Mitigation of Inverter-Induced Noncirculating Bearing Currents by Introducing Grounded Electrodes into Stator Slot Openings

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Abstract—Modern converter-supplied ac motors are exposed to bearing currents. Despite extensive research and development, the industry still does not have a final solution with acceptable cost and high efficiency. This article focuses on capacitive bearing currents. After a brief explanation of the phenomenon, an unconventional approach for effective mitigation of the capacitive bearing currents is proposed. The approach suggests using grounded electrodes in the slot openings to reduce the stator-winding-to-rotor-core capacitance and thereby the bearing currents. Different electrode diameters are considered and evaluated by a finite element method (FEM) analysis. The results are verified by laboratory tests. The bearing voltage ratios of the original and modified induction motor are compared.

Index Terms—Ball bearings, electrical discharge machining bearing currents, electrical machines, finite element analysis (FEA), induction machines, variable speed drives.

I. INTRODUCTION

Bearing currents are an adverse phenomenon in modern electrical drives. The problem was recognized already in the infancy of electrical motors. The converter era emphasizes the problem, and it remains more or less an open challenge for the industry and researchers. The problem is aggravated by the fact that there are still no standard strategies to fight the bearing currents, and plenty of knowledge related to the problem is not publicly available.

The origins of bearing currents and the current paths inside an electrical machine can be different, but most modern machines suffer from parasitic currents caused by inverter-induced high values of \( \frac{du}{dt} \) and common-mode voltage high-frequency components. An industrial electrical machine always has a common magnetic circuit, a multiphase stator winding, a rotor, and, in most cases, ball or roller bearings. As there are conductive parts insulated from each other, an electrical machine can be represented as a set of parasitic capacitances. These capacitances are shown in Fig. 1; they are the stator-winding-to-rotor-core capacitance \( C_{wr} \), stator-winding-to-stator-core capacitance \( C_{ws} \), stator-core-to-rotor-core capacitance \( C_{sr} \), and bearing capacitance \( C_b \). Parasitic current paths: a: circulating, b: noncirculating bearing currents.

Fig. 1. Schematic of the parasitic capacitances in an electrical machine: Stator-winding-to-rotor-core capacitance \( C_{wr} \), stator-winding-to-stator-core capacitance \( C_{ws} \), stator-core-to-rotor-core capacitance \( C_{sr} \), and bearing capacitance \( C_b \). Parasitic current paths: a: circulating, b: noncirculating bearing currents.

Among the abovementioned bearing currents, there are other less significant types of parasitic currents in electrical drive systems: shaft grounding current and stator grounding current, which are reported e.g., in [1]–[3].

A. Circulating Bearing Currents

Although the circulating bearing currents are not in the scope of this article, a short description of them is given in the following. Circulating bearing currents form closed loops within an electrical machine, as indicated by “a” in Fig. 1. The
low-frequency circulating currents have been known since the infancy of electrical machines and are mainly caused by an unbalanced magnetic flux, which results from an imperfect motor geometry (which was relevant in early machines), or stator segmentation (relevant in modern large-scale ones). These currents are extensively described in [1], [4], and [5].

Another factor contributing to circulating bearing currents is a high common-mode $du/dt$ value, which forces part of the current to leak from the stator windings through the stator-winding-to-stator-core stray capacitance to the ground [6]. The inductive effect causes high-frequency circulating bearing currents to be generated. Along with low-frequency circulating currents, this mechanism has a considerable contribution in relatively large machines (with a rated power of 75 kW and higher) as described in [4], [7]–[9].

### B. Noncirculating Bearing Currents

1) **Overview:** A part of the current flowing in the stator winding leaks through the stray capacitance to the stator core and another part to the rotor. The part that leaks to the stator contributes to the circulating bearing currents and usually flows to the machine grounding terminal without causing immediate harm. In contrast, the other part that leaks to the rotor (indicated by “b” in Fig. 1) travels through the bearings on its way to the grounding of the system. This current may cause electrical discharges and is extremely harmful to the ball bearings.

A large proportion of modern ac electrical drives are equipped with a frequency converter, which supplies the motor with higher harmonics, high $du/dt$ values, and common-mode voltage. These features drive the capacitive currents to flow through their parasitic paths. Thus, steel bearings usually suffer from noncirculating bearing currents when a pulsewidth modulated (PWM) voltage-source frequency converter is employed.

An uncommon mitigation method of capacitive currents is studied here. The method is based on modifying the electrical machine by reducing the capacitive coupling between the stator winding and the rotor core. As a result, the bearing voltage ratio (BVR) and thereby bearing currents are reduced.

2) **Mitigating Techniques Available:** Various methods have been developed to mitigate bearing currents. Table I lists the state-of-art techniques of reducing capacitive bearing currents.

