Bearing Currents and Their Relationship to PWM Drives

Doyle Busse, Jay Erdman, *Member, IEEE,* Russel J. Kerkman, *Senior Member, IEEE,*
Dave Schlegel, *Member, IEEE,* and Gary Skibinski, *Member, IEEE*

***Abstract*— This paper examines ac motor shaft voltages and the resulting bearing currents when operated under pulse width modulation (PWM) voltage source inverters. The paper reviews the mechanical and electrical characteristics of the bearings and motor in relation to shaft voltages and bearing currents. A brief review of previous work is addressed, including the system model and experimental results. The theory of electric discharge machining (EDM) is presented, including component calculations of the system elements. The effect of system elements on shaft voltages and bearing currents are evaluated experimentally and the results compared to theory. A design calculation is proposed that provides the relative potential for EDM. Finally, the paper will present quantitative results on one solution to the shaft voltage and bearing current problem.**

***Index Terms*— Bearing capacitance, bearing current, bearing current density, bearing threshold voltage, electric discharge machining, electrostatic shielded induction motor, rotor shaft to ground voltage, stator to rotor capacitance.**

I. Introduction

In recent years, the powering of induction motors from variable frequency drives (VFD) has become increasingly popular. Even though the induction motor is a very rugged device, the bearings are now subject to additional modes of failure due to bearing currents. Bearing currents in larger ac motors have been known for many years. The cause has been understood to be induced by magnetic dissymetries in the construction of the motor resulting in destructive bearing currents.

Shaft voltages and their resulting currents were recognized by Alger [1] in the 1920's. Since then, numerous investigations of the problem have been reported with recent contributions by Costello and Lawson [2], [3]. In recent years, the effect of pulse width modulation (PWM) drives operating ac motors has been studied. All motors have some level of shaft voltage and resulting bearing current. In addition, bipolar junction transistor (BJT) and insulated gate bipolar transistor (IGBT) inverters experience electric discharge machining (EDM) currents. Two key elements are which voltage conditions will break down the insulating grease film and how the resulting current densities affect bearing life.

This paper will focus on the mechanisms that cause these voltages and the ability of bearings to withstand the resulting currents. Possible mechanisms for bearing damage when operating on VFD include electric field breakdown of the oil film resulting in EDM currents and lower level dv/dt or electrostatically induced currents altering the chemical composition of the lubricant.

Recently, the authors presented their findings on EDM and its relationship to PWM inverter operation [4]. In contrast to traditional magnetic imbalance effects found in sine wave-driven machines, it was shown that PWM inverters serve to excite a capacitive coupling between the stator and rotor. This coupling combined with the high-frequency electrical characteristics of the bearing allow the motor shaft voltage to instantaneously achieve potentials over 20 times that observed on sine wave operation.

The current resulting from the motor shaft voltage is limited by the bearing impedance. As motor speed increases, the bearing resistance attains values in the megohm range [4]. Technical literature indicates that as speed increases, the balls ride an oil film, forming a boundary between the race and the ball with the exception of instantaneous asperity point contacts. An asperity is the deviation from the mean surface, usually in microns.

Fig. 1 shows the surface roughness of a bearing race that demonstrates electrical fluting damage [5]. The paper investigates the theoretical and empirical basis of bearing oil film charging with PWM voltage source inverters. The dielectric strength of typical lubricating films is determined along with an explanation of why the film can withstand rotor shaft voltages in the range of 10 to 30 V peak for short periods.

This paper explores the relevant bearing failure mechanisms in addition to the failure indicators of shaft voltage and bearing current magnitudes. The point contact area is calculated and a current density is specified to project bearing life. The paper presents motor and bearing capacitance characteristics for a wide horsepower range and relates them to an equivalent common mode motor and bearing model. A steady-state analysis of the full model leads to the development of a voltage ratio, which is convenient for analyzing the potential for shaft voltages and bearing currents. A reduced second-order model is proposed for analysis purposes. Experimental results, examined in the context of the second-order model, demonstrate the effects of drive system components on shaft voltages, and how the excitation voltage, coupling capacitances, and bearing characteristics relate to EDM and dv/dt currents. Finally, the paper will analyze a proposed solution to the bearing current problem and quantify the improvement by comparing the magnitudes of dv/dt and EDM currents.

Manuscript received January 24, 1996; revised July 26, 1996.

The authors are with Rockwell Automation–Allen Bradley Company, Mequon, WI 53092 USA.

Publisher Item Identifier S 0885-8993(97)01959-5.

