Calculation of Circulating Bearing Currents in Machines of Inverter-Based Drive Systems

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***Abstract*—The high-frequency circulating bearing current that may occur in machines of inverter-based drive systems can be described by an eddy-current model. The parameters of an equivalent circuit are derived from the model. The ratio between bearing current and common-mode current amplitudes for different machines is calculated. The theoretical maximum ratio is about 0.35. Copper loops applied for bearing current measurement may decrease the circulating bearing currents up to almost 40%.**

***Index Terms*—Common-mode voltage, inverter-induced circulating bearing currents, variable-speed drives.**

I. Introduction

FAST-SWITCHING insulated gate bipolar transistor inverters may cause additional bearing currents in inverter-based drive systems. The high-frequency circulating bearing current is one of the different principal contributing phenomena. It occurs in addition to the "classical" bearing current due to magnetic asymmetries of large line-fed motors. The inverter-induced circulating bearing currents follow the same path as the "classical" ones; yet, their origin is very different [1]–[8].

If no additional measures such as the use of filters or chokes that are designed for use in the inverter output are taken, the inverter is a common-mode voltage source that exposes the motor terminals to high dv/dt. This causes an additional high-frequency common-mode current I_{com}, mainly because of the interaction of the high dv/dt at the motor terminals and the capacitance between motor winding and frame C_{wf}. The frequencies of these high-frequency common-mode currents range from 100 kHz up to several megahertz [9].

In conventional machines, if no mitigation methods such as additional conductive shielding in the stator slots [10] are applied, the common-mode current excites a circumferential magnetic flux ("ring flux" or "common-mode flux") around the motor shaft. This flux induces a shaft voltage v_{sh} along the shaft of the motor. If v_{sh} is large enough to puncture

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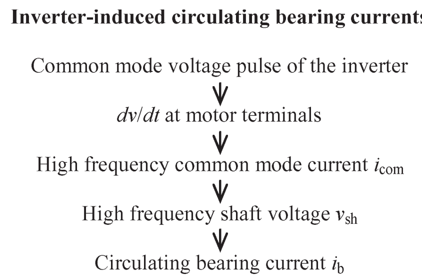

Fig. 1. Mechanism of inverter-induced circulating bearing currents.

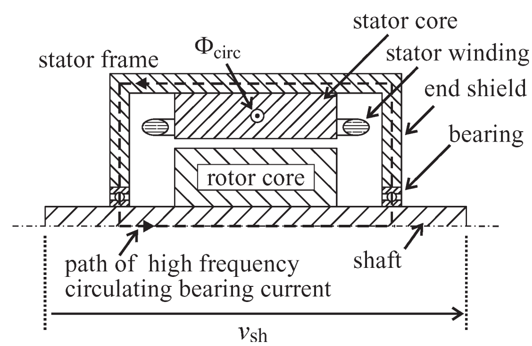

Fig. 2. Path of high-frequency circulating bearing current.

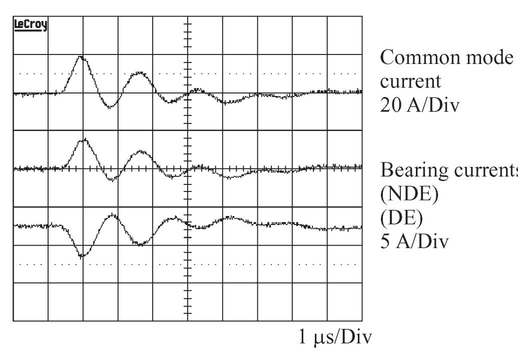

Fig. 3. Circulating bearing currents, induction motor, 400-mm frame size, 500-kW rated power, motor speed $n = 3000$ r/min, and bearing temperature $\vartheta_{\mathrm{b}} \approx 70\ ^{\circ}\mathrm{C}$.

the lubricating film of the bearing and destroy its insulating properties, it causes a circulating bearing current i_{b} along the loop "stator frame–nondrive end–shaft–drive end." Because this type of bearing current is due to inductive coupling, it mirrors the common-mode current. It is of opposite direction in both bearings (Figs. 1–3). Peak bearing current amplitudes $\hat{\imath}_{\mathrm{b}}$ vary—depending on the motor size—i.e., $\hat{\imath}_{\mathrm{b}} \approx 0.5 - 20$ A (power rating up to $P_{\mathrm{r}} = 500$ kW).

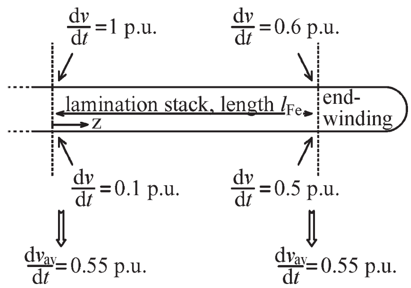

Fig. 4. Sketch of one turn of stator winding and distribution of dv/dt along the stack length.

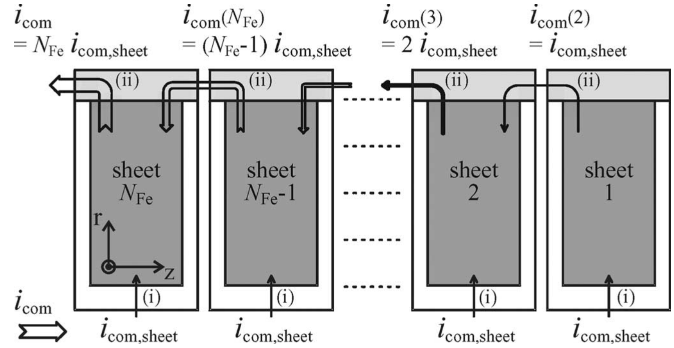

Fig. 5. Common-mode currents of individual sheets flowing from the stator winding [case (i)] and from the neighboring sheet [case (ii)].

