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Novel Stator Slot Opening to Reduce Electrical Machine Bearing Currents

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Ball bearings are largely used in electrical machines, where the high frequency common mode currents affect their lifetime. This document presents a novel Zig-Zag stator slot opening geometry to reduce the winding-to-rotor capacitance C_{wr} with the consequent reduction of Bearing Voltage Ratio and electrical discharge machining bearing currents. An improved analytical model to permit the calculation of C_{wr} for unusual slot opening geometries is implemented. Electrostatic and electromagnetic Finite Element Analysis comparisons between the Zig-Zag, oblique and original (classical slot opening configuration) machines are performed. These comparisons suggest that the Zig-Zag model presents the best performance in terms of Bearing Voltage Ratio reduction, while keeping torque performance close to the original machine. An additional comparison between the novel Zig-Zag model and the classical one with reduced slot opening to have the same C_{wr} values is proposed, showing an higher degradation in terms of torque performance for the latter. The study shows that the Zig-Zag model could be a good candidate to reduce effectively electrical machine bearing currents. A validation test is proposed on two motorette prototypes having classical and Zig-Zag slot opening configurations, respectively. Moreover, the improved analytical method can be helpful for engineers and researchers to calculate C_{wr} with a good accuracy for unusual slot opening geometries.

***Index Terms*—Analytical model, Bearing currents, Dielectric breakdown, Discharges, Electric machines, Finite Element Analysis.**

I. Introduction

Circulating bearing currents are linked to premature failing of ball bearings in electrical machines, affecting their lifetime. The common-mode-voltage V_{COM} generated by inverter's switches is source of these high frequency circulating bearing currents [1], [2], [3]. Nowadays, the use of high frequency Pulse Width Modulation (PWM) inverters with high dv/dt generates wide spectrum of common mode currents which can partially circulate in the ball bearings, contributing to their degradation. Different control strategies have been implemented to reduce circulating bearing currents in electrical machines, by compensating the common-mode-voltage V_{COM}, directly [4], [5], [6]. Additionally, bearings can be affected by Electric Discharge Machining (EDM) bearing currents which have an impulsive behaviour and are directly linked to the common-mode-voltage V_{COM} by Bearing Voltage Ratio (BVR) which works as a divider generated by the machine parasitic capacitances [7]. Many works proposed different modellings for the capacitance estimations based on the measurements [8]- [9], using 2D [10]- [11] and 3D [12] Finite Element Analysis (FEA). It is possible to mitigate these high frequency parasitic currents by modification or implementation on the machine design. Authors in [13] proposed an oblique slot opening geometry to reduce the shaft-to-frame voltage in AC motors. An evaluation on the mitigation effects on circulating bearing currents by a slot-embedded electrostatic shield was studied in [14]. For the same target, Vostrov et. all suggested an extended ground electrodes to mitigate their circulation [15]. Alternatively, authors in [16] analysed the suppression of discharging bearing currents by an electromagnetic shield applied to slot wedge. In [17], an electrostatic shielding on the rotor side was proposed to reduce bearing currents in doubly-fed induction generators. This paper proposes a novel Zig-Zag slot opening geometry to reduce EDM bearing currents by the winding-to-rotor capacitance C_{wr} reduction. In addition, an improved analytical method for its calculation is implemented. These proposed analytical equations permits to have good accuracy in C_{wr} calculation even for unusual slot opening geometries. Electrostatic and Electromagnetic Finite Element Analysis comparisons between classical, modified oblique and modified Zig-Zag slot opening are performed. In the end, a direct electromagnetic comparison between the novel Zig-Zag model and reduced slot opening of the classical model is proposed while keeping the same C_{wr} values. The results suggest that the proposed novel Zig-Zag slot opening geometry can effectively mitigate EDM bearing currents due to a reduction of the winding-to-rotor capacitance C_{wr}, while keeping acceptable torque performance. An experimental test is carried out on two motorette prototypes, having classical and zig-zag slot openings respectively, to support and validate the concept.

