Suppression for Discharge Bearing Currents in Variable-Frequency Motors Based on Electromagnetic Shield

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High frequency current in the bearings of variable-frequency motors coupled with their shafts is a common issue that will shorten the bearings lifetime ultimately. A new method could be used to suppress high frequency discharge bearing currents (HFDBC) was proposed in this paper. In this method, an electromagnetic shielding slot wedge (ESLW) was used to reduce the capacitive coupling between the stator windings and the rotor. From the perspective of electromagnetic field, electromagnetic coupling caused by the common mode voltage could be blocked by this electromagnetic shield layer. Additionally, the mathematic model of suppression method was given and the starting performance of the motor was analyzed. Finally, an experimental platform was set up and a motor was modified to evaluate the suppressing effectiveness. The shaft voltage and bearing currents of the modified motor，under ESLW layer presented and absented, were measured and compared, and the effects of the shielding slot wedge were evaluated respectively when the motor operated at load and no-load.

Index Terms—**Bearing currents, electromagnetic shield, copper wedge, PWM inverter**

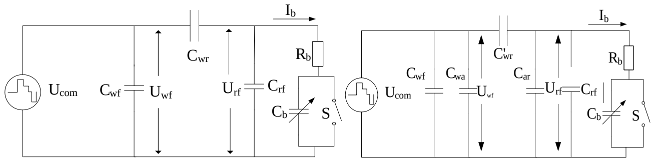
I. Introduction

With the rapid development of modern drive technology, the variable frequency speed regulation system suffer more parasitic effects, such as bearing currents, cable overvoltage and electromagnetic interference[1]. The inverter outputs high frequency common mode voltage, which excites the parasitic capacitance in the motor, and the high frequency current flow through the parasitic capacitance forming HFDBC and voltage across the stator and rotor (bearing inner race and outer race) is defined as shaft voltage. The discharge occurred in the bearing inner ring, causing pitting and fluting in the bearing races [2]. Actually, the high-frequency discharges bearing current are the main cause of bearing failure. Furthermore, the bearing currents cause the vibration and noise and affect the stability of the system. Therefore, the suppression of high-frequency discharge bearing currents is concerned in this paper.

Bearing currents suppression techniques commonly used in an engineering project include common-mode voltage filters, ceramic bearings, and shaft-ground connection with an electric contact brush. In addition, dual-bridge inverters which can reduce bearing currents effectively have been proposed by some scholars [3]. The static charge dissipation method was utilized creatively to suppress the bearing voltages [4]. This paper proposed a novel suppression technique based on theory of electromagnetic shielding. By finite element simulation, starting performance analysis of the motor and prototype experiment, electromagnetic shielding effectiveness will be evaluated.

II. Principle of Shielding Slot Wedge

Due to distribution of parasitic capacitance, the common-mode voltage transmits via the capacitance and causes bearing current through capacitive coupling. Consequently, the shaft voltage and bearing current depend on parasitic capacitance. Hence, a special wedge can be inserted in the slot of stator as an electromagnetic shield to destroy capacitance circuit, as shown in Fig.1. Where U_{com} is the common-mode voltage; Us is the voltage between rotor and stator core/frame; C_{wr} is the stator winding to rotor parasitic capacitance; C_{wf} is the stator winding to stator core/frame the parasitic capacitance; C_{rf} is the rotor to stator core/frame parasitic capacitance; C_b is the bearing insulation capacitance; R_b is the bearings impedance. The breakdown and the insulation state of lubricating grease are simulated by the voltage-controlled switches S.