Techniques aimed to reduce the frequency converter higher voltage harmonics and common-mode voltage are reported extensively in the literature with a wide range of different solutions [10]–[15]. Converter modifications offer significant potential in reducing bearing currents. Such solutions, however, always require to make a choice between an effective but complicated and expensive layout, or less effective but inexpensive software solutions.

It is also possible to suppress the common-mode voltage and higher harmonics on their way from the inverter to the motor by installing a common-mode voltage filter [2], [7], [16]. However, $du/dt$ filters [15]–[19] and common-mode chokes [20]–[22] do not reduce EDM currents.

EDM bearing currents can also be suppressed by introducing machine modifications. For instance, the stray current circuits can be broken partially or completely by minimizing the capacitive couplings [6], [23]–[31] or using ceramic ball bearings [2], [32].

The negative effects of the capacitive currents on the bearings can be reduced if alternative and safe paths for the stray currents are provided. This can be implemented for instance by using conductive grease [33], [34] or shaft grounding devices. Shaft grounding devices form a straightforward and effective countermeasure [35], which has a major drawback: the brushes wear out, they may have contact problems and be sensitive to external conditions, and thus require frequent maintenance. However, various offbeat designs such as microfiber brushes [36], [37] and the use of contactless capacitive shunting [38] can be promising options. Different electrostatic shields reduce capacitive couplings and decrease stray currents.

The present article reviews and verifies the approach of grounded electrodes, discussed in [31]. The approach is aimed at a reduction in PWM-caused EDM bearing currents on the machine side. The proposed design further develops the principle of electrostatic shield applied to reduce capacitive coupling between the rotor core and the stator winding and is not effective against other types of parasitic currents or in cases where, e.g., static electricity can build up and lead to discharges.

The theoretical principles, a FEM-based evaluation, and results obtained from laboratory tests are presented. The results are analyzed and compared with theoretical findings. Finally,
this article is concluded by an evaluation of the feasibility of the approach.

Unlike the previous study [31], the present article considers an actual electrical machine and verifies the theoretical findings by laboratory experiments. In this article, a refined finite element analysis (FEA) is applied. This article focuses on practical implementation, describes the system mounting process, and discusses possible issues caused by the system. In addition, possible drawbacks, application notes, limitations, scaling considerations, installation complexity, and costs are addressed.

II. THEORETICAL BACKGROUND

The stator-winding-to-rotor-core capacitance plays an important role in the occurrence of noncirculating bearing currents. A reduction in the capacitance should obviously increase the overall impedance of the stray current circuit, reduce the voltage between the bearing raceways, and prevent bearing lubricant breakdown, which usually leads to EDM current and harmful pitting on bearing raceways.

In the following, the stator-winding-to-rotor-core capacitance \( C_{\text{wr}} \) will be in the focus of the study, and the method for mitigation of this capacitance is the main contribution of this article.

Fig. 2 illustrates a simple plate capacitor equivalent circuit of an electrical machine’s stator slot. The winding and the rotor surface can be considered electrodes of the capacitor, whereas the winding insulation and the air gap represent the dielectric between these electrodes. This structure offers a path for high-frequency current components. This capacitive coupling is increased by the contribution of the winding overhang. This contribution is taken into account in the calculations.

As suggested in [31], an effective reduction in the bearing current can be reached by partial electrostatic shielding. Then, capacitive current will bypass the rotor and the bearing. This can be implemented by introducing a grounded electrode in the slot opening, as shown in Fig. 3.

The electrode is supposed to act as a partial electrostatic shield. A similar shielding design was proposed in [23] and the approach found a promising countermeasure for EDM current suppression [24]–[27]. The present article is aimed to further investigate the influence of the shield design options, provide a calculation technique, and contribute to the numerical data related to an industrial electrical machine.

When the electrode is placed into the slot opening or the slot key, the original stator-winding-to-rotor-core capacitance is split into two capacitances in series: the winding-to-electrode \( C_{\text{wr}} \) and the rotor-to-electrode \( C_{\text{er}} \). Additionally, because the grounded electrode does not cover all the gaps between the stator teeth, some residual stator-winding-to-rotor-core capacitance \( C_{\text{wr}}' \) remains as a parallel path, Fig. 3. When using metallic bearings, at certain periods, the rotor has a galvanic connection with the ground. Thus, the rotor side of the equivalent capacitor in Figs. 2 and 3 is grounded. However, if the newly introduced conductor was also grounded (Fig. 3), the capacitive current would not flow through the rotor anymore because a low-impedance bypass is provided. Even though some part of the current may still flow through the remaining \( C_{\text{wr}}' \), its value would be significantly reduced as \( C_{\text{wr}}' << C_{\text{wr}} \).