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II. Analytical Model

A. General Model

This subsection introduces an improved analytical model to calculate the winding-to-rotor capacitance C_{wr} even for unusual slot opening geometries. The classical equation can be written as:

$$C_{wr} = N\frac{\epsilon_0 wL}{h}, \quad (1)$$

where N is the machine slot number, ϵ_0 is the vacuum permittivity, w is the effective wedge of slot opening, L is

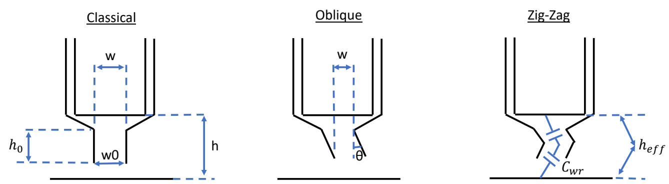

Fig. 1. Slot opening geometries

the stack length and h is the distance between winding and slot opening. It describes with a good approximation C_{wr} in machines which present a classical slot opening. However, it cannot be used for unusual slot opening geometries. It can be demonstrated using the equation proposed in [13] to calculate the angle θ for oblique geometries:

$$w = w_0 - h_0 tg(\theta), \tag{2}$$

where w_0 is the wedge slot opening. Setting as constraint $w = 0$, C_{wr} should be equal to 0, according to equation (1). However, $C_{wr} \neq 0$ as it will be shown in section III with electrostatic finite element analyses.

For obtaining the angle θ for the proposed zig-zag slot opening machine, the parameter x is added in the equation (2) as written below:

$$w = w_0 - \frac{h_0}{x} tg(\theta). \tag{3}$$

If $x = 2$ the zig-zag 'discontinuity' is in the middle of the original slot opening height (see Fig. 1). For adapting the equation to unusual slot opening geometries, the effective height h_{eff} between windings and rotor should be taken into the account. For this purpose, h_{eff} should be used instead of the original h. The effective height h_{eff} can be written as:

$$h_{eff} = \frac{h}{cos(\theta)}. \tag{4}$$

Indeed, this new parameter can take into the account the increased distance between windings and rotor due to the modified geometry.

Moreover, the slot opening w_0 should replace the effective slot opening w in the equation (1). Therefore, the improved equation to calculate the winding-to-rotor capacitance C_{wr} for both original and unusual slot openings can be written as:

$$C_{wr} = N \frac{\epsilon_0 w_0 L}{h_{eff}}. \tag{5}$$

B. Case study

The proposed analytical equation (5) is used to calculate the winding-to-rotor capacitance for the case study. The machine parameters are $N = 18$, $w = 0$ mm, $w_0 = 3$ mm, $L = 66.4$ mm, $h = 3$ mm and $h_0 = 1.5$ mm. Using these values in the equations (2), (3) with $x = 2$ and (5), considering that $\epsilon_0 = 8.85e^{-12}$ F/m, it is possible to obtain analytically C_{wr} for the classical, oblique and Zig-Zag slot opening geometries, respectively. The results are summarised in Table I where it is possible to see that the Zig-Zag model presents a lower winding-to-rotor capacitance C_{wr} by 75.85% with respect to the original geometry whereas the oblique model reduces this parasitic capacitance by 55.38%. The higher reduction by Zig-Zag model is due to the fact that $\theta_{oblique} < \theta_{Zig-Zag}$ so that h_{eff} oblique $< h_{eff}$ Zig-Zag, with the consequence that C_{wr} oblique $> C_{wr}$ Zig-Zag ($\theta_{oblique} = 63.43^o$, $\theta_{Zig-Zag} = 75.96^o$).

TABLE I
C_{wr} ANALYTICAL

Geometry	C_{wr}	Units
Original	10.60	pF
Oblique	4.73	pF
Zig-Zag	2.56	pF

III. FEA: ELECTROSTATIC SIMULATIONS

This section shows the parasitic capacitance winding-to-rotor C_{wr} and stator-to-rotor C_{sr} values obtained with finite element simulations for the machine topologies under study (see parameters in the subsection II-B). Both parasitic capacitances are carried out setting 2 nodes in the machine model. Indeed, C_{wr} is calculated setting the windings and rotor regions as perfect conductors with a voltage $V = 1$ V and $V = 0$ V, respectively whereas the stator is set as inactive. On the contrary, C_{sr} is obtained setting as perfect conductors stator and rotor regions with $V = 1$ V and $V = 0$ V, respectively, while the stator is set to be inactive.

