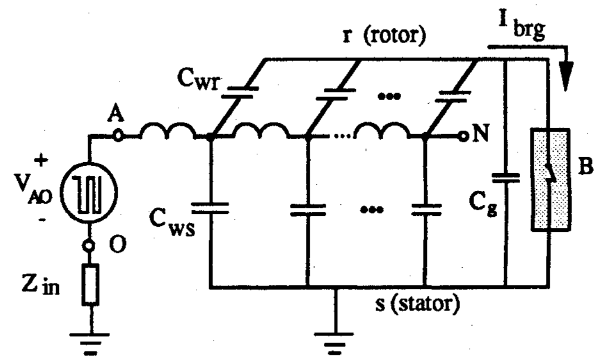

Fig. 1. Principle of bearing current generation in inverter-motor system.

The distributed parameter circuit in Fig. 1 is, however, not suitable for a simplified analysis of the bearing currents. Equivalent lumped parameter circuit models are developed in this paper to describe the parasitic coupling phenomenon. In principle, the parasitic coupling circuits are the same as transmission line circuits. Based on transmission line theory, a distributed parameter circuit can be modeled by an equivalent lumped parameter π-network which gives the same input and output relationship. The method is applied to give a model of coupling from motor windings to stator irons—the motor grounding current model, and a model of coupling from motor windings to the rotor irons—the bearing current model. The model parameters are then identified by matching the calculated model outputs with those of experimental measurement. The validation of the modeling is demonstrated by the fact that the models can reproduce a variety of experimental results obtained on the test motor. Therefore, the proposed models can be used to analyze the effect of bearing currents and facilitate the determination of solutions to suppress these currents. As the motor grounding current is a major source of conducted electromagnetic interference (EMI) in inverter-motor systems,

Paper IPCSD 96–30, approved by the Industrial Drives Committee of the IEEE Industry Applications Society for presentation at the 1995 IEEE Industry Applications Society Annual Meeting, Lake Buena Vista, FL, October 8–12. Manuscript released for publication April 22, 1996.

S. Chen is with the GM Research & Development Center, Warren, MI 48090 USA.

T. A. Lipo is with the Department of Electrical and Computer Engineering, University of Wisconsin, Madison, WI 53706–1691 USA.

D. Fitzgerald is with the Motion Control Division, Yaskawa Electric America Inc., Northbrook, IL 60062–2028 USA.

Publisher Item Identifier S 0093-9994(96)06638-8.

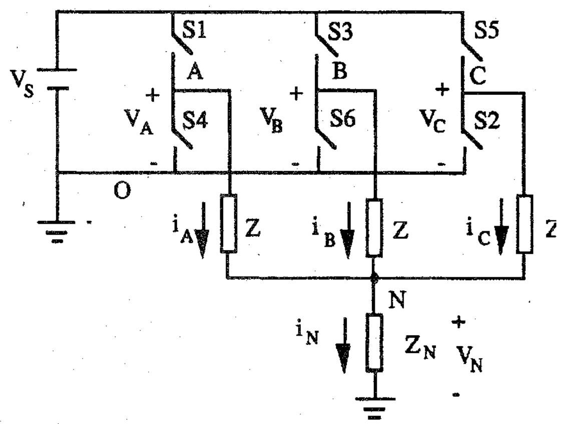

Fig. 2. Three-phase inverter-load system including common mode impedance Z_n.

the motor grounding current model can thus be applied to the analysis of conducted EMI in motor-drive systems.

II. Common Mode Excitation and Response

For a balanced three-phase inverter-load system shown in Fig. 2, the three-phase load is represented by Z. Assume that the zero sequence impedance of the load is Z_O and that there exists a common mode impedance Z_N from the neutral point N to the ground. Due to existence of common mode excitations, such a system must contain both differential mode and common mode responses. While the differential mode response has been well known as the three-phase input and output relationship, the common mode response has not yet been formally established. The purpose of Section II is to derive a common mode circuit model which describes only the common mode response of the system.

In general, for any three-phase load Z, the zero sequence voltage and current are defined by

$$V_O = \frac{V_{AN} + V_{BN} + V_{CN}}{3} = \frac{V_A + V_B + V_C}{3} - V_N \quad (1)$$

and

$$i_O = \frac{i_A + i_B + i_C}{3} \quad (2)$$

respectively. The relationship between zero sequence voltage and current is governed by

$$V_O = i_O Z_O. \quad (3)$$

Based on (1)–(3), the common mode current, i_N, and the common mode voltage at neutral point, V_N, can be derived as

$$i_N = i_A + i_B + i_C = 3i_O = \frac{3}{Z_O + 3Z_N}\frac{V_A + V_B + V_C}{3} \quad (4)$$

and

$$V_N = \frac{3Z_N}{Z_O + 3Z_N}\frac{V_A + V_B + V_C}{3}. \quad (5)$$

It is interesting to notice that the three-phase balanced impedance Z does not appear in (4) and (5). This implies that the common mode circuit can be decoupled from the differential mode circuit in a balanced three-phase system.

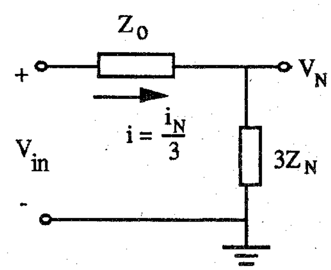

Fig. 3. Model of common mode excitation.

Since only the zero sequence impedance of the three-phase load Z is common to all three phases, it is reasonable that Z_O, instead of Z, will appear in the common mode equations (4) and (5).

As the common mode voltage V_N and common mode current i_N are the only physically meaningful common mode outputs in the system, a model of common mode excitation can be readily obtained based on (4) and (5). By defining an equivalent common mode voltage input

$$V_{\text{in}} = \frac{V_A + V_B + V_C}{3} \quad (6)$$

the common mode model can be simply represented by Fig. 3.

III. Modeling of Coupling from Windings to Stator—Motor Grounding Currents

The coupling between the motor windings and the rotor is much less than the coupling between the same windings and the stator. The modeling will use this fact and only consider the coupling between the windings and the stator. A distributed circuit model of coupling between the stator windings and the stator can be represented by Fig. 4. In Fig. 4, Z denotes the impedance per unit length of motor phase windings, and Z_{ws} the per unit length windings to stator parasitic coupling impedance which is mainly capacitive. Due to symmetric design of motor structures, a uniform distribution of parasitic coupling impedances is assumed. This assumption will apply to parasitic couplings from the windings to both the stator and the rotor.

Theoretically, the circuit represents a three-phase transmission line with one of its terminations shorted as the winding neutral N. As is treated in transmission line theory, if only the input and output characteristics are of interest, an equivalent π-network can be used to describe the input and output relationship. In other words, for each phase, the distributed parameter circuit can be replaced by an equivalent π-network. By adding all three parallel connected neutral to ground impedances, an equivalent lumped parameter circuit model is obtained as shown in Fig. 5. In this model, $V_N$is the voltage of motor neutral point and I_{ws} is the total coupling current from the windings to the stator. All parameters in the model are to be determined which are functions of Z and Z_{ws}.

Based on the derivation in Section II, a simplified model of common mode excitation can be drawn as shown in Fig. 6 where L_o, C_o, and R_o are the zero sequence components contained in L_s, C_s, and R_s of Fig. 5. As the voltage of the motor neutral point and the total coupling current from the