Mitigation of inverter-induced noncirculating bearing currents by introducing grounded electrodes into stator slot openings

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Mitigation of inverter-induced noncirculating bearing currents by introducing grounded electrodes into stator slot openings


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 paper 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 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, 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 \(C_{wr}\), the stator-winding-to-stator-core capacitance \(C_{ws}\), the stator-core-to-rotor-core capacitance \(C_{sr}\), and the capacitance of the bearing \(C_b\).

Different types of bearing currents are recognized. Two main groups can be distinguished: circulating (also called inductive or classical) and noncirculating (also called capacitive or electrical discharge machining, EDM) currents. Fig. 1 illustrates the stray current paths for both types of bearing current. In modern machines, the dominating type of bearing current typically depends on the frame size. Smaller machines often suffer from EDM currents and larger from circulating currents, respectively. Among the above-mentioned 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 paper, 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], [5].

Another factor contributing to circulating bearing currents is a high common-mode \(\frac{du}{dt}\) 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 \( \frac{dU}{dt} \) 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 pulse-width-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-the-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, \( \frac{dU}{dt} \) 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.

**TABLE I**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Effectiveness*</th>
<th>Drawbacks</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special modulation strategies [11], [12]</td>
<td>Good: 60% reduction</td>
<td>Limited by the hardware options</td>
<td>Low</td>
</tr>
<tr>
<td>New circuit layouts for converters [7]–[9]</td>
<td>Excellent: possible to reach complete elimination</td>
<td>Requires new layout development and adding new components</td>
<td>High</td>
</tr>
<tr>
<td>Common-mode voltage filter [2], [7], [16]</td>
<td>Good: 70–100% reduction</td>
<td>Difficulties in the installation may arise</td>
<td>High</td>
</tr>
<tr>
<td>Ceramic (hybrid) bearings [2]</td>
<td>Excellent: up to complete elimination</td>
<td>Reduced mechanical load rating, may also require insulated coupling for the connection of a load machine</td>
<td>High</td>
</tr>
<tr>
<td>Conductive grease [33]</td>
<td>Average: 50% reduction</td>
<td>Lubrication effectiveness reduced</td>
<td>Moderate</td>
</tr>
<tr>
<td>Rotor grounding brushes [35], [39]</td>
<td>Good: 80% reduction</td>
<td>Requires service</td>
<td>Low</td>
</tr>
<tr>
<td>Electrostatically shielded rotor [23], [31]</td>
<td>Good: reduction of 50–100%</td>
<td>Mounting complexity</td>
<td>High</td>
</tr>
<tr>
<td>Brushless grounding device [38]</td>
<td>Good: 80% reduction</td>
<td>Requires significant space for installation; produces extra losses by air friction</td>
<td>Moderate</td>
</tr>
<tr>
<td>Bearing protection microfiber ring [36]</td>
<td>Good: 50–90% reduction</td>
<td>Must be properly installed; still requires service</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

* The percentages given refer to reduction in the EDM current peak amplitude, where 0% means no effect, 100% means complete elimination.

The present paper 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, the paper is concluded by an evaluation of the feasibility of the approach.

Unlike the previous study [31], the present paper considers an actual electrical machine and verifies the theoretical findings by laboratory experiments. In this paper, a refined FEA is
applied. The paper 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 $C_{wr}$ will be in the focus of the study, and the method for mitigation of this capacitance is the main contribution of this paper.

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.

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 paper 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 $C_{we}$ and the rotor-to-electrode $C_{re}$. Additionally, because the grounded electrode does not cover all the gaps between the stator teeth, some residual stator-winding-to-rotor-core capacitance $C_{wr}'$ 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 were 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 $C_{wr}'$, its value would be significantly reduced as $C_{wr}' << C_{wr}$.

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 bearing voltage ratio (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 $U_{cm}$. BVR can be defined with the machine capacitances [2], [41]:

$$BVR = \frac{U_b}{U_{cm}} = \frac{C_{wr}}{C_{wr} + C_{sr} + 2C_b} \quad (1)$$

where $U_b$ is the voltage between the shaft and the grounding, $U_{cm}$ is the common-mode voltage, and $C_{wr}$, $C_{sr}$, and $C_b$ are the stator-winding-to-rotor-core, stator-core-to-rotor-core, and bearing capacitance respectively.
Capacitances shown on the right in Fig. 5. When defining the BVR based on voltage is observed over the bearing as the bearing voltage divider. A share of the high-frequency common-mode machine (Fig. 2) to be replaced with the series-connected modified machine is written as the capacitive voltage divider principle, the equation for the stator-winding-to-rotor-core capacitance 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 $U_b$.

The 2D 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 original machine multiplied by a factor of 40/60, resulting in $C_{wr,ew} = 84\text{ pF}$.}

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 finite element analysis, 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 Table II, the 2D FEM-calculated capacitances that do not take the end-winding region into account are indicated by the subscript "core", $C_{wr, core}$. The updated stator-winding-to-rotor-core capacitance in which the lamination stack and the end-winding regions are considered is denoted by $C_{sr}$ in Table II and later on in the paper. 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 $C_{wr}$. The data are analyzed further in the Discussion section.