II. Calculation of Common-Mode Ring Flux

If no mitigation methods such as additional conductive shielding in the stator slots [10] are applied, the common-mode current i_{com} excites the high-frequency common-mode flux Φ_0, which can induce high-frequency circulating bearing currents. Without the use of additional special measures, the current enters the machine via the stator windings and leaves through the grounding connection(s) of the motor, thereby passing the stator stack lamination. Understanding of the resultant generation of the common-mode flux is essential for the comprehension of the circulating bearing current phenomenon. Important work in this field is reported in [11] and [12], which is used here as a starting point.

The current distribution in the stator lamination can be described by an eddy-current model with sinusoidal variation of the parameters with respect to the time. The stator lamination stack is represented by a 2-D model with cylindrical symmetry, using the cylindrical coordinate system (r, φ, z). The common-mode flux is supposed to flow in the azimuthal direction, i.e., $\vec{\underline{H}} = (0, \underline{H}_{\varphi}(r,z), 0)$. The current density has only an r-component and a z-component, i.e., $\vec{\underline{J}} = (\underline{J}_{\mathrm{r}}(r,z), 0, \underline{J}_{\mathrm{z}}(r,z))$. The laminations of the stator stack are insulated from each other by a coating. It is assumed that the contact impedance between the laminations and the stator frame is very small and that the conductivity of the lamination sheets is significantly larger than the conductivity of the frame. Furthermore, it is supposed that the circumferential flux flows mainly in the cylindrical part of the stator lamination stack, which is the so-called stator iron back. Therefore, stator teeth and coil ends are excluded from the model. Furthermore, for further calculation, the density of the common-mode current as it enters the stator lamination stack from the stator winding is assumed to be homogeneous along the length of the stack length l_{Fe}. In fact, dv/dt decreases along the phase winding. Therefore, the flow of common-mode current across the stator winding insulation onto the lamination is not constant along the winding. However, averaging over one phase at a given distance from the end of the lamination stack into axial (z-) direction results in an approximately constant distribution of the common-mode current along the stack length (Fig. 4).

For frequencies of several 100 kHz, the skin depth δ_{s} is less than 50 μm and is much smaller than the thickness of a lamination sheet b_{Fe} of typically 0.5 mm. In this case, the lamination can be described by an analytical model for 1) one conducting half-plane, if the current enters from the stator slot and leaves through the stator housing, and 2) two conducting half-planes, if the current enters the sheet on one side of the stator housing and leaves at the other side through the stator housing. The field solution in one sheet with current flowing both from the winding and the neighboring sheet is given by superposition of the two models [11], [12] (Fig. 5).

With these assumptions, given the number of sheets of the stator core stack N_{Fe}, the inner and outer diameters of the stator lamination d_{si} and d_{se}, and the height of the stator slot h_{s}, the analytical solution of the common-mode flux is

$$\Phi_0 = \mu \frac{N_{\mathrm{Fe}} i_{\mathrm{com}}}{2\pi} \ln\left(\frac{d_{\mathrm{se}}/2}{d_{\mathrm{si}}/2 + h_{\mathrm{s}}}\right) \frac{\delta_{\mathrm{s}}}{\sqrt{2}}. \quad (1)$$

As the common-mode flux varies with time, it induces a voltage in the loop "stator frame–nondrive end–shaft–drive end" (Fig. 2), as expressed by

$$\begin{aligned} v_{\max} &= 2\pi f \Phi_0 \\ &= \mu_0 \mu_{\mathrm{r}} N_{\mathrm{Fe}} \hat{i}_{\mathrm{com}} f \ln\left(\frac{d_{\mathrm{se}}/2}{d_{\mathrm{si}}/2 + h_{\mathrm{s}}}\right) \frac{\delta_{\mathrm{s}}}{\sqrt{2}}. \end{aligned} \quad (2)$$

The number of sheets of the stator core stack N_{Fe} is proportional to the length of the stator core l_{Fe}, which is proportional to the frame size of a machine h. Furthermore, the stator winding-to-frame capacitance C_{wf} is proportional to h^2, i.e., the square of h, and the common-mode current i_{com} is approximately proportional to C_{wf} [13]. As the skin depths $\delta_{\mathrm{s}} \propto 1/\sqrt{f\mu_{\mathrm{r}}}$, the common-mode flux decreases with $1/\sqrt{f\mu_{\mathrm{r}}}$, resulting in the following equations:

$$\Phi_0 \propto i_{\mathrm{com}} l_{\mathrm{Fe}} \propto h^3 \quad (3)$$

$$\Phi_0 \propto 1/\sqrt{f} \quad (4)$$

$$\Phi_0 \propto \sqrt{\mu_{\mathrm{r}}} \quad (5)$$

$$v_{\max} \propto i_{\mathrm{com}} l_{\mathrm{Fe}} \propto h^3 \quad (6)$$

$$v_{\max} \propto \sqrt{f} \quad (7)$$

$$v_{\max} \propto \sqrt{\mu_{\mathrm{r}}}. \quad (8)$$

Both common-mode flux Φ_0 and induced voltage v increase with the cube of the frame size h. The frequency f has an