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Grounded Electrodes Approach to Reduce Bearing Currents: Robustness Analysis for Open-Slots Machines

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***Abstract*—Bearing currents, a critical concern in modern electric motors powered by frequency converters, lead to overheating, increased vibration, and accelerated wear. The Grounded Electrodes Approach (GEA) involves placing thin grounded wires within stator slot openings to act as partial electrostatic shields, targeting the reduction of parasitic capacitance between the winding and the rotor. This paper presents an in-depth analysis of the GEA and extends previous findings by numerically exploring the impact of electrode misplacement on the effectiveness of bearing current mitigation in open-slot machines. Various misplacement scenarios are considered, providing valuable insights for optimizing the application of the GEA in practical settings. The outcomes contribute to the ongoing discourse on reliable electric machine design, offering nuanced perspectives on electrode positioning's critical role in bearing currents mitigation for open-slots configurations.**

Keywords—ball bearings, bearing currents, capacitive coupling, electrical machines, induction machines, parasitic capacitance, EDM currents, variable frequency drives

I. Introduction

Electric motors serve as the backbone of diverse industrial applications, propelling machinery that spans from everyday household appliances to sophisticated manufacturing systems. Despite their ubiquitous presence, the operational efficiency and reliability of electric motors face a formidable challenge in the form of bearing currents—a parasitic phenomenon that manifests as electrical currents passing through motor bearings. These currents can give a rise to the cascade of adverse effects, including overheating, heightened vibration, degradation of grease, diminished efficiency, and accelerated wear of bearings. The repercussions extend further, leading to premature bearing failures, complete drive system breakdowns, increased maintenance costs, and operational downtime.

A. Bearing currents threat

Concern about bearing currents is not a recent one, with various types and origins comprehensively documented throughout the history of AC machines [1], [2]. Bearing currents due to machine unbalanced magnetic circuit or eccentric rotor are known as classical, or non-circulating, or inductive bearing currents. They were the dominant type of parasitic currents in the electric machines' infancy period and remain an up-to-date issue in the context of large electric machines, typically characterized by a shaft height of 280 mm and beyond [3].

However, the prominence of bearing currents has reached new heights in modern electric machines, particularly those powered by voltage-pulse-width-modulating frequency converters. The surge in popularity of these converters, driven by rapid development in power electronics and a push toward higher operating frequencies for enhanced efficiency and performance, has elevated the significance of addressing the detrimental effects of bearing currents of another type. In this realm, the focus has predominantly shifted towards non-circulating bearing currents, named also capacitive, or Electric Discharge Machining (EDM) bearing currents. These non-circulating bearing currents stem from common-mode voltage, high du/dt values, and the presence of parasitic capacitances within AC machines, where winding-to-rotor capacitance plays a pivotal role in their propagation [4], [5].

The presence of circulating (or inductive) bearing currents alongside non-circulating ones adds further complexity in ensuring the reliability of large AC machines. This paper, however, focuses on the reduction of non-circulating bearing currents. An example of countermeasures against circulating currents is given in [4].

Various countermeasures have been explored to mitigate non-circulating bearing currents in modern drive systems [6]. These include strategies on the inverter side, such as reducing common-mode voltage and employing different filters, as well as measures on the machine side, ranging from reducing parasitic capacitance to adopting hybrid or ceramic bearings, implementing shaft grounding devices, and utilizing special conductive grease.

All these measures are scalable and applicable to machines of different sizes and power ranges.

Nowadays, hybrid bearings and shaft grounding devices are the most popular upgrades for addressing the issue of bearing currents [7].

Hybrid bearings, where the regular steel balls are replaced by ceramic balls, are the most effective way to eliminate bearing currents. However, their cost can surpass that of

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standard bearings by tenfold or more [8]. Particularly for induction motors in a range of few kilowatts, the price of hybrid bearings often matches or exceeds that of an entirely new machine, raising economic concerns about their utilization. Moreover, hybrid bearings typically exhibit a reduced load capacity compared to conventional ones [9].