The electrodes are introduced in all stator slot openings and connected to the ground terminal at one end. Connecting the electrodes at only one end prevents the formation of closed loops, which could result in the appearance of a squirrel cage effect and extra eddy current losses [31], [40]. Fig. 4 shows a machine stator equipped with grounded electrodes. Different designs and positions of the electrode system were presented in [31]. In this study, however, the simplest option with a single-wire electrode was chosen for a detailed analysis and empirical verification of the method.

A common parameter to evaluate the potential risk of bearing currents is the BVR. Together with the supply voltage, the voltage across the bearing can be determined with the BVR known. The BVR is the ratio between the bearing voltage \( U_b \) and the common-mode voltage at the motor terminals \( U_{\text{cm}} \). BVR can be defined with the machine capacitances [2], [41]:

\[
\text{BVR} = \frac{U_b}{U_{\text{cm}}} = \frac{C_{\text{wr}}}{C_{\text{wr}} + C_{\text{er}} + 2C_b} \tag{1}
\]

where \( U_b \) is the voltage between the shaft and the grounding, \( U_{\text{cm}} \) is the common-mode voltage, and \( C_{\text{wr}} \), \( C_{\text{er}} \), and \( C_b \) are the stator-winding-to-rotor-core, stator-core-to-rotor-core, and bearing capacitance, respectively.
Fig. 4. Concept of grounded electrodes mounted in slots. (a) grounded electrode and (b) stator stack with electrodes installed. The electrodes can be joined either by a ring at the stack end and grounded together or separately. 1: electrodes, 2: common collecting conductor (ring), 3: wire to the network PE terminal, and 4: stator.

Fig. 5. Equivalent circuit of the main capacitances of an ac motor: left – regular ac motor, right – the motor equipped with stator grounded electrodes. The elements making up the capacitive voltage divider are highlighted in both circuits.

Equation (1) can be explained by using the equivalent circuit of the machine capacitances shown in Fig. 5, left [2], [37]. The figure demonstrates that the parasitic capacitances form a capacitive voltage divider. A share of the high-frequency common-mode voltage is observed over the bearing as the bearing voltage $U_b$.

When grounded electrodes are applied, the equivalent circuit must be changed accordingly. The electrodes cause the stator-winding-to-rotor-core capacitance $C_{wr}$ of the regular machine (Fig. 2) to be replaced with the series-connected capacitances $C_{we}$ and $C_{er}$ and the parallel residue capacitance $C_{wr}^*$ (Fig. 3). The equivalent circuit of the modified machine is shown on the right in Fig. 5. When defining the BVR based on the capacitive voltage divider principle, the equation for the modified machine is written as

$$BVR = \frac{U_b}{U_{cm}} = \frac{C_{wr}^*}{C_{wr} + C_{sr} + 2C_b + C_{er}}$$  

where $C_{wr}^*$ is the residual stator-winding-to-rotor-core capacitance and $C_{er}$ is the capacitance between the rotor core and the electrode introduced in the slot opening. The term $C_{we}$ is not presented in the BVR equation because this capacitance stays in parallel with the voltage divider and does not affect the ratio.

In theory, the BVR is defined with the machine capacitances. In practice, the capacitances cannot be directly measured. The problem in measurements is that in a real machine there is always extra stator-to-frame capacitance $C_{sf}$ in parallel, which cannot be eliminated. It is, e.g., ~10 nF with 15 kW machines, while $C_{wr}$ is only 100–200 pF (1–2% of $C_{sf}$). The limited accuracy of inductance, capacitance, and resistance meters (so-called “LCR meters”) and uncertainties in measurements make the practical measurement of $C_{wr}$ difficult. However, the machine stray capacitances can be found according to the circuit relationship as described in [42]. Alternatively, the BVR can be defined as a ratio of the bearing voltage to the common-mode voltage [41], [43]. Both methods were utilized in the present work.

III. EXPERIMENTAL EVALUATION

The quantitative evaluation of the proposed approach was performed by a study of a 15 kW 4-pole 36-slot ABB M3BP160 MLB4-series induction motor.

A. FEM-Based Evaluation of the Method

Preliminary results were obtained by a FEA, performed in the FEMM v.4.2 software. The modeling approach introduced in [31] was applied. The slot dimensions used in the computation are shown in Fig. 6. The lamination stack length is 272 mm.

In the study, the capacitances $C_{wr}$ and $C_{sr}$ were estimated for an unmodified machine and for a machine equipped with slot electrodes. The capacitances calculated for the whole machine and the BVRs obtained are collected in Table II. The BVRs were calculated using (1) for the original machine and (2) for the machine with grounded electrodes. In the BVR calculation, the ceramic bearing capacitance $C_b$ was measured to be 27 pF.