The electrostatic energy in the wedge, slot opening and airgap is carried out, calculating the capacitances as:

$$C = \frac{2E}{V^2}, \tag{6}$$

where E is the electrostatic energy. Considering that $V = 1$ V and $V = 0$ V, it is possible to re-write (6) as:

$$C = 2E. \tag{7}$$

The obtained results are summarised in Table II, where it is clear the C_{wr} reduction for the proposed novel Zig-Zag model with strong benefit on the BVR. Indeed, it is 0.70% with which is lower than 1.60% respect to the original machine.

Imposing 3 nodes in the system with windings $V = 1$ V, stator $V = 0$ V and rotor $V = 0$ V, it is possible to get the potential vector curves winding-to-rotor for the three models as shown in Fig. 2, where it is possible to see how the Zig-Zag model presents higher "shielding" performance with respect to both original and oblique ones.

TABLE II
C_{wr},C_{sr},BVR - FEA

Geometry	C_{wr} [pF]	C_{sr} [pF]	BVR [%]
Original	11.20	470	2.30
Oblique	5.30	478	1.14
Zig-Zag	3.30	484	0.70

The proposed analytical method, for C_{wr} calculation, shows good accuracy compared against electrostatic FEA results. Indeed, the error is 5.36% for the original machine, 10.75% for the oblique and 22.42% for Zig-Zag ones. It is worth to

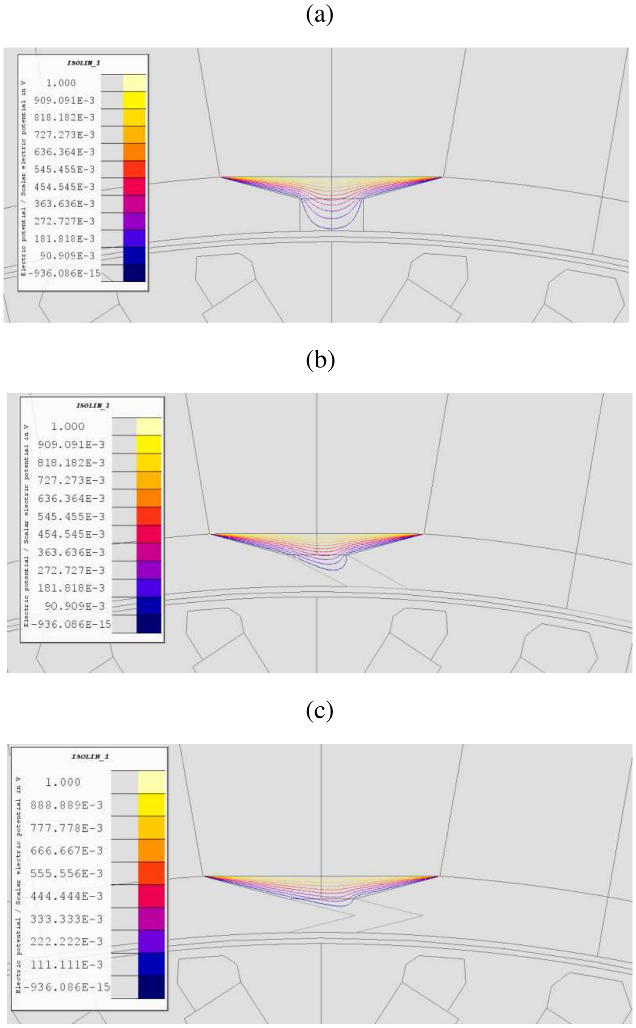

Fig. 2. Electric potential lines comparison: (a) Classical; (b) Oblique; (c) Zig-Zag.

notice that the improved analytical model does not present any difference with respect to the original one for classical slot opening geometries. In contrast, it improves the analytical calculation for unusual slot opening geometries.