Shaft grounding carbon brushes are affordable and straightforward solution capable of reducing bearing voltage by 75–80% [10]. The cost of a set of carbon brushes typically falls within a few USD range, rendering the solution financially accessible. Maintaining a low-impedance contact between the shaft and the brush is crucial for safeguarding the electric machine against bearing currents. However, the need for continuous servicing due to natural brush wear and external factors such as oil, dust, and rust accumulation constitutes the primary drawback of carbon brushes as a countermeasure.

Unlike carbon brushes, the shaft grounding implemented with the conductive microfiber do not require service, as claimed in [11]. Nonetheless, the cost of shaft grounding rings employing conductive microfiber is comparable to that of hybrid bearings, presenting pricing as its drawback.

In this paper, further analysis of the technique based on machine geometry is performed, particularly, the Grounded Electrodes Approach (GEA) introduced in [5].

B. Parasitic capacitances

From the electrostatic understanding, a capacitance can be found when two conductive objects are divided with a layer of insulation. In an electric machine, there are main constructive parts separated by an air gap – rotor and stator, and stator winding, placed in the stator slot and insulated with a thin layer of the mainwall insulation. This structure follows well the described logic; thus, any AC machine can be represented as a set of following parasitic capacitances. C_{wr} – capacitance between the winding and the rotor, C_{ws} – capacitance between the winding and the stator, and C_{sr} – capacitance between the stator and the rotor. Additionally, bearing capacitance C_b can be found between the bearing's raceways. Parasitic capacitances of a typical AC machine are illustrated in Fig. 1.

C. Bearing Voltage Ratio

Parasitic capacitances of an electric machine form a capacitive voltage divider. The input of this divider is at the machine's neutral point, and the output is at the shaft (and the inner raceway of the bearing attached on the shaft). At the same time, frequency converters often supply the phases of an electrical motor in such a way that the sum of instantaneous voltages on the phases is not zero (while it is zero with a pure sinusoidal supply) and, therefore, form common-mode voltage. This common mode voltage is applied to the voltage divider formed by the capacitances of a motor. As a result, part of that voltage is applied to the bearings provoking bearing currents and the EDM mechanism [12] of the bearings' destruction.

The exact amount of the common-mode voltage reflected by the capacitive voltage divider, made of parasitic capacitances, can be defined with the Bearing Voltage Ratio *BVR*:

$$BVR = \frac{C_{wr}}{C_{wr} + C_{sr} + C_{er} + 2C_b} \cdot 100\%, \qquad (1)$$

where C_{wr} is the total winding-to-rotor capacitance, C_{sr} is the stator-to-rotor capacitance, C_{ws} is the total winding-to-stator capacitance, C_{er} is the extra capacitance between the electrode and rotor, and C_b is the bearing capacitance.

An equivalent circuit showing the machine as a capacitive voltage divider is extensively explained in prior works. The conventional definition of the *BVR* equation explained, for example, in [3], [13], comes with no C_{er} term, which is an extra term to be considered, when the machine is modified with the GEA as a countermeasure against the bearing current phenomenon (discussed in the next section). The need to update the *BVR* equation for the machines modified according to GEA was justified in [6], [14], [15]. For the regular, i.e., non-modified with a GEA machine, the term C_{er} should be taken as 0 F, that is omitted.

D. The Grounded Electrodes approach

Among different countermeasures against capacitive bearing currents, one option is to reduce the voltage applied to the bearings to an acceptable level. This can be achieved if the *BVR* is reduced. From (1), it can be concluded that C_{wr} is the main capacitive coupling that impacts the *BVR*, and reduction of C_{wr} will mitigate the bearing current phenomenon.

One of the options to reduce the C_{wr} is to electrostatically shield the parts forming the capacitive coupling. Prior studies [13] show that partial shielding of the winding-to-rotor capacitance can reduce *BVR* significantly. Shielding is supposed to be implemented with thin grounded electrodes placed in the slot opening over the stator winding, between the stator and rotor. The electrodes should be placed in such a way as to be an obstacle for the electric charge trending to charge the rotor via capacitive coupling. The positioning of a grounded electrode is shown in Fig. 2. The described method to reduce *BVR* and mitigate bearing currents was introduced first in [13] and referred to as the GEA in [5].

