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Vincent Mallard, C. Demian, Jean-Francois Brudny, Guillaume Parent. The use of Segmented-Shifted GO Sheet in Magnetic Circuits of Small AC Motors. XVIII International Symposium on Electromagnetic Fields (ISEF), Sep 2017, Lotz, Poland. hal-04114204

HAL Id: hal-04114204

<https://hal.science/hal-04114204v1>

Submitted on 5 Jun 2023

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The use of segmented-shifted GO sheets in magnetic circuits of small AC motors

V. Mallard^{**}, C. Demian^{*}, J.F. Brudny^{*} and G. Parent^{*}

^{*} Univ. Artois, EA 4025, Laboratoire Systèmes Electrotechniques et Environnement (LSEE), F-62400 Béthune, France

[†] FAVI SA, F-80490 Hallencourt, France

Abstract—Reduction of iron losses for AC rotating machines represents a major concern for the constructors. One of the possibilities to answer to this problematic is the employment of segmented-shifted Grain-Oriented sheets to build the stator magnetic circuit of small AC motors. Basic concepts are presented and a comparison with a non-segmented shifted structure is exposed. The results show that even if an increase of the iron losses was observed, the total losses are reduced thanks to the decreasing of stator Joule losses due to decreasing of the stator current.

Keywords - AC machine efficiency, Iron losses; Grain-Oriented electrical steel; Shifting principle; Segmented-shifting principle;

I. INTRODUCTION

The important development of renewable energy is a fact; nevertheless, this will not be able to sufficient for electrical energy needs like the field of transport. The design of electrical machine should be leading to rethink in order to improve the efficiency and support the energy transition. Usually, to increase the efficiency of an electrical machine, these are built to work at lower induction. This technique has the disadvantage of increasing the volume and the mass of the machine which implies an increase in the quantity of necessary material [1], [2], [3]. At the same time, researchers are trying to develop more energy-efficient materials [4]. A number of improvements have been made and this is due to advances in the manufacture of the electrical steel which result from a more optimal molecular composition in addition to an improved fabrication process [5].

The most common material used by machine manufacturers to build the magnetic circuit of the rotating machines is an isotropic non-oriented electrical steel, referenced NO. The second major class of electrical steel materials is Grain-Oriented (GO). Despite the very good performances according to its easy magnetization direction, the strong anisotropy made this technology unprofitable for small and medium power motors, except for some specific applications [6], [7]. For that reason, in the field of rotating electric machines, this material is restricted to very high power machines where the important dimensions of the magnetic circuit make the use of the segmentation unavoidable.

Firstly, the authors propose to answer this problematic by using a new magnetic circuit made of Grain-Oriented (GO) electrical steel. Indeed, many studies, in this field, realized by our laboratory shows the increasing performance of the machine by using the shifted techniques and GO sheets [8], [9], [10]. In order to push forward these investigations, in this article, the authors purpose the employment of segmented-shifted GO sheets in a magnetic circuit of the small AC motors.

The paper starts with a presentation of the segmented-shifting principle and a simplified structure was built. The second part of the paper is dedicated to experimental results. The iron losses and stator currents evolution were compared for two different structures. This allows us to understand the complex 3D phenomena inside the proposed structures. The third part is dedicated to a finite element analysis. A conclusion was drawn at the end of the paper.

II. EXPERIMENTS ON STATIC MACHINES

A. Shifting principle

In industry GO steel is used especially in unidirectional fields for manufacturing the transformer cores due to his high magnetic properties along the Rolling Direction (RD). It can be noted degradation of performances when the value of anisotropy angle α evolves from 0° to 55° . This value of 55° is very close to that determined theoretically considering the "Goss texture" which leads to angle of 54.73° [8]. When α change from 55° to 90° , the global performance improves but still remain poor. These considerations justify that for the GO material the major drawback is related to the fact that these steels are difficult to compatible with rotating field characteristics of AC machines [7].

In order to exploit on the rotating magnetic field the properties of GO materials for $\alpha=0^\circ$, the authors proposed a new assembly technique that will be developed in this article.