IV. FEA: Magnetic Simulations

A. Comparison between Zig-Zag, Oblique and Original slot openings

This subsection presents the torque performance and efficiency FEA of the nine-phase interior permanent magnet machine under study for the three proposed different slot opening geometries (see parameters in the subsection II-B). The main machine parameters are reported in Table III.

Indeed, it is worth to investigate how slot opening modifications could affect the machine performance. Torque comparison is shown in Fig. 3, where it is possible to see a torque reduction by 5.38% for the oblique and 2.76% for Zig-Zag models with respect to the original one. These slight decrements are due to an increased flux leakage. It is important

TABLE III
Main Machine Geometry Parameters

Parameter	Size	Unit
Stack length	66.4	mm
Stator outer diameter	200	mm
Stator inner diameter	141	mm
Toot width	15	mm
Slot opening width	3	mm
Airgap	0.5	mm

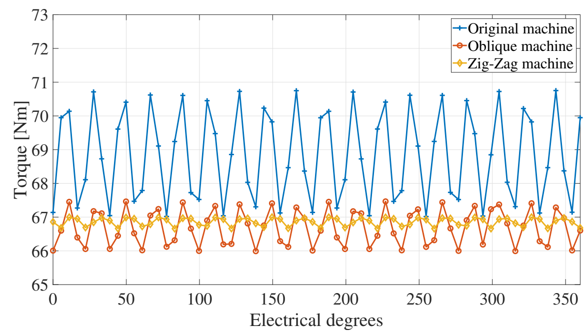

Fig. 3. Torque comparison.

to notice that the Zig-Zag model presents better performance than oblique one. On the other hand, these unusual slot opening geometries have better torque ripple performance with a reduction by 2.33% for the oblique and 4.74% for the Zig-Zag with respect to the original machine (see Fig. 3 and 4). Even in this aspect, the Zig-Zag model presents better performance with respect to the oblique one. For the efficiency calculation, iron losses are calculated using FEA approach with the Bertotti's law. Considering that machine speeds are set at $\omega = 1350rpm = 141.37rad/s$, the efficiency is calculated as below:

$$\eta = \frac{\omega T}{\omega T + P_I + P_J}, \tag{8}$$

where T is the torque, P_I are the iron losses and P_J the Joule losses.

The efficiency is $\eta = 92.80\%$ for the original machine, $\eta = 92.50\%$ for the oblique and $\eta = 92.70\%$ Zig-Zag ones, respectively. Torque, losses and efficiency are summarised in Table IV for all three geometries.

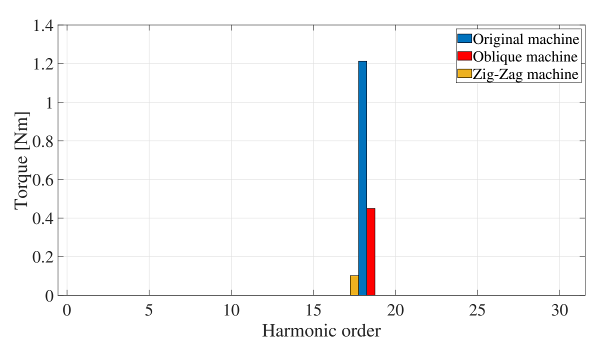

Fig. 4. Fast Fourier Transform - Torque comparison without fundamental component.

TABLE IV
PERFORMANCE COMPARISON - FEA

Geometry	T [Nm]	T_{ripple} [%]	$P_I[W]$	$P_J[W]$	η [%]
Original	68.80	5.23	25.7	718	92.8
Oblique	65.10	2.90	25.8	718	92.5
Zig-Zag	66.90	0.49	25.8	718	92.7

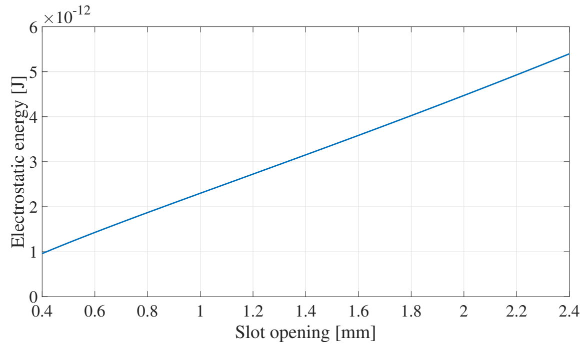

Fig. 5. Sensitivity analysis of electrostatic energy against slot opening wedge.