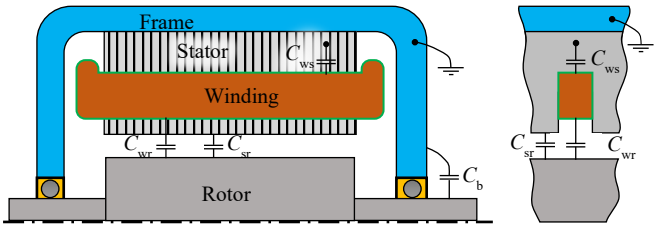

Fig. 1. A regular AC electric machine is represented as a set of parasitic capacitances: C_{wr} – winding-to-rotor capacitance, C_{ws} – winding-to-stator capacitance, C_{sr} – rotor-to-stator capacitance, and C_b – capacitance between the bearing raceways.

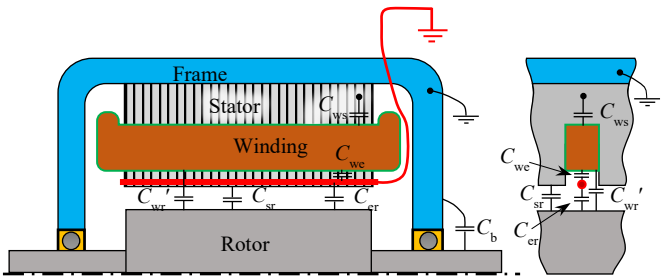

Fig. 2. The Grounded Electrodes Approach applied to the machine: a thin electrode is introduced in the slot opening of each slot and grounded at one end. C_{we} and C_{er} represent winding-electrode and electrode-rotor capacitances respectively. C_{wr}' is the residual winding-to-rotor capacitance, wherein $C_{wr}' << C_{wr}$.

The logic behind the approach is to reduce parasitic capacitive coupling between winding and rotor. In fact, as can be seen in Fig. 2, the capacitance C_{wr} is divided into two capacitances in series – one is between the winding and the grounded electrode, and another one is between the electrode and the rotor. They are further recalled as C_{we} and C_{er} respectively. Since the electrode is grounded, all charge and capacitive current reaches the electrode through C_{we} and is safely discharged to the ground terminal with no harm to the bearings.

As far as the grounded electrode is thin and overlaps the slot opening partially, a portion of the original winding-to-rotor capacitance – C_{wr}'– remains in parallel. However, in a machine modified according to the GEA, the residual winding-to-rotor capacitance is significantly suppressed, and the shaft voltage caused by that residual capacitance does not exceed the threshold value of activation of the Electric Discharge Machinery (EDM) mechanism (the actual reason of bearings damage).

When the machine is equipped with the GEA, *BVR* and thus shaft voltage can be reduced by 50–100%, depending on the stator's geometry. The number and diameter of the electrodes affects the shaft voltage reduction potential as well, as was studied and reported in [13]. The actual cost of implementing GEA can vary depending on the installation method. The most cost-effective implementation is anticipated when applied during the manufacturing stage, integrating the grounded electrode into the slot wedges or insulation. In this scenario, there is no need for specific operation to insert the electrode into the slot clearance, and the cost of GEA is primarily determined by the additional materials utilized, (i.e., copper wire).

E. Focus and structure of the paper

This paper addresses the need for a robustness analysis of the GEA when applied to open-slot machines.

In the previous research [5], [6], [13]–[15] the assumption was that these slot-embedded electrodes were well-positioned, precisely placed at the center line of the slot with no horizontal or vertical offset from the desired position. This paper extends our exploration by delving into the influence of electrode misplacement on the bearing currents reduction ability. Through numerical studies encompassing various misplacement scenarios, it is aimed to provide a comprehensive understanding of how the GEA performs in practical situations. The case of study concerns a 38.6 kW permanent magnet synchronous machine which has open stator slots with rectangular slot profile.

The structure of this paper unfolds as follows. This extended Introduction sets the stage for a comprehensive exploration of the GEA's robustness in mitigating bearing currents in the context of open-slot machines. Thus, the parasitic capacitances of a regular electric machine, the *BVR*, and the conception of the GEA were given in the Introduction. In the Investigation section, the machine under study is introduced, details of the grounded electrode positioning cases are modeled, and specifics on the numerical modeling employed are provided. Following this, the Results section presents the outcomes of the investigation. Further, in the Discussion section, the results are analyzed and interpreted. The Summary section closes the paper with concluding notes.