**Table II**

<table>
<thead>
<tr>
<th>Motor type</th>
<th>$C_{wr, core}$</th>
<th>$C_{wr}$</th>
<th>$C_{sr}$</th>
<th>$C_{BVR}$</th>
<th>BVR, [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular motor; no grounded electrodes</td>
<td>126</td>
<td>210*</td>
<td>2.61</td>
<td>–</td>
<td>7.32</td>
</tr>
<tr>
<td>Modified motor; grounded electrodes applied. Electrode diameters:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 mm</td>
<td>88.1</td>
<td>172*</td>
<td>2.61</td>
<td>229.6</td>
<td>5.63</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>69.5</td>
<td>154*</td>
<td>2.60</td>
<td>364.8</td>
<td>4.84</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>55.6</td>
<td>140*</td>
<td>2.60</td>
<td>495.3</td>
<td>4.25</td>
</tr>
<tr>
<td>0.75 mm</td>
<td>41.8</td>
<td>126*</td>
<td>2.59</td>
<td>680.0</td>
<td>3.64</td>
</tr>
<tr>
<td>1.0 mm</td>
<td>30.2</td>
<td>114*</td>
<td>2.59</td>
<td>912.5</td>
<td>3.11</td>
</tr>
</tbody>
</table>

Values indicated by * are found as $C_{sr}-C_{er}$. Values indicated by * correspond to $C_{er}$ of Fig. 3.

**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 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 non-drive end, the electrodes were connected to the ground terminal. Fig. 7 shows the slots and a general view of the modified machine.

![Fig. 7](image)

**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 mentioned above, 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 RLC measuring device and a measurement frequency of 1 kHz. The measurement results were further processed using the formulas proposed in [42].

The capacitances of $C_{wr}$ and $C_{er}$, 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 $C_{er}$. The process of finding the values of $C_{er}$ and $C_{sr}$ in such a machine requires development of a new calculation approach. However, in Fig. 5 (right), the capacitances $C_{wr}$ and $C_{sr}$ are connected in parallel, and thus, the equation numbered (8) in [42] can be used to determine the total value of $C_{wr}+C_{sr}$.

The bearing capacitance was measured to be $C_b = 27\mu F$. The results are presented in Table III.

**Table III**

<table>
<thead>
<tr>
<th>Motor type</th>
<th>$C_{wr}$ or $C_{sr}$</th>
<th>$C_{er}$</th>
<th>$C_{sr} \pm C_{er}$</th>
<th>BVR, [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular motor; no grounded electrodes</td>
<td>180.7</td>
<td>2.08</td>
<td>–</td>
<td>7.8</td>
</tr>
<tr>
<td>Modified motor; grounded electrodes with a diameter of 0.3 mm are applied</td>
<td>63.3*</td>
<td>–</td>
<td>2.25</td>
<td>2.7</td>
</tr>
</tbody>
</table>

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

**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 bearing voltage ratio was defined as $U_b / U_{cm}$ using (1) or (2). Because of the stator delta connection, an artificial star for measuring $U_{cm}$ was formed with three 10 MΩ resistors. To facilitate shaft voltage measurement, ceramic ball bearings were used. $U_b$ and $U_{cm}$ were measured with Rohde&Schwarz RT-ZD01 differential probes. The laboratory setup is illustrated in Figs. 8 and 9.
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.

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.

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

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.

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

$U_b$ and $U_{cm}$ peak values were used in the analysis. The measured BVRs and the obtained average BVR value are shown in Table IV. On average, a 44% reduction in the BVR was achieved with this simple test approach.

<table>
<thead>
<tr>
<th>Supply frequency, [Hz]</th>
<th>BVR [%], peak-to-peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular machine</td>
</tr>
<tr>
<td>10</td>
<td>7.13</td>
</tr>
<tr>
<td>20</td>
<td>7.15</td>
</tr>
<tr>
<td>30</td>
<td>7.13</td>
</tr>
<tr>
<td>40</td>
<td>7.05</td>
</tr>
<tr>
<td>Average value</td>
<td>7.1</td>
</tr>
</tbody>
</table>

IV. DISCUSSION

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.

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.

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 2D FEM-based approach.

Fig. 13. BVR computed and measured for the original and modified motor with 0.3 mm electrodes on the slot keys.
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:

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 $C_{ws}$, 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 V 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 paper, the electrode with a diameter of 0.3 mm was successfully placed in the existing $1 \times 3.5$ 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 paper 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 2D-FEM computations, it was shown with a 15 kW industrial motor that installing only one thin grounded electrode on the slot key effectively reduces the stator-winding-to-rotor core capacitance responsible for the noncirculating bearing currents. Increasing the electrode diameter results in a minor additional reduction in the BVR.
A four-pole 15 kW industrial induction motor was modified and tested. The practical results are in line with the computed values. Based on both a theoretical analysis and laboratory tests, it can be concluded that introducing grounded electrodes is an effective countermeasure against capacitive bearing currents.

Even though the presented countermeasure can 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 are 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 is an open question and should be investigated in the future work.

VI. REFERENCES

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