B. Comparison between Zig-Zag machine and Original one with a reduced slot opening

In this subsection, a comparison between the Zig-Zag model and the original machine with a reduction of its slot opening (SO) is proposed. The original machine SO is reduced according to a sensitivity analysis (see Fig. 5) to get similar value of C_{wr}. Fig. 5 shows that to have a $E = 1.69$ J and in consequence $C_{wr} = 3.39$ pF (see eq. (7)) the new SO should be $w_{new} = 0.8$ mm. This new geometry permits to have $C_{sr} = 500$ pF and BVR = 0.67% which is slight lower with respect to Zig-Zag model (BVR =0.71%) due to the an higher value of stator-to-rotor capacitance C_{sr}. This increased value could be due to the fact that there is an higher stator volume (increased teeth volume) in the new machine model. However, comparing the torque performances, it is clear that the Zig-Zag model is the best option to reduce the BVR keeping the torque performance at an acceptable level. Indeed, the average torque is higher by 4.35% and the ripple lower by 3.62% with respect to the reduced SO machine (see Fig. 6 and 7) which presents $T = 63.99$ Nm and $T_{ripple} = 4.11\%$. The efficiency of reduced SO model is $\eta = 92.3\%$, 0.4% lower than Zig-Zag counterpart (see Table IV).

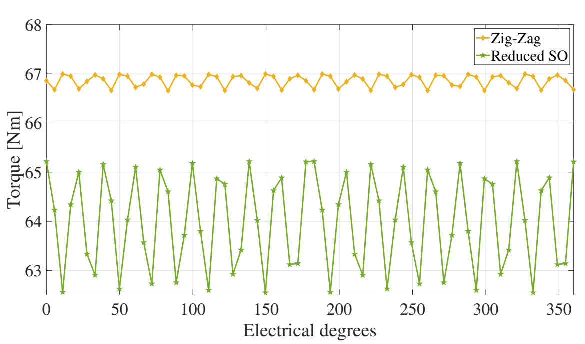

Fig. 6. Torque comparison: Zig-Zag vs reduced slot opening

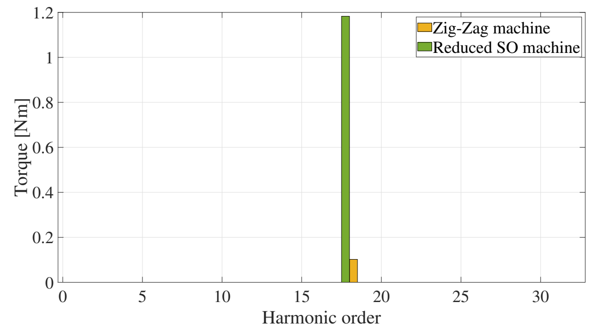

Fig. 7. Fast Fourier Transform - Torque comparison: Zig-Zag vs reduced slot opening

V. EXPERIMENTAL VALIDATION

This section proposes the validation of winding-to-rotor capacitance C_{wr} reduction, by the proposed novel slot opening design, on two motorettes which have classical and zig-zag slot openings, respectively. The motorettes' parameters are listed in Table V.

TABLE V
MOTORETTES GEOMETRY PARAMETERS

Parameter	Size	Unit
Slot pitch	20.0	mm
Slot height	18.0	mm
Slot wedge	1.5	mm
Slot opening wedge - w_0	3	mm
Slot opening height - h_0	1.5	mm
height between windings and rotor - h	4.15	mm
Airgap	0.5	mm
Stack length - L	25.0	mm