II. Investigation

A. Machine studied

In the present paper, an open slot machine is considered [16]. Open slots are applied when they greatly facilitate the winding work. Open slots can be applied e.g. in high-speed machines where the operation frequency is high, and the slot height is significant. In such machines, the skin effect can strongly increase the winding resistance. The effect of skin effect can be avoided by fully transposed Litz wire, for example. The assembly of Litz wires requires open slot geometry [17].

The machine adopted for the case of study is a 38.6 kW permanent magnet synchronous machine designed in [16]. For the purpose of the current study, the geometry of a stator slot is repeated before further analysis. The example machine has a rotor diameter of 330 mm, a lamination stack length of 75 mm, and 18 stator slots. The dimensions of the stator slot are shown in Fig. 3.

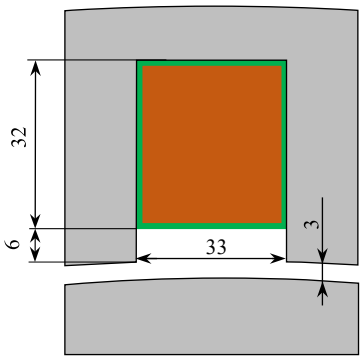

Fig. 3. Stator slot of the machine under the study with dimensions given in mm.

Ball-bearings, used in moderate speed electric machines to ensure smooth and low-friction rotation of the rotor, also have their capacitance C_b. For the machine studied, the bearing capacitance is assumed to be 27 pF similarly to other machines of medium power range [6].

B. Cases considered

To study the influence of the positioning of the electrode on the effectiveness of the GEA in *BVR* reduction, a list of cases was studied. The electrode applied in the study was 0.3 mm in diameter. Differently positioned electrodes are studied under the following cases.

First, the stator slot of the given open-slot machine was modelled with no grounded electrode installed. This case is addressed as Case 1. Next, under Case 2, the scenario with the electrode placed at the center line of the slot and with the distance between the electrode and rotor equal to machine air gap is modelled. Cases 1 and 2 are basic cases and represent the idea behind the GEA. The electrodes positioned in the center of the slot opening were studied in detail in the previous works [6], [14], where the approach was introduced and its effect was evaluated.

Cases 3-31 represent the situations when the grounded electrode is placed in the slot with angular (horizontal, *x*-), radial (vertical, *y*-), or combined (x- and y-) shift from the basic case. The offsets of the electrode positioning for different cases in relation to Case 2 are listed in Table I.

TABLE I. GROUNDED ELECTRODES APPROACH MOUNT CASES INVESTIGATED

Case number	*x* offset, mm	*y* offset, mm
1	-	-
2	0	0
3	0	1.9
4	0	3.8
5	0	5.7
6	0	-1.5
7	0	-2.9
8	±5.4	0
9	±5.4	1.9
10	±5.4	3.8
11	±5.4	5.7
12	±5.4	-1.5
13	±5.4	-2.9
14	±10.8	0
15	±10.8	1.9
16	±10.8	3.8
17	±10.8	5.7
18	±10.8	-1.5
19	±10.8	-2.9
20	±16.3	0
21	±16.3	1.9
22	±16.3	3.8
23	±16.3	5.7
24	±16.3	-1.5
25	±16.3	-2.9
26	±16.7	-0.3
27	±16.7	-1.5
28	±16.7	-2.9
29	±18	-0.3
30	±18	-1.5
31	±18	-2.9

Fig. 4 graphically shows the positioning of the electrode for each instance investigated. Due to the symmetricity of the slot, only cases with positive *x*-offset are modelled. To build the robustness map covering the whole area of the slot clearance and part of the air gap available for electrode placement, the results are mirrored.

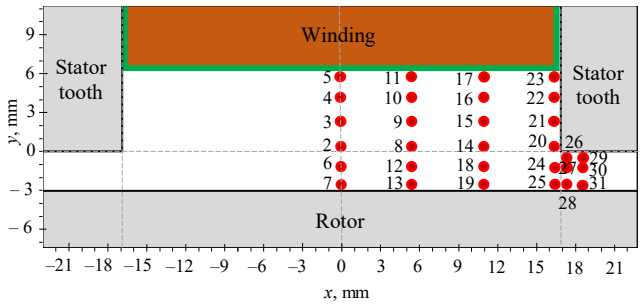

Fig. 4. The area of the slot clearance and air gap of the open-slot machine under study with the depicted cases of grounded electrode positions.

