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Investigation and Mitigation of Premature Bearing Degradation in Motor Drive System

Fei Fan, *Student Member, IEEE*, Kye Yak See, *Senior Member, IEEE*, Joseph Kiran Banda, Xiong Liu and Amit Kumar Gupta

Abstract— Pulse width modulated (PWM) variable frequency drives (VFDs) are commonly adopted in modern control of electro-mechanical drive systems. The use of insulated-gate bipolar transistor (IGBT) and higher switching frequencies has improved the efficiency of the motor drive systems significantly but they also cause high frequency common-mode (CM) currents in the motor bearings. Hence, new drive installations failed prematurely within months, which results in unnecessary down time. Mitigation techniques such as CM filter and motor shaft grounding ring are possible solutions to prevent this kind of premature failure. In this paper, using a 5.5 kW motor drive system as a case study, the cause of bearing degradation is investigated and the various mitigation techniques are carefully evaluated.

Index Terms—Common-mode (CM), CM voltage, variable speed drives, shaft voltage, bearing current.

I. INTRODUCTION

PERFORMANCE improvements of VFD and competitive pricing of power electronics have resulted in dramatic increase in the use of inverter controlled induction machines, ranging from less than 1 kW up to a few MW [1-3]. On the other hand, it has been reported that the machine bearing surfaces were damaged due to the induced bearing currents, which contribute over 50% of all motor failures [4]. The subject of bearing failure has been studied extensively and the prevention of bearing failure in VFD machines becomes an important design consideration. Three main mitigation methods for bearing degradation problem are soft switching technology or advanced PWM techniques [4-5], CM filter [6-7], insulated motor bearing, shaft grounding ring and Faraday shield [8]. For a large number of inverter-driven induction machines which have already been used in industrial applications, solutions such as shaft grounding brush or CM filter are preferred, as they do not require major modifications to the machines and hence more convenient and cost effective.

In this paper, an IGBT-based VFD system with a 5.5 kW induction motor is setup to understand the cause of bearing degradation and effectiveness of mitigation techniques. By analyzing the experimental results of the VFD system, it allows in-depth understanding of the cause and effect chain of bearing degradation. The effectiveness of shaft grounding brush and

CM filter are also evaluated for the reduction of CM current.

II. COMMON-MODE BEARING CURRENT AND EXPERIMENTAL SETUP

A. CM noise source and bearing current paths

Fig. 1 shows a typical motor drive system. The inverter is connected to the induction machine through three-phase cable. The motor drive system is usually sit on a metallic frame that serves as a ground plane. The CM voltage is defined as the average of the AC terminal voltage at the output of inverter with respect to the ground plane. For a commonly used two-level PWM voltage source inverter, the resultant CM voltage is a high frequency step waveform with high dv/dt , which appears between stator windings and the machine frame. When the lubricating film of the bearing is intact, the stator winding-to-frame capacitance C_{wf} , stator winding-to-rotor capacitance C_{wr} , rotor-to-frame capacitance C_{rf} , drive end bearing capacitance $C_{b,DE}$, and non-drive end bearing capacitance $C_{b,NE}$ will form a capacitive voltage divider as shown in Fig. 2. Therefore, the bearing voltage V_b or the shaft voltage mirrors the machine side CM voltage at the neutral of stator winding V_{sng} with a ratio defined as “bearing voltage ratio (BVR)” [9], expressed in (1). The dv/dt across the intact bearing can cause small capacitive bearing current which is not harmful. However, the lubricating film may break down when the bearing voltage exceed a certain threshold voltage. Then the energy stored in the bearing capacitances will be discharged instantly, resulting in high

Fig. 1. Motor drive system configuration.

Fig. 2. Equivalent circuit of motor stray capacitances

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X. Liu, and A. K. Gupta are with Rolls-Royce Singapore Pte. Ltd. (e-mail: XiongShawn.Liu@rolls-royce.com).

amplitude electric discharge machining (EDM) bearing current through the bearings.

$$\text{BVR} = \frac{\text{shaft voltage}}{\text{common mode voltage}} = \frac{C_{wr}}{C_{b,ODE} + C_{b,DE} + C_{rf} + C_{wr}} \quad (1)$$

The net CM current flowing through the induction motor produces a high frequency magnetic flux that circulates around the machine shaft, inducing an axial voltage between both ends of the shaft. The circulating type bearing current driven by the shaft end-to-end voltage is proportional to the shaft length, which increases with the machine size. Therefore, damage caused by circulating bearing current mostly happened in high power motor drive systems above 100 HP [10].