The two-dimensional (2-D) FEM results only correspond to the lamination stack region and ignore the contribution of the end windings. According to [44], in 15 kW machines, the proportion of the end winding is about 40% of the total stator-winding-to-rotor-core capacitance. Therefore, the end winding capacitance $C_{wr,ew}$ can be found from the core-area capacitance $C_{wr,core}$ of
the slots and a general view of the modified machine.

Fig. 7. Left: The stator slots with grounded electrodes added. Right: A general view of the modified machine. 36 wires coming from the stator openings. In serial manufacturing, introducing electrodes into the stator region. The electrodes were fixed in the middle of the slot openings. In serial manufacturing, introducing electrodes into the slot openings. In serial manufacturing, introducing electrodes into the slot openings. In serial manufacturing, introducing electrodes into the slot openings. In serial manufacturing, introducing electrodes into the slot openings.

the original machine multiplied by a factor of 40/60, resulting in $C_{\text{sr, core}} = 84 \, \text{pF}$.

In Table II, the 2-D FEM-calculated capacitances that do not take the end-winding region into account are indicated by the subscript “core”, $C_{\text{wr, core}}$. The updated stator-winding-to-rotor-core capacitance in which the lamination stack and the end-winding regions are considered is denoted by $C_{\text{wr}}$ in Table II and later on in the article. The stator-core-to-rotor-core capacitance is not affected by the end windings; and therefore, there is no need for a similar correction in $C_{\text{sr}}$. The data are analyzed further in the discussion section.

B. Verification With a Real Electrical Machine

A study on a real machine was carried out in the laboratory. First, the BVR of the 15 kW motor equipped with ceramic ball bearings was measured. Then, the motor was equipped with enamelled copper wire slot electrodes with a diameter of 0.3 mm. The electrodes were placed on the slot insulation along the lamination stack length. They did not cover the end-winding region. The electrodes were fixed in the middle of the slot openings. In serial manufacturing, introducing electrodes into the slot keys would be reasonable. At the drive end of the core, the electrodes were only cut making sure that they did not have any galvanic contact to the stator core. At the nondrive end, the electrodes were connected to the ground terminal. Fig. 7 shows the slots and a general view of the modified machine.

Values indicated by $*$ are found as $C_{\text{wr, core}} + C_{\text{wr, ew}}$.

Values indicated by ' correspond to $C_{\text{er}}$ of Fig. 3.

### Table II

| Motor type                      | $C_{\text{wr,core}}$ [pF] | $C_{\text{wr}}$ [pF] | $C_{\text{er}}$ [nF] | $C_{\text{sr}}$ [pF] | BVR [%] |
|---------------------------------|----------------------------|----------------------|---------------------|---------------------|---------|
| Regular motor; no grounded electrodes | 126                        | 210*                 | 2.61                | –                   | 7.32    |
| Modified motor; grounded electrodes applied. Electrode diameters: | | | | | |
| 0.1 mm                          | 88.1                       | 172**                | 2.61                | 229.6               | 5.63    |
| 0.3 mm                          | 69.5                       | 154**                | 2.60                | 364.8               | 4.84    |
| 0.5 mm                          | 55.6                       | 140**                | 2.60                | 495.3               | 4.25    |
| 0.75 mm                         | 41.8                       | 126**                | 2.59                | 680.0               | 3.64    |
| 1.0 mm                          | 30.2                       | 114**                | 2.59                | 912.5               | 3.11    |

### Table III

| Motor type                      | $C_{\text{sr}}$ or $C_{\text{sr}}^*$ [pF] | $C_{\text{er}}$ [nF] | $C_{\text{sr}} + C_{\text{ew}}$ [nF] | BVR [%] |
|---------------------------------|------------------------------------------|---------------------|-----------------------------------|---------|
| Regular motor; no grounded electrodes | 180.7                                    | 2.08                | –                                 | 7.8     |
| Modified motor; grounded electrodes with a diameter of 0.3 mm are applied. | 63.3*                                     | –                   | 2.25                              | 2.7     |

Value indicated by $*$ is correspond to $C_{\text{er}}$ of Fig. 3.

#### 1) Verification With Machine Capacitances Measured:

In a similar way as it was done in the theoretical stage, the BVRs were found for both the original and modified machines using the actual values of the capacitances employed in (1) and (2). As was abovementioned, straightforward measurement of the machine stray capacitances is not possible, and the technique presented in [42] was repeated in this work to establish the desired values. The initial measurements were performed with disconnected motors at a standstill state using an Agilent U1733C LCR measuring device and a measurement frequency of 1 kHz. The measurement results were further processed using the formulas proposed in [42].