C. FEM modelling details

All cases listed are studied using the Finite Element Analysis (FEA). The computations are done in the software FEMM v. 4.2, where the slot opening with certainly positioned grounded electrode (Fig. 4) is modelled as an electrostatic problem in 2D.

Parasitic winding-to-rotor and rotor-to-stator capacitances, and rotor-to-electrode capacitance for the cases with grounded electrode involved, were found using the electrostatic definition of the capacitance:

$$C = \frac{Q}{U}, \tag{2}$$

where Q is electric charge observed at the capacitor's plates, and U is the voltage applied to the plates.

When the machine is considered analogously with the capacitor, its structural elements – winding, rotor, stator, and optionally the slot-embedded copper electrodes, can be considered as capacitor's plates. In order to determine the capacitances in (1), in electrostatic problem defined for FEA for a single slot, the voltage of 1 V is applied to the rotor, and other parts (stator, winding, and electrode) are given a potential of 0 V. Then, upon the computation is completed, the electric charge accumulated at the stator, winding, and electrode can be assessed and further used to determine the capacitances C_{sr}, C_{wr}, and C_{er} using (2). Since the voltage of 1 V was chosen, the absolute values of capacitances turn to be equal to the accumulated charges.

To observe the parasitic capacitances for the whole machine, values found for a single slot are multiplied by the number of slots, presented in (1), and *BVR*s for given cases are established.

III. RESULTS

The examination involved a numerical analysis of the instances outlined in Table I. The summary of parasitic capacitances and calculated *BVR*s are listed in Table II. The capacitances are shown for the entire machine and were calculated as single slot capacitances multiplied by the number of slots.

TABLE II. PARASITIC CAPACITANCES FOR THE WHOLE MACHINE AND *BVR*S OBSERVED FOR STUDIED CASES

Case number	C_{wr}, pF	C_{sr}, nF	C_{er}, pF	*BVR*, %
1	34.107	0.130	–	15.60
2	29.276	0.130	0.014	12.86
3	29.020	0.130	0.009	13.04
4	30.017	0.130	0.005	13.66
5	32.893	0.130	0.001	15.05
6	30.432	0.130	0.021	12.93
7	32.647	0.130	0.068	11.47
8	29.439	0.130	0.014	12.94
9	29.187	0.130	0.009	13.12
10	30.150	0.130	0.005	13.72
11	32.920	0.130	0.001	15.06
12	30.432	0.130	0.021	12.93
13	32.648	0.130	0.068	11.47
14	30.569	0.129	0.013	13.52
15	30.382	0.129	0.008	13.71
16	31.037	0.130	0.004	14.15
17	33.145	0.130	0.001	15.16
18	31.358	0.129	0.020	13.40
19	32.987	0.130	0.068	11.60
20	34.001	0.126	0.005	15.51
21	34.054	0.129	0.001	15.58
22	34.054	0.130	0.001	15.58
23	34.079	0.130	0.000	15.59
24	33.771	0.124	0.016	14.87
25	33.917	0.127	0.066	12.08
26	34.068	0.125	0.006	15.54
27	33.884	0.123	0.015	14.96
28	33.969	0.127	0.066	12.11
29	34.107	0.127	0.004	15.58
30	34.058	0.123	0.014	15.11
31	34.065	0.127	0.065	12.18

Figs. 5 and 6 illustrate the variations in winding-to-rotor and electrode-to-rotor parasitic capacitances, respectively, as influenced by the positioning of the grounded electrode. Conversely, Table II reveals that the stator-to-rotor capacitance remains relatively consistent across different placements of the grounded electrode, exhibiting negligible fluctuations.

Fig. 7 portrays a sensitivity map for the positioning of the grounded electrode for a single slot. This map illustrates the *BVR* value varying with the grounded electrode position in the *xy*-plane.