Fig. 3 illustrates the bearing current propagation paths via both capacitive and inductive couplings. The motor load is usually connected to the motor shaft through an insulated coupling. The motor, the inverter and the load all are grounded with some forms of electrical connections. Inverter-induced bearing currents have three components: the capacitive bearing current, the EDM current and circulating bearing current, which are indicated by green, purple and red dashed lines, respectively. Capacitive bearing current and EDM current have the same propagation path from motor stator winding to ground while the circulating bearing current flows in the “stator frame–

Fig. 3. Propagation paths for bearing currents.

inverter end bearing–shaft–load end bearing” loop.

B. Experimental setup

Fig. 4 shows the experimental setup connecting a voltage source PWM inverter and a 5.5 kW induction machine via 5 m unshielded cable. In the PWM controller, three-phase balanced reference signals are compared with a repetitive 3 kHz triangular carrier signal to generate the sinusoidal PWM (SPWM) gate signals for the IGBTs. The presence of line impedance stabilization network (LISN) is necessary because it prevents external conducted emission on the mains from contaminating the measurement and provides stable and clean power to the inverter. All the subsystems including the induction machine are placed on a large metal sheet according to the conducted emission testing requirement of CISPER 25 [11]. All the measurements are performed under no load condition which represents the worst case scenarios of CM current [12]. As shown in Fig. 5, a tip made of carbon fiber is attached to the shaft to obtain the shaft voltage and a grounding brush of the same material can be used to provide a low

impedance path between the rotating shaft and the machine frame.

Machine bearings are modified to provide direct access to the bearing current as shown in Fig. 5. Both the drive and non-drive ends bearings are covered with an insulating support layer and the bearing outer surface and frame are connected via a short

Fig. 4. Experimental setup of a PWM inverter and a 5.5 kW induction machine

Fig. 5. Test instrument for shaft voltage and bearing current measurements

wire which facilitates the measurement of bearing current.

In the experiment, an oscilloscope (Tektronix MD04104C, 1 GHz bandwidth, 3 GS/s sampling rate) is chosen for the measurement. Three differential probes (THDP0200, 200 MHz bandwidth) and a passive probe (Tektronix P2220) with AEGIS probe tip (SVP-TIP-9100) are selected to measure the inverter terminal voltages and shaft voltage, respectively. CM current and bearing current are measured with a RF current probe (Solar Electronic 9134-1, 100 MHz bandwidth).

III. ANALYSIS OF MEASUREMENT RESULTS

A. Causes of bearing degradation

Fig. 6 shows the measurement results when the machine rotating speed is 800 rpm. Different time scales are chosen to illustrate the operating behavior of the motor drive system. Fig 6(a) is based on the inverter output frequency while Fig. 6(b) is based on the carrier frequency. The DC voltage after diode bridge rectifier is around 580 V. The voltage-source PWM inverter with a switching frequency of 3 kHz is operating at an output frequency of 40 Hz under the so-called “voltage-per-hertz control”. The line frequency voltage and current shown in Fig. 6(a) will not interact with the parasitic capacitances inside

the motor. However, high frequency CM voltage with high dv/dt capacitively induced a high frequency shaft voltage according to BVR, as shown in Fig. 6(b).

(a) Output frequency-based time scale: DC link voltage (top), line-to-line voltage v_w (middle), phase current i_v (bottom)

(b) Switching frequency-based time scale: CM voltage (top), shaft voltage v_{sh} (bottom)

Fig. 6. Measurement on a 5.5 kW, 6-pole induction motor at 800 rpm, switching frequency $f_{sw} = 3$ kHz.