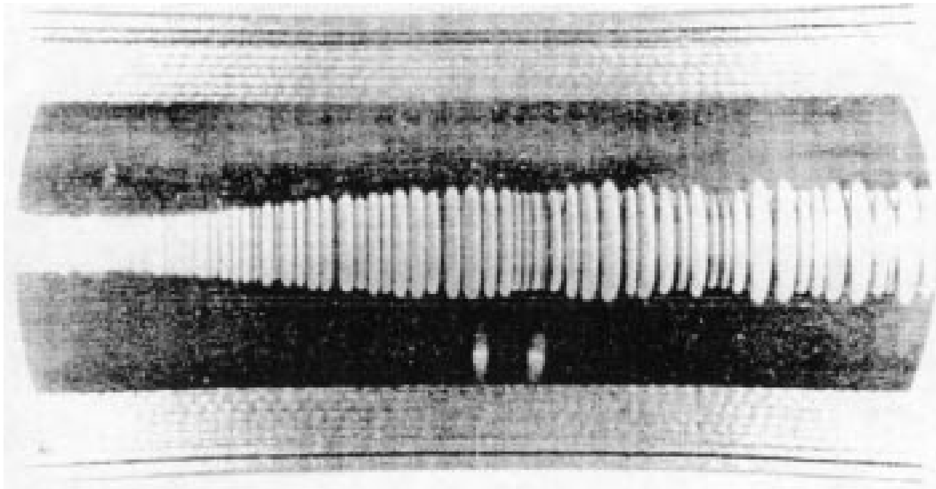

Fig. 1. Surface roughness of a ball bearing race [5].

II. Safe Bearing Current Levels

This section of the paper will describe electrostatically induced bearing failure mechanisms. It discusses shaft voltages as a failure indicator and proposes current magnitudes as an additional indicator for PWM voltage source inverters. A theory of Hertzian contact area is provided and employed to calculate the bearing current density and bearing life degradation.

A. Failure Mechanisms of Bearings

Bearing failures can be attributed to induced bearing currents in addition to traditional mechanical and thermal failure mechanisms. Bearing currents can result from machine construction or the type of application. Mechanical failures can be produced by excessive vibration, while thermal failures result from overloads, which increase bearing temperature and decrease mechanical life. Perhaps the most common mechanical failure is subsurface cracking, due to normal contact stresses, resulting in spalling or flaking of the race surface. A surprisingly large number of failures are due to improper installation.

Machines contain magnetic dissymmetries inducing end to end rotor shaft voltage that result in bearing current. Bearing current and its induced mechanical wear do not exist if shaft voltage is less than a critical bearing threshold voltage $(V_{\rm th}(\Lambda))$ required to break down the insulating grease, which is a function of lubricant thickness and surface roughness (Λ) [6]. $V_{\rm th}(\Lambda)$ is 0.2 to 1 V under 60-Hz sine wave operation [7], [8]. Low bearing currents result when shaft voltage is slightly greater than $V_{\rm th}(\Lambda)$ and induce a chemical change of low resistivity lubricants, ultimately reducing life by raceway corrosion [9]. High shaft voltages, resulting from the bearing oil film acting as a capacitor in high-resistivity lubricants, which is charged to common mode voltage levels, may produce damaging EDM currents. When race to ball asperity contacts come close, the oil film's electric field increases, leading to breakdown with high discharge currents that create a localized elevated temperature of the race and results in molten pits. The pits eventually lead to fluting of Fig. 1 and reduced mechanical life [10]. Small machines typically maintain a shaft voltage less than $V_{\rm th}(\Lambda)$ threshold. Large machines may employ lubricants with increased $V_{\rm th}(\Lambda)$, thus reducing EDM current [11].

Machine applications with belt-driven rotors or in ionized air are known to exhibit electrostatically induced charge on the bearing capacitance (C_b) and possibly result in damaging EDM current. PWM motor drives are known to naturally charge C_b thru the stator to rotor coupling capacitance $(C_{\rm sr})$. Rotor to ground voltage $(V_{\rm rg})$ is determined by voltage divider action between $C_{\rm sr}$, the parallel combination of rotor to frame capacitance $(C_{\rm rf})$ and C_b, and stator neutral to ground voltage $(V_{\rm sng})$ of Fig. 2. Since $V_{\rm sng}$ modulates around 0 V with peaks of plus and minus 1/2 bus voltage $(V_{\rm bus})$, the rotor shaft voltage charges to high open circuit voltages, before asperity contact closure causes film breakdown. With high $V_{\rm sng}$ values, PWM inverters produce higher EDM currents than those observed with sine wave operation. Furthermore, $V_{\rm sng}$ induces dv/dt currents through the bearing film and also through bearing asperity points when in contact. The common mode equivalent model of Fig. 2 will be used throughout this paper, with all the components explained. More detailed analyzes and parameter measurement techniques for the model may be found in [4], [12], and [13].

B. Shaft Voltage as a Degradation Indicator

End to end *axial shaft voltages* >200 mVrms on sine wave excitation indicate magnetic dissymmetry, creating high localized bearing current. The magnitude of the *rotor shaft voltage to ground* is an indication that excessive wear may occur when operated on PWM driven drives. Fig. 3 shows three different shaft voltage phenomenon occurring in a bearing lubricated with high resistivity grease.

Region A (115–265 μS): $V_{\rm sng}$ and $C_{\rm sr}$ charge the high-resistivity mineral oil film forming C_b. A plateau value, determined by $C_{\rm sr}$ in series with $(C_b||C_{\rm rf})$ capacitive divider action, is explained in Section III. At the end of *Region A*, $V_{\rm sng}$ modulates to a higher level, causing the $V_{\rm rg}$ to increase. The oil film breaks down at 35 Vpk, creating a 3-Apk EDM pulse. Film thickness is typically 0.2 to 2 μm depending on oil temperature [8]. Lower film thickness occurs at higher bearing