The motorette cores were manufactured with electrical steel laminations (M330-35A), and a sheet of copper (9.50 mm x 25.00 mm x 0.55 mm) is used as conductor into one of the two slots. The 'airgaps' are made by plastic materials. The 'rotors' are 'emulated' by a sheet copper having the same dimensions of the one into the slot, positioned under the slot opening. The total capacitance C_{tot} is measured between the copper sheet into the slot and 'rotor', using the two terminals of an impedance analyzer (HIOKI-IM3570) at 1 MHz and 1 V, connecting together stator and 'rotor' in short circuit. The motorettes, the measurement setup to get C_{tot} and its equivalent circuit are shown in Fig 8. In this measure setup, the total capacitance C_{tot} can be written as below:

$$C_{tot} = C_{wr} + C_{ws}, \tag{9}$$

where C_{ws} is the winding-to-stator capacitance which is in parallel with C_{wr}. Therefore, the winding-to-rotor capacitance C_{wr} can be written as:

$$C_{wr} = C_{tot} - C_{ws}. \tag{10}$$

Removing the rotor, it is possible to measure the winding-to-stator capacitance C_{ws}.

The test results are reported in Table VI. The experimental test shows that the proposed Zig-Zag slot opening can effectively reduce the C_{wr}. Indeed, this paratactic capacitance is

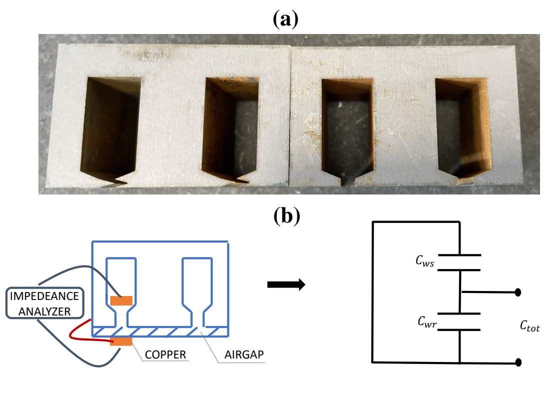

Fig. 8. (a) - Motorette stators; (b) - Measurement setup to get C_{tot} and its equivalent circuit.

TABLE VI
EXPERIMENTAL TEST RESULTS ON MOTORETTES

Geometry	C_{tot} [pF]	C_{ws} [pF]	C_{wr} [pF]
Classical	4.38	4.09	0.29
Zig-Zag	4.00	3.87	0.13
Reduction	8.67%	5.37%	55.17%

reduced by 55.2% with respect to the classical slot opening geometry. The FEA results, using the same condition of test (with a sheet copper in a single slot), show that the C_{wr} reduction for the Zig-Zag slot opening is 66.2%, with C_{wr} = 0.59 pF for the classical and C_{wr} = 0.20 pF for Zig-Zag geometries. Given the small capacitance values, there is a displacement between FEA and experimental test in terms of absolute values. It could be justified by manufacturing tolerances. However, the reduction trend is confirmed. The decision of using copper sheet as conductor into the slot, instead of a classical coil, was based on reducing the comparison error. Indeed, the sheet copper permits to fix the distance from the rotor with more accuracy. Moreover, a classical coil could have a non-uniform distribution into the slots, having unbalanced turns in the bottom part of the slot with respect to the top one.

VI. Conclusions

This work proposed an unusual Zig-Zag slot opening geometry to reduce the winding-to-rotor capacitance C_{wr} in electrical machines. An improved analytical model to calculate C_{wr} for unusual slot opening geometries is implemented. The Zig-Zag machine was compared with an unusual oblique slot opening and a classical one. This comparison has shown that the Zig-Zag model presents the lower BVR which deals with lower EDM bearing currents. In terms of performances, the proposed Zig-Zag model presents a slight average torque reduction and an improved torque ripple with respect to the original machine. The main drawback could be the difficulties in terms of manufacturing to have an automatic process for this unusual Zig-Zag slot opening geometry. Therefore, it is possible to affirm that the novel Zig-Zag geometry permits to have less EDM bearing currents, while keeping good level of torque performance. Moreover, the improved analytical method can be helpful for engineers and researchers to calculate C_{wr} with a good accuracy for unusual slot opening geometries. A validation test on two motorette prototypes has shown that the Zig-Zag slot opening can effectively reduce the winding-to-rotor capacitance C_{wr}.

VII. Acknowledgment

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