First attempt to use GO sheets in a magnetic circuit of a small AC motor was the use of shifting principle. This structure is stacked by shifting the RD of each successive lamination respectively by a constant spatial angle " β " (Fig. 1a). Consequently, the easy magnetization directions of the Stator Magnetic Circuit (SMC) laminations are distributed helicoidally along its axis. The choice of the value of " β " in this case can cover all values between 0° and 90° . However, the work presented in [8], shows that the optimal value of " β " in terms of energy efficiency is found at 90° . In this case the structure allows decreasing iron losses in the machine compared with stators made of NO sheets of the same thickness.

The main disadvantage of this technique is that during the transition of the field line from one lamination to another, this one is forced to circulate in "z" axis passing through the natural air-gap of the laminations formed by their insulation layer.

B. Segmented-shifting principle

To minimize the length of the field lines observed with the shifting technique, the authors propose the segmentation of the

laminations at the same time with using the shifting technique. Each lamination is divided into 6 identical parts and each segment is cut considering the RD, 90° for segment S1 and 0° for segment S2 (Fig. 1a). In this way, as shown in Fig. 1b, for two adjacent laminations the RD is shifted to an angle close to 90° .

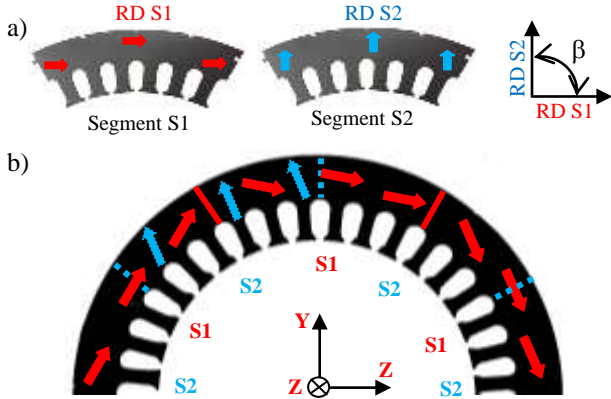


Fig. 1: Implementation of shifted segments in SMC

Once the inferior sheet has been constituted, for example segments S2, it is covered by the superior laminations made identically, segments S1. Fig. 1b presents the final combination considering two consecutive sheets. It appears six separate areas, each area being characterized by the RD of the upper and lower sheets.

C. Magnetic circuit configuration

In order to validate these different assembly techniques, using real machine prototypes have the disadvantage of being expensive and requiring relatively long construction times. The static machine prototypes which are a simplified SCM of the real machines can easily test different configurations corresponding to different values of " β " and various qualities of electrical steels. In fact, the only restrictions concern the cutting of laminations, the SMC and the coils being manufactured in our laboratory. The geometry of stator laminations corresponds to that presented in real machines. Their stator and rotor magnetic circuits are realized with GO sheets 0.35 mm thick (Fig. 2). The 4-poles windings of these machines were implemented by making two three-phase windings. First one, composed of 45 turns per phase and per pair of poles, is the primary coil powered by a three-phase supply voltage. The second one, situated in the same slots as the first, with only 3 turns per phase and per pair of poles, corresponds to a measuring winding.

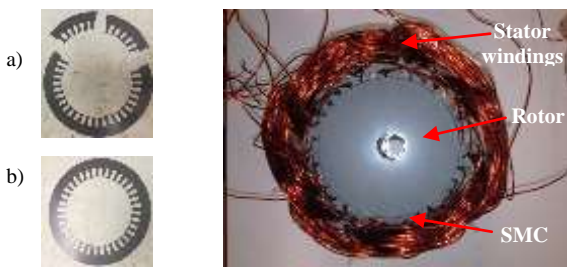


Fig. 2: Implementation stack with an example of a) segmented and b) non-segmented sheet

The comparison between different structures was made using two identical rotors build using 0.35 mm GO sheets, according to the shifting principle. To simplify the cutting

process, non-slotted rotors are considered. As the rotor does not have any winding, the frequency of the stator and the rotor are identical ($s=1$). In these conditions, the measuring winding allows, using precision digital power meter, to measure the induction $\hat{b}_{ag(s)}$ in the air-gap at the same time with iron losses $P_{\mu(s)}$ and reactive power $Q_{\mu(s)}$ quantities.

III. IRON LOSSES AND STATOR CURRENT

In the next, the two studied structures are considered: GO₃₅90 for non-segmented shifted structure and GO₃₅90S for segmented shifted structure. These are powered by a balanced three-phase sinusoidal voltage system. In terms of size the two structures are identical and build with 0.35mm thick laminations. The difference is that the GO₃₅90 is a shifted 90° structure, and the GO₃₅90S is a segmented and shifted 90° structure.