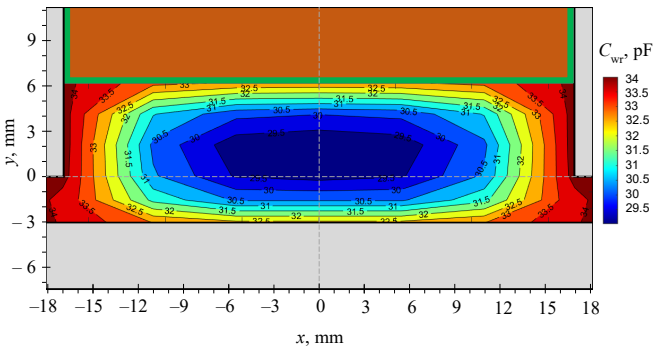

Fig. 5. The whole machine's winding-to-rotor parasitic capacitance C_{wr} as a function of grounded electrode position. Capacitance values are in pF.

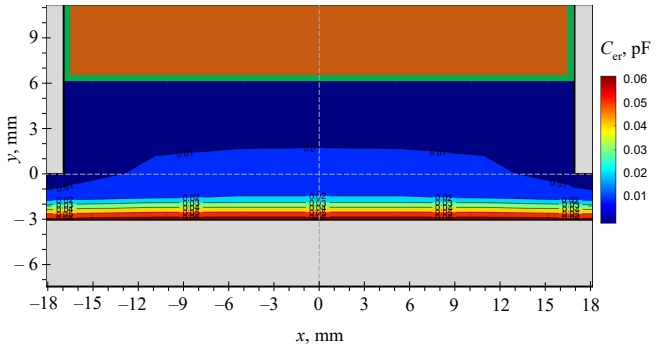

Fig. 6. Dependence of the total electrode-to-rotor capacitance C_{er} on the position of the grounded electrode. Capacitance values are in pF.

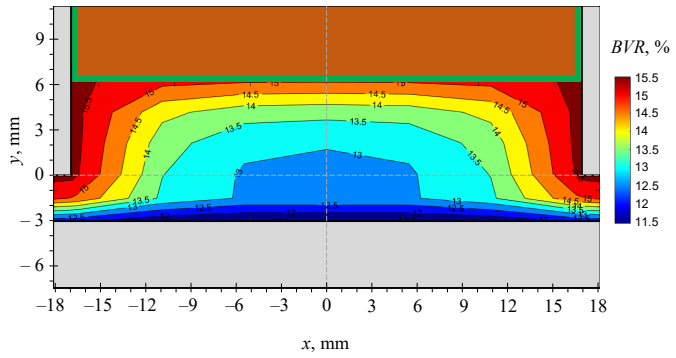

Fig. 7. Sensitivity map of the grounded electrode positioning influencing the Bearing Voltage Ratio: the open-slot machine's *BVR* as the function of electrode offset by *x*- and *y*- axis. *BVR* values are in %.

IV. DISCUSSION

As can be noticed in Table II, the application of the GEA significantly affects the winding-to-rotor parasitic capacitance C_{wr} and brings a new capacitance between the rotor and grounded electrode C_{er}. According to (1), reduction of C_{wr} together with introduction of C_{er} in the denominator should result in *BVR* suppression, and consequently, in the reduction of non-circulating bearing currents' threat.

Deviation of the electrode positioning in the slot opening area from the centered reference point (Case 2) is causing the changes in the observed capacities. Changes of capacitances C_{wr} and C_{er} depending on the actual position of the electrode are presented in Figs. 5 and 6.

Based on Fig. 5, the winding-to-rotor parasitic capacitance C_{wr} exhibits its minimum values when the grounded electrode is precisely centered (as in Case 2). Moreover, in the context of the specific open-slot machine under consideration, this capacitive coupling remains effectively suppressed even when the electrode is horizontally offset by up to 6 mm, equivalent to 1/5 of the total slot width, on both the left and right sides. A vertical offset up to 3 mm, or half of the total slot opening clearance, is deemed acceptable when the shift is directed towards the winding. However, should the grounded electrode shift below the stator teeth line into the machine air gap zone, or if it approaches too closely to the stator walls or winding, its efficacy in suppressing the winding-to-rotor parasitic capacitance diminishes and the value of C_{wr} grows up to the value observed in the original machine with no electrodes installed (Case 1). The optimal region for positioning the grounded electrode to achieve the maximal reduction of C_{wr} is marked with the darkest blue in Fig. 5.