a) Circuit without ESLW b) Circuit with ESLW

Fig.1 Common mode equivalent circuit model

After the shielding slot wedge was inserted into the motor, winding to slot wedge capacitance C_{wa} and slot wedge to rotor capacitance C_{ar} were introduced into the circuit, additionally the C_{wr}' is winding end to rotor capacitance. The voltage, Urf, across the bearing could be rewrite to (2) from (1):

$$U_{rf} = U_{wf} \frac{C_{wr}}{C_{wr} + C_{rf}} \tag{1}$$

$$U_{rf} = U_{wf} \frac{C^{'}_{wr}}{C^{'}_{wr} + C_{ar} + C_{rf}} \tag{2}$$

Obviously, according to (2) U_{rf} will decrease as the shielding slot wedge C_{wr} decreases to C_{wr}'. Once the shielding slot wedge was connected to the ground the high frequency common mode current flows from C_{wf} and C_{wa} into frame, but the rotor and bearings. Moreover, the rotor-frame voltage U_{rf} builts up process, responsible for the most severe electric discharges in the bearings, is suppressed. Consequently, the bearing current decreases significantly.

III. Design of Shielding Slot Wedge

The electromagnetic field in the inverter fed motor is considered as time-harmonic electromagnetic field that can be expressed following equations.

$$\begin{cases} \nabla \times \boldsymbol{H} = \gamma \boldsymbol{E} + j\omega\bar{\varepsilon}\boldsymbol{E} = j\omega\bar{\varepsilon}_e\boldsymbol{E} \\ \nabla \times \boldsymbol{E} = -j\omega\bar{\mu}\boldsymbol{H} \\ \nabla \cdot \boldsymbol{B} = 0 \\ \nabla \cdot \boldsymbol{D} = 0 \end{cases} \tag{3}$$

Where $\boldsymbol{H}$ is magnetic field strength, $\boldsymbol{E}$ is electric field strength, $\bar{\varepsilon}_e$ is the complex permittivity, $\bar{\mu}$ is the complex permeability. $\boldsymbol{B}$ is the magnetic flux density and $\boldsymbol{D}$ is the electric displacement vector. In good conductor, the magnetic field strength component lag 45° of the electric field intensity, and the electromagnetic wave attenuation fast in good conductor of electricity. Depth of penetration is given below.

$$d = \frac{1}{k''} = \sqrt{\frac{2}{\omega\mu\gamma}} \quad (4)$$

According to properties of copper conductors, $\gamma=5.8\times10^7$S/m; when frequency of electromagnetic wave (f) is 50Hz, its penetration depth (d) is 4.95mm; when frequency f=16kHz, the penetration depth d=1.2mm. Therefore, the thickness of the shielded copper strip is set to 2mm. Theoretically, electromagnetic waves varied from 1 kHz to 16 kHz could be effectively shielded by the copper conductors with 2mm thickness. Therefore, high-frequency discharge bearing currents can be effectively reduced by ESLW and the life of bearings was extended.

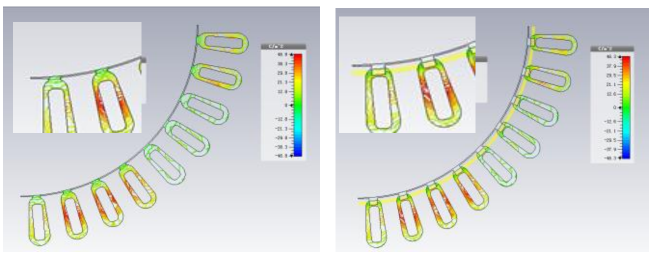
IV. FEM ANALYSIS OF ELECTRIC FIELD

To analyze the proposed ESLW, the model presented in Fig.2 mainly adopts finite element simulation based on Maxwell's equation:

$$\frac{1}{\mu}\nabla\times\nabla\times\mathbf{E}+\sigma\frac{\partial\mathbf{E}}{\partial t}+\varepsilon\frac{\partial^2\mathbf{E}}{\partial t^2}=-\frac{\partial\mathbf{J}_s}{\partial t} \quad (5)$$

Where μ is the permeability **E** is the electric field strength, ε is the permittivity, σ is the conductivity and $\mathbf{J}_s$ is the applied current density. Due to the high frequency common mode voltage, the high frequency magnetic field intensity in this model is small enough to ignore the influence on the magnetization curve of silicon steel sheet.