The capacitances of $C_{\text{wr}}$ and $C_{\text{sr}}$, which have to be known for the BVR calculation of the original machine (1), were found by using the algorithm and equations given in [42]. The equation of the BVR for the modified machine (2) has an extra term of $C_{\text{er}}$. The process of finding the values of $C_{\text{er}}$ and $C_{\text{sr}}$ in such a machine requires development of a new calculation approach. However, in Fig. 5 (right), the capacitances $C_{\text{sr}}$ and $C_{\text{er}}$ are connected in parallel, and thus, the equation numbered (8) in [42] can be used to determine the total value of $C_{\text{sr}} + C_{\text{er}}$.

The bearing capacitance was measured to be $C_{\text{b}} = 27 \, \text{pF}$. The results are presented in Table III.

#### 2) Verification With the Bearing Voltage to the Common-Mode Voltage Ratio:

In the no-load test, when the machine was supplied by an ABB ACS400 frequency converter, the BVR was defined as $U_{\text{b}} / U_{\text{cm}}$ using (1) or (2). Because of the stator delta connection, an artificial star for measuring $U_{\text{cm}}$ was formed with three 10 MΩ resistors. To facilitate shaft voltage measurement, ceramic ball bearings were used. $U_{\text{b}}$ and $U_{\text{cm}}$ were measured with Rohde & Schwarz RT-ZD01 differential probes. The laboratory setup is illustrated in Figs. 8 and 9.

Fundamental frequencies of 10, 20, 30, and 40 Hz were used. Examples of the shaft voltage waveforms taken from the original and modified machines at the 20 Hz supply frequency are shown in Fig. 10. Examples of the common-mode voltage waveforms for both motors are shown in Fig. 11. The waveforms taken for 10, 30, and 40 Hz fundamental frequencies are almost identical to the ones shown for 20 Hz.

The shaft voltage measured from the modified motor has a notably lower amplitude than in the regular motor. The amplitude of the common-mode voltage, as seen in Fig. 11, remains at the same level for both motors.

$U_{\text{b}}$ and $U_{\text{cm}}$ peak values were used in the analysis. The measured BVRs and the obtained average BVR value are shown...
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Fig. 8. Left: Laboratory setup; 1: multichannel oscilloscope Yokogawa DL850, 2: artificial neutral point connection, 3: motor under test, 4: Rohde & Schwarz RT-ZD01 differential probe for the shaft voltage measurement, 5: Rohde & Schwarz RT-ZD01 differential probe for the common-mode voltage measurement, 6: brush connection to the shaft, and 7: slot electrodes collected at the external terminal block, connected to the frame and further to the ground terminal of the system. Right: ABB ACS400 frequency converter was used to supply both the original and the modified motor.

Fig. 9. Laboratory setup; 1: Yokogawa DL850, 2: artificial neutral point connection, 3: motor, 4: differential probe for $U_b$, 5: differential probe for $U_{cm}$, 6: brush connection, 7: electrode terminal box, 8: 36 electrodes. The parts indicated by red show the elements added to the modified motor.

Fig. 10. Measured shaft voltage at the 20 Hz fundamental PWM supply for the regular and modified 15 kW induction motors.

Fig. 11. Measured common-mode voltage at 20 Hz for the regular and modified 15 kW induction motors.

Fig. 12. BVR and $C_{wr}/C_{wr,nom}$ as a function of the diameter of the grounded electrode placed on the slot key. $d = 0$ corresponds to the original motor.

TABLE IV
| Supply frequency, [Hz] | BVR [%], peak-to-peak | Modified machine |
|------------------------|------------------------|------------------|
| 10                     | 7.13                   | 3.97             |
| 20                     | 7.15                   | 3.98             |
| 30                     | 7.13                   | 3.92             |
| 40                     | 7.05                   | 3.93             |
| Average value          | 7.1                    | 3.95             |

...in Table IV. On average, a 44% reduction in the BVR was achieved with this simple test approach.

IV. D I S C U S S I O N

Fig. 12 shows FEA results for both the BVR and $C_{wr}/C_{wr,nom}$ as a function of electrode diameter. $C_{wr,nom}$ is the stator-winding-to-rotor-core capacitance of the unmodified motor.

Introducing even a thin grounded electrode gives a significant reduction in $C_{wr}$ and a corresponding reduction in the BVR. According to Fig. 12, when 0.1 mm electrodes are mounted on the slot keys, the BVR decreases by almost 25% (from BVR = 7.32% to BVR = 5.63%). A further increase in the electrode diameter reduces the BVR more, but less dramatically.

In the laboratory tests, the machine was equipped with 0.3 mm slot-key-surface electrodes. The measurement results, given in Tables III and IV, show a decreasing BVR trend and are in line with theory. Fig. 13 compares the experimentally obtained BVRs with the values given by the 2-D FEM-based approach.