The variation in electrode-to-rotor capacitance C_{er} as a function of electrode position is illustrated in Fig. 6. When the electrode remains within the slot clearance zone, C_{er} exhibits minimal changes, with only a slight increase observed when the electrode is positioned closer to the center of this region. However, a significant increase in capacitance occurs when the electrode approaches the rotor. Notably, deviations along the *x*-axis have negligible impact on C_{er}; instead, proximity to the rotor is the primary determinant of capacitance variation.

To effectively suppress *BVR*, minimizing C_{wr} is paramount. Additionally, maintaining a high value of C_{er} can help reduce *BVR*. However, given that C_{wr} outweighs C_{er} by several orders of magnitude, the impact of C_{er} on *BVR* is relatively minor. Fig. 7 illustrates the overall behavior of *BVR* as a function of grounded electrode offset. Notably, the position of the electrode with zero offset (Case 2) proves to be the most advantageous, as it ensures the lowest *BVR* among practically feasible options.

Overall, the most significant drop in *BVR* occurs when the electrode is shifted to its maximum negative position along the *y*-axis. This happens because of the dramatic increase in C_{er} due to the electrode's extreme proximity to the rotor surface (Cases 7, 13, 19, 25, 28, 31). However, these options are impractical because positioning the electrode in such close proximity to the moving rotor poses a significant collision risk and requires exceptional precision in both electrode positioning and the machine assembly.

According to Fig. 7, misplacement of the grounded electrode by up to 6 mm (1/3 of the slot opening width) along *x*-axis and up to 2 mm of positive offset along *y*-axis (1/3 of the slot clearance height) does not bring any notable decrease in the efficacy of *BVR* suppression. A deviation of the electrode towards the rotor (negative offset values along *y*-axis) can be acceptable in machines with large airgap, where a safe distance between the electrode and the rotor can be ensured. From the bearing current suppression point of view, such a shift does not impair the efficiency of the approach.

In general, open-slot machines have a relatively large area in the wedge region, suitable for the grounded electrode placement, wherein *BVR* is more sensitive to precise radial positioning (*y*-axis) and leaves more sensitivity margin in horizontal mounting.

If offsets are larger than those mentioned above, the effect of the GEA decreases. The efficacy of *BVR* reduction significantly drops and remains barely notable, when the grounded electrodes are placed in close proximity to the stator winding, as in Cases 5, 11, 17, 23.

The effect of the GEA disappears totally if the grounded electrodes are in close proximity to the stator walls, as in Cases 20–23, 26, 29. In those cases, the *BVR* values are nearly equal to the value of unmodified machine from Case 1.

The findings presented in this study regarding the efficacy of the GEA for bearing voltage reduction are applicable not only to the specific machine under consideration but can also be generalized and scaled to other machines with open-slot designs.

In the given work, a slot opening of a simple rectangular shape was analyzed. Further research of the GEA is to conduct a similar sensitivity analysis for the machines with semi-closed slots in order to clarify the effects caused by the complicated geometry of the slot clearance area formed by the stator teeth with wide tooth tips.

V. Conclusion

This paper considers the efficacy of the Grounded Electrodes Approach in mitigating non-circulating bearing currents and the Bearing Voltage Ratio (*BVR*), as a measure for bearing currents' threat, within electric machines with open slots. Main focus primarily revolved around assessing the sensitivity of *BVR* reduction to electrode misplacement.

The findings show that the diametral (horizontal) misalignment of the electrode exerts a relatively minor influence on the *BVR* reduction compared to the radial (vertical) displacement. It is imperative, however, to avoid placing electrodes too close to the stator teeth, as this nullifies the beneficial effects of the Grounded Electrodes approach.

Vertical misalignment has a more pronounced impact on *BVR*, which is improved by positioning the electrode close to the rotor in the air-gap area. Nonetheless, maintaining a safe distance between the electrode and the rotor is paramount to avert any potential collision hazards. On the other hand, the electrode should not be in a close proximity to the winding as it will deteriorate the whole positive effect of the electrode.

VI. References

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