As shown in Fig.2, a simulation model is built at frequency of 5 kHz. The electric field intensity of the motor with ESLW reduced significantly. The electric displacement vector at the notch of the motor is significantly reduced because of the ESLW. The simulated results clearly show that the proposed technique can effectively suppress the parasitic capacitance between the stator windings and rotor. But it is worth noting, due to skin effect, the displacement current distribution is uneven, lead to relatively clutter distribution of the electromagnetic field.



a) Motor stator without ESLW　　b) Motor stator with ESLW

Fig.2 The electric displacement vector of motor at 5 kHz

ESLW can be served as slot wedges to block electromagnetic coupling produced by the high-frequency common-mode voltage. Once the electromagnetic transmission was blocked, the discharging bear currents would be suppressed and shaft voltage would decrease.

V. EXPERIMENT AND RESULTS

Experiment system in Fig.3 has been set up to verify the theoretical analysis result. The modified test motor is a 380V, 3kW three-phase induction motor with shielding copper strips. The stator with ESLW is shown in Fig.4, and the shaft voltage and the bearing current can be measured.

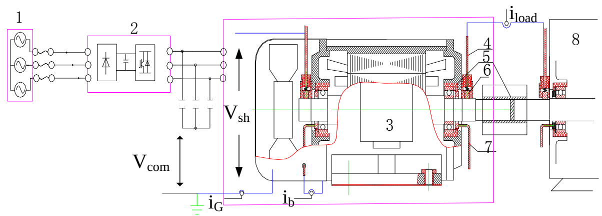


Fig.3 Experiment system: 1 Fundamental frequency power 2.Inverter 3. Test motor 4.Brush copper loop5. Nylon plastic insulation 6.Brush 7. Bearing signal copper loop 8 Load motor

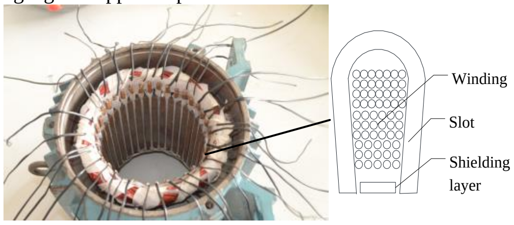
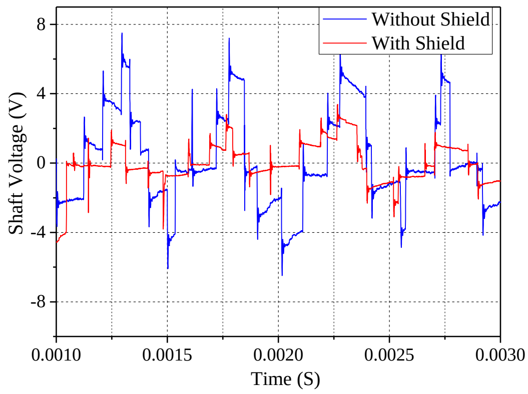
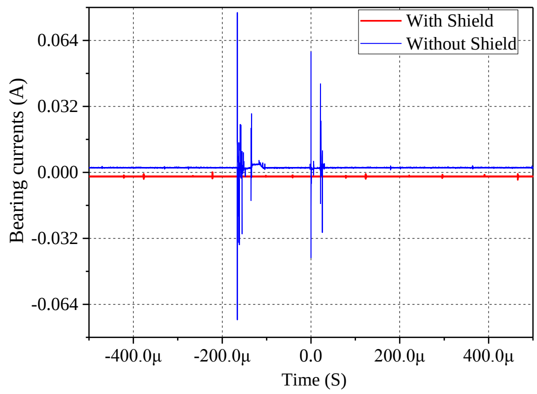


Fig.4 Stator with ESLW

The shielding effectiveness is shown in Fig.5. The peak value of the shaft voltage reduces from 7.8V to 3V and the bearing currents almost disappear. Further experiment results and discussing will be given in the full paper.



a) Shaft voltage



b) Bearing currents

Fig.5 Experiment results

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