Fig. 3 and Fig. 4 show, the iron losses evolution laws, function of air-gap induction peak \hat{b}_{ag} , determined using the measuring winding and the R.M.S. value of the absorbed stator current I^s .

According to the presented results, the segmented shifting technique leads to increase $P_{\mu(s)}$. In return, the stator current for GO₃₅90S is much lower than the values obtained for the shifted configuration.

In an attempt to justify this rather surprising result, the identification of the path followed by the field line in different stators is made. For given \hat{b}_{ag} , the teeth are practically solicited in the same way. Regarding the yoke, considering GO₃₅90S it is much better exploited from a magnetic point of view. This particularity is based on how the field lines spread inside the yoke. For GO₃₅90 structure, the magnetic field circulates from one lamination to another mainly following the principle of energy minimization while for the GO₃₅90S the field lines circulate along the RD.

As the paths of the field lines are performed symmetrically with respect to the axis, it is deduced that the iron volume which is considerate in definition of iron losses is therefore more important for GO₃₅90S, leading to increasing iron losses for this configuration.

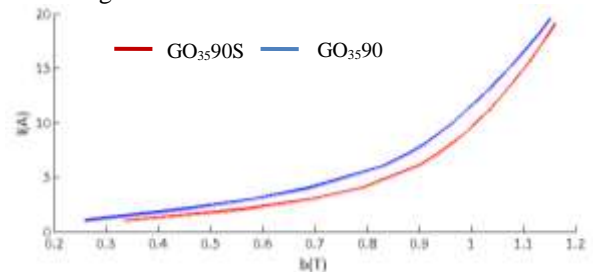


Fig. 3: Comparisons of I_s^s RMS values

Concerning this increase in iron loss, it is necessary to be more nuanced because this spread of the field lines inside the yoke lead to a reduction of the induction in the yoke. This helps to attenuate this increase in iron loss due to the higher iron volume used in the yoke. Regarding the magnetizing current, the formulated considerations for GO₃₅90 structure show that there are 2 saturated areas for every non-segmented lamination corresponds to the hard magnetization direction. For GO₃₅90S

it seems that is not the case. The ampere-turns consumed by iron are more important for the shifted structure so that for the same induction value in the air-gap $GO_{35}90$ requires more magnetizing current compared to $GO_{35}90S$.

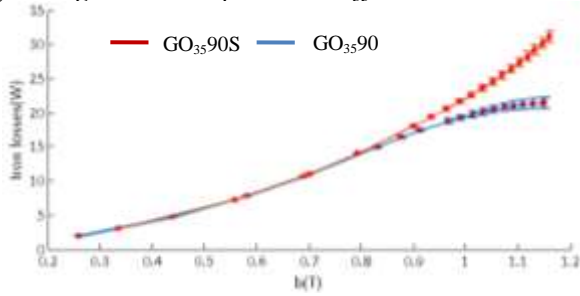


Fig. 4: Comparisons of iron losses values

As magnetizing current occurs largely in the stator current definition, results that for a given $\hat{b}_{ag(s)}$ the $I_{(s)}^s$ for $GO_{35}90S$ becomes smaller than for $GO_{35}90$.

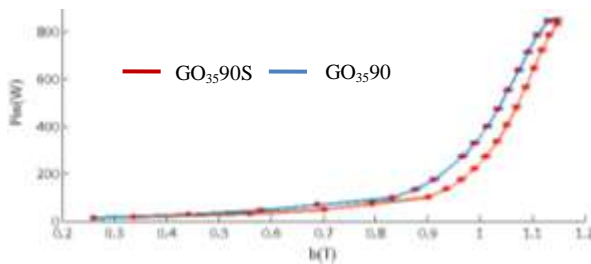


Fig. 5: Absorbed power

To assess the effects of increases of iron losses and the decreasing of stator Joule losses due to decreasing of the stator current, Fig. 5 compares the absorbed power for the two GO structures. As can be observed, overall, the total losses are considerably reduced (ratio 1.5 to 2) with $CGO_{35}90S$ structure.