In the case of an electrode diameter of 0.3 mm, the difference between the calculated and measured BVRs was 44% when the measured capacitances were used and 18% when the BVR was...
obtained by using the common-mode and shaft voltage amplitudes. The analytical calculations underestimated the effect. The main reasons that may cause an error in the calculation results are as follows:

1) Inaccurate motor geometry; it was measured by the authors. A ±0.5 mm error in dimensions is possible.
2) Simplified representation of the winding: the winding was modeled as a solid piece of copper instead of thin copper wires.
3) Share of the end winding, which is taken as 40%, is a rough estimation and can vary depending on the design.
4) In the FEM calculations, meshing and numerical issues may also contribute to the error.

Furthermore, when the capacitance measurement was performed, the limited accuracy of the RLC meter and the measurement issues mentioned at the end of Section II also contribute to the error. Based on that, the BVR measurement performed as a ratio of shaft-to-common voltages is preferable in practical cases.

However, the results have an acceptable accuracy and a matching trend. The behavior of the BVR and $C_{wr}$, caused by the varying electrode diameter shown in Fig. 12 obtained by an analytical approach, can be considered verified in practice. The calculation method can be applied in similar studies.

As stated in [3], [45], the bearing EDM threshold voltage is usually 10–30 V, and can be only 5 V in the smallest machines [46]. The bearing voltage peak value of the tested 15 kW machine modified with the 0.3 mm diameter wire had $U_b = 10$ V and can be considered relatively safe.

Different designs of electrostatic shields tested by different authors on the machines in the range of 3–37 kW [23]–[26] give a bearing voltage reduction of 50%–70%. In our test bench, a reduction in $U_b$, from the peak value of 20 to 10 V, i.e., a 50% reduction, was obtained. With the change in the wire diameter, this number is expected to vary together with the BVR as shown in Fig. 12, i.e., with a growing wire diameter, the effectiveness of $U_b$ reduction should also increase.

Applying the presented approach to frequency-converter-supplied electrical machines could increase the overall reliability of the system by a significant reduction in the noncirculating bearing currents. Even though the introduction of complicated structures (as in [31]) or extra wedges (as in [30]) into the slot opening definitely require special tools and skills, introducing only one thin electrode seems efficient and can be considered a possible practical modification in electrical machines. The installation of grounded electrodes requires minimum space in an electrical machine and in most cases, regardless of the machine size, it can be implemented in the existing winding position while the slot copper space factor remains unchanged.

In the test machine presented in this article, the electrode with a diameter of 0.3 mm was successfully placed in the existing 1 × 3.5 mm slot opening. The simplicity and low cost of the machine modification are among the advantages of the proposed approach.

The approach presented here has about the same bearing current reduction potential as the approach of introducing extra wedge insulation presented in [30]. A FEM-based computation, conducted for both approaches with the same machine geometry, gives almost equal BVR reduction indicators. During verification with an actual machine, it turned out that the modification proposed in the present article reduces the shaft voltage amplitude to the same level as the application of thicker wedges. Taking this into account, the choice between the proposed method or countermeasures suggested in [30] should mainly be made on the basis of considerations other than the degree of reduction in the BVR.

The approach is highly applicable to machines of different power ratings. With different machine sizes, the size of the slot opening varies accordingly. In larger machines, several thin wires can be integrated into the slot key to achieve a significant reduction in the BVR. To keep the desired BVR reduction rate in machines of different sizes, the diameter and number of wires in one slot opening should be adjusted individually in each case.

As suggested in [23], the utilization of electrostatic shields, which affect both the core area and the end windings, provides an opportunity to reduce the bearing voltage by 100%. Special end windings shields, such as [47], used in parallel with the method presented here, are expected to give the maximum possible bearing voltage reduction.

In large scale motors—with a shaft height larger than 280 mm (over 100 kW)—the suggested countermeasure should not be considered the main method because according to the literature, EDM bearing currents are not dominant compared with circulating bearing currents in high-power inverter motors.

One drawback of the proposed method is a possible minor increase in the circulating bearing currents as the occurrence of capacitive current from the winding to the slot key electrode is easier. However, $C_{wr}$ is much smaller than $C_{ws}$, and thus, its contribution to the circulating bearing currents is also negligibly small.

Another concern is that, in principle, electrode eddy currents can produce some extra losses. To minimize losses, the thinnest possible wire or a set of parallel insulated wires should be used [6].

Because copper wires have magnetic permeability close to unity, and because the magnetic flux is mainly concentrated in the stator teeth [24], the proposed mitigation method for bearing currents would not cause any negative effect on the
magnetic circuit and torque production characteristics of the machine.

Finally, a proper ground connection of the electrodes on the slots must be maintained. Using the modified machine with nongrounded slot electrodes would have a negative effect, which slightly increases the BVR. In the example case of the 15 kW machine, the BVR increased from 7.1 to 7.3% with disconnected electrodes.