As the ball bearing impedance is a nonlinear function of lubricating film parameters and it can alternate between insulating and conducting states at random. Fig. 7 captures the instant when EDM process occurs. At that instant, there is a breakdown in the lubricating film, causing the capacitance to discharge and results in a pulse current. The pulse current in an unmodified motor could be more pronounced than the value shown since the external wire and its bonding add to the loop impedance. After the bearing impedance restores back to capacitive, the bearing voltage starts to follow the CM voltage over BVR, thus the bearing voltage charges up to almost twice the normal level.

It is observed in Fig. 8 that circulating bearing currents at both drive and non-drive ends, i_{b-DE} and i_{b-NDE} have a current ripple with a peak-to-peak amplitude of 15 mA and a frequency around 3 MHz, which matches well with the CM current. The high frequency circulating bearing current can be considered as a transformer effect, where the the secondary side bearing current mirror the primary induced CM current.

Fig. 7. EDM current (top) and bearing current (bottom) for the 5.5 kW induction motor

Fig. 8. CM current and circulating bearing current at both ends of the bearings

The cause and effect chain of bearing degradation is summarized in Fig. 9, where PWM CM source generates high frequency CM voltage and CM current, causing bearing degradation via capacitive and inductive couplings, respectively. Shaft grounding brush bypasses the bearing voltage to reduce EDM current while CM filter attenuates the CM current to suppress the circulating bearing current. The effectiveness of these remedies will be evaluated as follows.

Fig. 9. Cause and effect chain of bearing damage

B. Bearing grounding brush

Fig. 10 shows the motor shaft voltage waveforms for both ungrounded and grounded conditions. The machine rotating shaft is grounded with a carbon fiber brush as shown in Fig. 5.

The grounding brush provides a low impedance path in parallel with the bearing lubrication film. Thus, peak-to-peak shaft voltage drops from more than 8 V to less than 2 V at the instant when the brush touches the rotating shaft. Therefore, the

EDM process can be prevented. However, there is no obvious reduction of the CM current and bearing current, as the CM impedance of the motor is dominated by the stator winding-to-frame capacitance, not the bearing capacitance.

The grounding brush helps to prevent bearing degradation caused by the EDM bearing current but has no impact on the CM current, which can be as high as tens of amperes in high power machines. It is reported that in a 500-kW machine, the bearing current induced by CM current can reach as high as 5 A peak-to-peak, which is good enough to destroy the insulating property of the lubricating film [13]. In order to reduce the CM current and bearing current effectively, CM filter will be a more feasible solution.

Fig. 10. Comparison of shaft voltages of ungrounded condition and grounded condition: shaft voltage v_{sh} (top), CM current i_{cm} (middle), bearing current i_b (bottom)

C. CM filter

High-power motor drive system usually requires thick multi-core power cables to handle large current ratings. These cables are too rigid to be bend and therefore winding a few turns on a magnetic core to achieve high CM inductance is ruled out. Usually, several one-turn CM chokes are necessary to provide high inductance. CM chokes with nanocrystalline core are selected because of their high permeability, high saturation flux density and low core loss. For the experiment, four one-turn CM chokes are added between the inverter and the induction motor to attenuate CM current. The size of the choke and the CM impedance of the four chokes together are shown in Fig. 11.

Fig. 11. CM impedance of the four one-turn CM chokes together

Fig. 12 shows the measured the CM currents with and without the CM chokes in time-domain. It is clearly observed the current spikes have reduced significantly due to higher CM impedance in the current propagation path. Fig. 13 shows CM currents in frequency-domain and the CM chokes begin to show their effect above 500 kHz. The attenuation offered by the CM chokes is clearly observed by comparing the spectrum envelopes of the CM currents with and without the CM chokes. For better visibility, the attenuation contributed by the CM chokes is plotted as a red curve in Fig 14. Most filters available in the market are designed and tested based on 50 Ω source and load terminations. Based on this scenario, the attenuation of the CM chokes can be estimated as follows:

$$Att = 20 \log \left| \frac{100 + Z_{CMC}}{100} \right| \quad (2)$$

where Z_{CMC} is the total CM impedance of the four chokes in Ω .