IV. FINITE ELEMENT ANALYSIS

A. General considerations

The complex phenomena occurring in the two structures cannot be identified without a complete analysis of the magnetic flux distribution inside the sheets. However, the very small thickness of the air-gaps between laminations makes experimental measurements almost impossible to perform. The use of numerical methods seems to be the most appropriate solution here. Because of the strong anisotropy of GO sheets, the magnetic flux distribution is very difficult to be predicted without 3D Finite Element (FE) simulations. The simulations are performed with GetDP in 3D magnetostatics with the h-phi formulation.

The non-segmented shifted structure and the segmented shifted structure are studied. The SMC machine prototypes made in our laboratory contain 100 sheets each. Modelling the whole SMC in 3D and taking into account the anisotropy of the material, the insulation and the interlaminar thicknesses would lead to non-acceptable computation times. For that reason, the model used is a reduced one, but it is representative of the phenomena that take place inside the structure. Thanks to the symmetry, in Z axis (Fig1) the model contains: a complete sheet (segmented or not) in the middle, and two half-sheets on one side and the other. The insulation and the interlaminar thicknesses are taken into account by introducing an air-gap (5 μm) between each lamination. Also our model considers the

non-linearity (saturation and anisotropy) of the GO sheets. Anisotropy into the plane of the sheet is defined according to the RD and the Transverse Direction (TD). These magnetic characteristics were determined by the measurements on standardised Epstein frame. Also, the magnetic characteristics in the Normal Direction (ND) defined into the Z axis normal to the plane of the sheet is deduced by a specific test bench [4], [11].

B. Non-Segmented shifted structure

The results of the FE simulations for this configuration are presented in Fig. 6 and in Fig. 7. It is interesting to note the distribution of induction b into the plane of the sheet and into the interlaminar air-gap between two laminations.

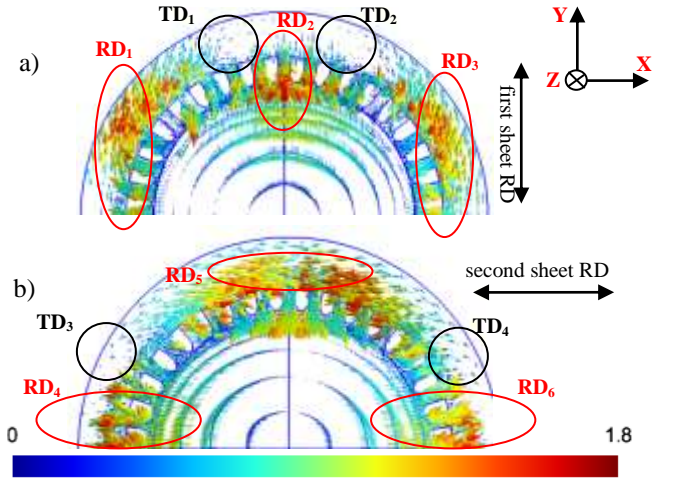


Fig. 6: Distribution of b in the plane of the sheet for a) first sheet and b) second sheet

According to the shifting principle the angle between the RDs of two consecutive sheets is 90° . As foresaw, the magnetic flux preferred to use RD areas where the material grains are conveniently oriented (Fig. 6, zones RD 1-6). When meeting the regions with a TD (zones TD 1-4) the magnetic flux passes through the air gap, leave the RD of the first lamination to reach the RD of the second lamination (Fig. 7, zones ND1-3). This phenomenon is similar to those been found in the literature [10] and can be explained because the magnetic flux prefers to follow the RD as long as possible in order to respect the principle of energy minimization.

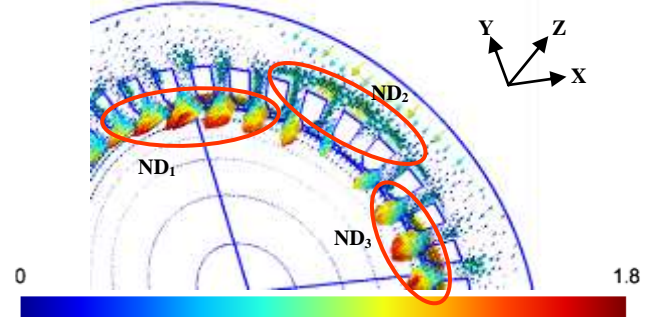


Fig. 7: Distribution of b in the interlaminar air-gap

C. Segmented shifted structure

In such configuration, the segments have the RD either in the direction of the stator yoke (Fig 8.a) for the first sheet or in the direction of the teeth for the second sheet (Fig. 8.b). The FE simulation results, show that the magnetic flux density is distributed mainly in the easy magnetizing direction of the