V. Conclusion

A method for suppressing noncirculating bearing currents, based on reducing the winding-to-rotor capacitance by installing grounded electrodes on slot keys, was studied. Based on 2-D-FEM computations, it was shown with a 15 kW industrial motor that installing only one thin grounded electrode on the slot key effectively reduced the stator-winding-to-rotor-core capacitance that could be concluded that introducing grounded electrodes is an effective countermeasure against capacitive bearing currents.

Even though the presented countermeasure could already be employed as a ready-to-use solution, the full potential of the approach has not yet been reached. The field reports and long-time running test results of the drive systems equipped with the proposed shielding system were of great interest.

Further studies into bearing current suppression techniques that work on the electrostatic shielding principle would be required to design a shielding system capable of reducing also capacitive coupling caused by the end-winding region. Finally, the question of the effectiveness and feasibility of the use of several different bearing current suppression techniques at a time was an open question and should be investigated in the future work.

REFERENCES

[1] J. Pyrhönen, V. Hrabovcova, and R. Scott Semken, Electrical Machine Drives Control: An Introduction, Hoboken, NJ, USA: Wiley, 2016, ch. 13.

[2] A. Muetze, “Bearing currents in inverter-fed AC-motors,” Ph.D. dissertation, Dept. Elect. Comput. Eng., Tech. Univ. Darmstadt, Darmstadt, Germany, 2004.

[3] T. Pfaznet, T. Boileau, C. Caironi, and B. Nahid-Mobarakeh, “A comprehensive study on shaft voltages and bearing currents in rotating machines,” IEEE Trans. Ind. Appl., vol. 54, no. 4, pp. 3749–3759, Jul./Aug. 2018.

[4] A. Muetze and A. Binder, “Calculation of circulating bearing currents in machines of inverter-based drive systems,” IEEE Trans. Ind. Electron., vol. 54, no. 2, pp. 932–938, Apr. 2007.

[5] S. Chen, T. A. Lipo, and D. W. Novotny, “Circulating type motor bearing current in inverter drives,” Ind. Appl. Mag., vol. 4, no. 1, pp. 32–38, 1998.

[6] P. Maki-Ontto and J. Laomii, “Bearing current prevention of converter-fed AC machines with a conductive shielding in stator slots,” in Proc. IEEE Int. Elect. Mach. Drives Conf., 2003, vol. 1, pp. 274–278.

[7] Variable Speed Drives & Motors. Motor Shaft Voltages and Bearing Currents Under PWM Inverter Operation, 2nd ed., 2006.

[8] A. Muetze, V. Niskanen, and J. Ahola, “On radio-frequency-based detection of high-frequency circulating bearing current flow,” IEEE Trans. Ind. Appl., vol. 50, no. 4, pp. 2592–2601, Jul./Aug. 2014.

[9] AEGIS, “What is the effect of PWM drives on electric motor bearings?,” Feb. 2018, [Online]. Available: https://est-aegis.info/tag/common-mode-voltage/, Accessed: Sep. 20, 2020.

[10] R. K. Dhatrak, R. K. Nema, S. K. Dash, and D. M. Deshpande, “Mitigation of bearing current and shaft voltage using five level inverter in three phase induction motor drive with SPWM technique,” in Proc. Int. Conf. Ind. Instruct. Control, 2015, pp. 1184–1189.

[11] D. Han, C. T. Morris, M. Li, and B. Sarlioglu, “Common-mode voltage cancellation in PWM motor drives with balanced inverter topology,” IEEE Trans. Ind. Electron., vol. 64, no. 4, pp. 2683–2688, Apr. 2017.

[12] C. T. Morris, D. Han, and B. Sarlioglu, “Reduction of common mode voltage and conducted EMI through three-phase inverter topology,” IEEE Trans. Power Electron., vol. 32, no. 3, pp. 1720–1724, Mar. 2017.

[13] H. Chen and H. Zhao, “Review on pulse-width modulation strategies for common-mode voltage reduction in three-phase voltage-source inverters,” IET Power Electron., vol. 9, no. 14, pp. 2611–2620, Nov. 2016.

[14] A. M. Hava and E. Un, “A high-performance PWM algorithm for common-mode voltage reduction in three-phase voltage source inverters,” IEEE Trans. Power Electron., vol. 26, no. 7, pp. 1998–2008, Jul. 2011.

[15] R. M. Tallam, R. J. Kerkman, D. Leggate, and R. A. Lukaszewski, “Common-mode voltage reduction PWM algorithm for AC drives,” IEEE Trans. Ind. Appl., vol. 46, no. 5, pp. 1959–1969, Sep./Oct. 2010.