Fig. 12. Time domain waveforms of CM currents with and without chokes

Fig. 13. Frequency spectrum of CM currents with and without chokes

Fig. 14. Estimated attenuation based on 50 Ω terminations and measured attenuation

The estimated attenuation is also plotted as a blue curve in Fig. 14. Large discrepancy between the estimated and measured attenuations is observed. The reason is that in the motor drive system, the CM filter will rarely be terminated with $50\ \Omega$ source and $50\ \Omega$ load. Therefore, the actual filter attenuation is very much dependent on the actual source and load impedances in a specific application.

IV. ACCURATE PREDICTION OF CM FILTER ATTENUATION

The CM impedance of the three-phase load can be measured offline as the motor speed has no impact to CM impedance of the motor over the mid-to-high frequency range.

An improved two-probe measurement method [14] that has the ability to extract the source impedance online is chosen to measure the source impedance of the motor drive system. This method offers excellent signal-to-noise ratio while protecting the vector network analyzer (VNA) ports. CM source impedance of the Vacon drive is measured with the method. With the measured impedance frequency response, the CM source impedance can be modelled with an equivalent circuit of a $3\ \Omega$ resistor, a $95.5\ \text{nH}$ inductor and a $19.9\ \text{nF}$ capacitor in series.

The CM impedance responses of the source, load and the CM chokes are plotted in Fig. 15. The source impedance is capacitive in nature at low frequency due to the physical insulation layer between the power MOSFET and the grounded chassis. When the frequency reaches the self-resonant frequency, the source impedance is dominated by the equivalent series inductance (ESL) and increases with frequency. CM load impedance is measured with an impedance analyzer at the cable terminals with respect to the ground plane. The load CM impedance is also capacitive in nature at low frequency due to the parasitic capacitances between stator winding and ground.

Fig. 15. CM impedance of the inverter (source), CM chokes and induction motor (load)

Attenuation of the four CM chokes is re-calculated based on the known source and load impedances:

$$\text{Att} = 20\log \left| \frac{Z_S + Z_L + Z_{CMC}}{Z_S + Z_L} \right| \quad (3)$$

where Z_S and Z_L are the measured CM impedances of the source and the load.

The calculated and measured attenuations are now in close agreement, as shown in Fig. 16. It is noticed that the CM chokes provide the highest attenuation at around 3 MHz and hence the CM current at 3 MHz is well attenuated, as shown in Fig. 13.

Fig. 16. Predicted attenuation based on accurate terminations and measured attenuation for CM chokes

To achieve even higher CM attenuation, one can consider a second order CM filter. A second order CM filter is designed by adding three $8\ \text{nF}$ Y-cap on each of the three phases on the motor side (load) with their neutral point grounded through a $22\ \Omega$ damping resistor, as illustrated in Fig. 17.

Fig. 17. CM model of motor drive system with LC filter

Attenuation of this LC filter can be calculated as follows:

$$\text{Att} = 20\log \left| \frac{Z_L(Z_S + Z_L + Z_P)}{(Z_S + Z_L)(Z_P \parallel Z_L)} \right| \quad (4)$$

$$Z_P = Z_{Y\text{-cap}} + Z_{\text{damping}} \quad (5)$$

where $Z_{Y\text{-cap}}$ is the sum of three Y-cap and Z_{damping} is the impedance of damping resistor.

Fig. 18 shows the calculated and measured attenuations of the second-order filter and both match well till 5 MHz. For frequency above 5 MHz, the measured attenuation is lower than that of calculated because the CM current is too small and below the noise floor of the measurement instrument. Using the first order CM chokes as a reference, the second order CM filter offers additional 5-10 dB attenuation in middle frequency range.

Fig. 19. Calculated attenuation and measured attenuation for second order CM filter

V. CONCLUSION

Induction machines driven by VFDs suffer from the premature bearing damage due to high frequency CM voltage and current. The cause and mechanism of high frequency bearing current is investigated. Mitigation techniques using grounding brush and adding CM filter are also experimentally studied and evaluated. It is found that CM filter is preferred for high-power machines where the circulating bearing current is dominant. With known source and load termination impedances, it is demonstrated that a suitable CM filter can be designed to attenuate the CM current effectively without a trial and error process.

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