sheets (zone Z_1, Z_2), despite the presence of the magnetic flux in certain teeth (zone Z_3). Saturation of well-oriented teeth in the second sheet (zone Z_4) leads to a transition of the magnetic flux to the TD presented in the first sheet teeth (zone Z_3). This phenomenon can be causing more iron losses.

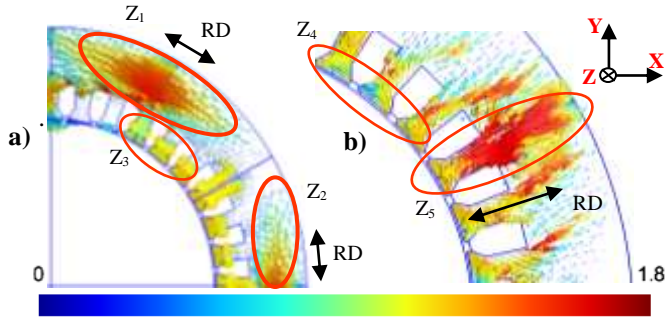


Fig. 8: Distribution of b in the plane of the sheet for a) first sheet and b) second sheet

However, compared to non-segmented shifted structure, the magnetic flux transition into the sheet is done in a "more homogeneous" way. The exception is in the joining zone of the two segments (zone Z_5). The phenomena produced in these regions can explain the results obtained in terms of iron losses. If we follow the field lines, a particular 3D distribution can be identified (Fig. 9 zone Z_6). Instead that the field lines pass from one segment to another into the same plane of the sheet, it prefers to enter into the sheet below (zone Z_7), to continue into the hard magnetizing direction and at the end, to enter into the adjacent segment.

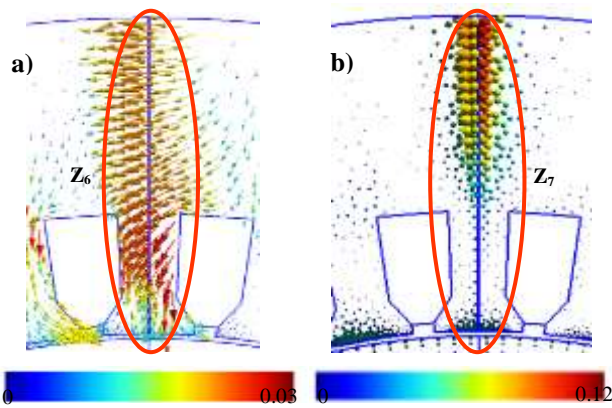


Fig. 9: Joining zone of the two segments. Distribution of b in: a) the plane of the sheet and b) the interlaminar air-gap

V. CONCLUSION

The study presented in this paper concerns the use of segmented-shifted GO sheets in magnetic circuits of the high-efficiency motors. Understanding the phenomena that occur inside the prototype allows an improvement of the segmented-shifting principle. The experiments on real prototypes show that the ampere-turns consumed by iron are more important for the shifted structure. In the same time, due to the phenomena spent in joining zone of the segmented structure sheets, the paths of the field lines increased, leading to increasing of iron losses for the segmented configuration. Even so, the total losses are reduced thanks to the decreasing of stator Joule losses due to decreasing of the stator current.

Another problem to solve is the saturation of well-oriented teeth. This can be done by doubling the surface of the teeth, which means adding another lamination oriented in the same

way. This will lead to a reduction of the level of the flux density in the teeth and, consequently, a reduction in iron losses which provides new perspectives for the application of GO steel for AC rotating electrical machines.

ACKNOWLEDGMENT

This work has been achieved within the framework of CE2I project (Convertisseur d'Énergie Intégr Intelligent) and FAVI. CE2I is co-financed by European Union with the financial support of European Regional Development Fund (ERDF), French State and the French Region of Hauts-de-France. FAVI is a French company specialized in copper alloy pressure die-casting. This program is also supported by ThyssenKrupp Electrical Steel which provided us GO materials.

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