[16] A. K. Ryszard Strzelecki and R. Smolenski, “Reduction of the bearing current in PWM motor drives by means of common mode voltage cancellation,” in Proc. 6th Int. Conf. Power Qual. Utilization, 2001, pp. 439–444.

[17] J. P. Srom, J. Tyster, J. Korhonen, M. Puthonen, and P. Silventoinen, “Active du/dt filter dimensioning in variable speed AC drives,” in Proc. 14th Eur. Conf. Power Electron. Appl., 2011, pp. 1–7.

[18] W. Wu, Y. Jiang, Y. Liu, M. Huang, Y. He, and S.-H. Chung, “A new passive filter design method for overvoltage suppression and bearing currents mitigation in a long cable based PWM inverter-fed motor drive system,” in Proc. IEEE 8th Int. Power Electron. Motion Control Conf., 2016, pp. 3103–3110.

[19] J. Kalaiselvi and S. Srinivas, “Passive common mode filter for reducing shaft voltage, ground current, bearing current in dual two level inverter fed open end winding induction motor,” in Proc. Int. Conf. Optin. Elect. Electron. Equip., 2014, pp. 595–600.

[20] N. Zhu, J. Kang, D. Xu, B. Wu, and Y. Xiao, “An integrated AC choke design for common-mode current suppression in neutral-connected power converter systems,” IEEE Trans. Power Electron., vol. 27, no. 3, pp. 1228–1236, Mar. 2012.

[21] A. Muetze, “Scaling issues for common-mode chokes to mitigate ground currents in inverter-based drive systems,” IEEE Trans. Ind. Appl., vol. 45, no. 1, pp. 286–294, Jan./Feb. 2009.

[22] H. W. Oh, “Common mode chokes or cores (CMCs) cannot prevent bearing failure in all motors,” in Proc. Motor Drive Syst. Conf., Jan. 2017, pp. 253–257.

[23] D. F. Busse, J. M. Erdman, R. J. Kerkman, D. W. Schlegel, and G. L. Skibinski, “An evaluation of the electrostatic shielded induction motor: A solution for rotor shaft voltage buildup and bearing current,” IEEE Trans. Ind. Appl., vol. 33, no. 6, pp. 1563–1570, Nov./Dec. 1997.

[24] F. J. T. E. Ferreira, M. V. Cistelecan, and A. T. de Almeida, “Evaluation of slot-embedded partial electrostatic shield for high-frequency bearing current mitigation in inverter-fed induction motors,” IEEE Trans. Energy Convers., vol. 27, no. 2, pp. 382–390, Jun. 2012.

[25] J. Quan, B. Bai, Y. Wang, and W. Liu, “Research on electrostatic shield for discharge bearing currents suppression in variable-frequency motors,” in Proc. 17th Int. Conf. Elect. Mach. Syst., 2014, pp. 139–143.

[26] S. Gerber and R. Wangi, “Reduction of inverter-induced shaft voltages using electrostatic shielding,” in Proc. Southern African Universities Power Eng. Conf./Robot. Mechatronics/Pattern Recognit. Assoc. South African , 2011, pp. 310–315.

[27] B. Heidler, K. Brune, and M. Doppelbauer, “Design aspects of an electrostatic shield in an electric machine for hybrid electric vehicles,” in Proc. 8th IET Int. Conf. Power Electron. Mach. Drives, 2016, pp. 1–6.

[28] J. Park, T. R. Wellawatta, S. Choi, and J. Hur, “Mitigation method of the shaft voltage according to parasitic capacitance of the PMSM,” IEEE Trans. Ind. Appl., vol. 53, no. 5, pp. 4441–4449, Sep./Oct. 2017.

[29] A. V. Kuntz, “A slot-wedge of an electric machine, by J. Pyrhönen, Nov. 2018. WO2018211174. [Online]. Available: https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2018211174, Accessed on: May 13, 2020.

[30] K. Vostrov, J. Pyrhönen, M. Niemelä, J. Ahola, and P. Lindh, “Mitigating noncirculating bearing currents by a correct stator magnetic circuit and winding design,” IEEE Trans. Ind. Electron., 2020.

[31] K. Vostrov, J. Pyrhönen, J. Ahola, and M. Niemelä, “Non-circulating bearing currents mitigation approach based on machine stator design options,” in Proc. 13th Int. Conf. Elect. Mach., 2018, pp. 866–872.
appropriate countermeasures.

 bearing current phenomena in electrical dives and development of the

of Technology LUT. His major research interest is the investigation of the

11760 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 68, NO. 12, DECEMBER 2021

A. Muetze and A. Binder, “Calculation of motor capacitances for pre-

“Dynamoelectric machines with shaft voltage prevention method and

et al.

J. A. Oliver, G. Guerrero, and J. Goldman, “Ceramic bearings for electric

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