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

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Research Article

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Abstract: In order to increase energy efficiency of AC rotating machines, one possibility is the use of Grain-Oriented steel sheets to build stator magnetic circuits in order to reduce iron losses. After presenting the general concept considering a non-segmented-shifted sheets prototype recently developed in our laboratory, a segmented structure is introduced. Experimental comparisons between these structures are performed using static machines. The main results are analysed using Finite Element modelling that leads to extract the particular physical concepts which govern these associations.

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

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1 Introduction

It is now recognized that developing renewable energies to reduce the use of fossil fuels can only be done efficiently by acting simultaneously on the devices concerned by increasing their energy efficiency. Considering the important role of electric motors, and more particularly asynchronous machines, in terms of power consumption, it seems obvious that their design must be reconsidered to accompany this energy transition.

Usually, to increase the efficiency of an electrical machine, these are built to operate 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 [1–3]. 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 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 AC 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. Even if the scientific literature proposes some solutions [6, 7], these are generally considerably increasing the costs of machines due to the specific assembly of the magnetic circuit. In order to be able to overcome these constraints, the authors propose to use a new magnetic circuit made of non-segmented GO electrical steel. Indeed, many studies, in this field, realized by our laboratory show the increasing performance of the machine by using the shifted techniques [8–10]. In order to push forward these investigations, in this article, the authors purpose the employment of segmented-shifted GO sheets to design a magnetic circuit. The paper starts with a presentation of the non-segmented and segmented-shifting principle with a very limited number of segments compared to what is generally found in the literature. Specific prototypes, defined as static machines, are presented and built. The second part of the paper is dedicated to experimental results. The iron losses and stator currents evolution were compared for segmented and non-segmented structures. The third part is dedicated to a finite element analysis. This allows us to understand the complex 3D phenomena inside the stator magnetic circuits. A conclusion was drawn at the end of the paper.

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2 Principles and Prototype designs

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 an angle of 54.73° [8]. When α change from 55° to 90°, the global performance improves but still remains poor. These considerations justify that for the GO material the major drawback is related to the fact that these steels are difficult compatible with rotating field characteristics of AC machines [7].

In order to exploit the properties of GO materials for α = 0° on the rotating machines, the authors proposed new assembly techniques based on the shifting principle.

2.1 Shifting principle

First attempt to use GO sheets in Stator Magnetic Circuit (SMC) of a small AC motor was the use of shifting principle only. This structure is stacked by shifting the RD of each successive lamination respectively by a constant spatial angle "β" [1]. Consequently, the easy magnetization directions of SMC laminations are distributed helicoidally along its axis. The choice of the value of "β" can cover all values between 0° and 90°, taking into account nevertheless a constraint related to the fact that the teeth must, for example, be overlapped. Under these conditions, the studies carried out showed that the field line transited from one sheet to another to evolve, if possible, according to an RD in order to satisfy the principle of the minimization of energy. However, the work presented in [8], shows that, in these conditions, the optimal value of "β" in terms of energy efficiency is found for 90°. In this case the structure allows decreasing magnetizing current and iron losses compared with stators made of NO sheets of the same thickness.

2.2 Segmented-shifting principle

The analysis of the previous structures shows that the natural air gaps between sheets are of the order of 5 µm, and the field lines that meet it during its transition from one sheet to another did not affect in a significant way, the energetic performances of the structure. For that reason, the authors decided to apply at a more local level the shifting principle in order to accentuate the gains already noted. To do this, it is necessary to use the segmentation of the sheets. It is the presence of this new technique along with maintaining as shifting mechanical angle the value of 90°, which makes the originality of this article.

Each lamination is divided into 6 identical parts and each segment is cut considering the RD. This RD is perpendicular to the axis of symmetry of the segment (thus practically perpendicular to the axis of the teeth) for segments S1 which constitute "sheet 1"and overlap with the axis of symmetry of the segment S2 (thus practically similar to the axis of the teeth) for segments S2 which constitute "sheet 2" (Figure 1a). In this way, as shown in Figure 1b, for two adjacent segments of a sheet, the RD are shifted.

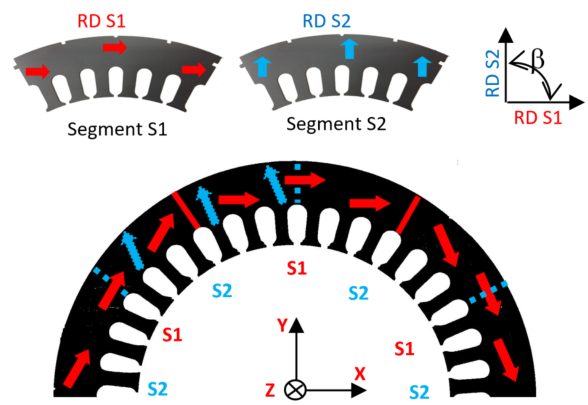

Figure 1: Implementation of shifted segments in SMC

Once the inferior sheet has been constituted, for example segments S2, it is covered by the superior laminations made identically with segments S1 whose axis of symmetry of one of them is shifted by 30° from the two segments S2 that it covers.

Figure 1b presents the final combination considering two consecutive sheets, knowing that this procedure is reproduced identically until the desired length of the magnetic circuit is obtained. In this way, it appears 12 separate areas, each area being characterized by the RD of the upper and lower sheets.

2.3 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 SMC of the real machines, can easily test different configurations corresponding to different values of "β" and various qual-

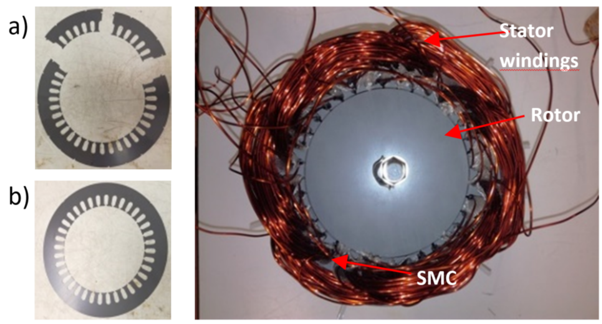

Figure 2: Implementation stack with an example of a) segmented and b) non-segmented sheet

ities 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 (Figure 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 pole pair, 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 pole pair, corresponds to a measuring winding.

The comparison between different structures was made using two identical rotors build according to the shifting principle. To simplify the cutting process, non-slotted rotors are considered. The frequency of the stator and the rotor are identical. In these conditions, the measuring winding allows, using precision digital power meter, to measure the air-gap induction peak value $\hat{b}_{ag}$ at the same time with the R.M.S. primary coil winding I, the iron losses P_{μ} and magnetizing power Q_{μ} quantities.

3 Iron losses and stator current

In the next, the two studied structures are considered: $GO_{35}90$ for non-segmented 90° shifted structure and $GO_{35}90S$ for segmented 90° shifted structure. These are powered by a balanced three-phase sinusoidal voltage system.

Figures 3 and 4 show, respectively, P_{μ} and I variations with $\hat{b}_{ag}$, for the two considered structures. It appears that $GO_{35}90S$, compared to $GO_{35}90$ leads to increase P_{μ} and to decrease I.

To assess globally these effects, Figure 5 compares the absorbed power P for the two GO structures.

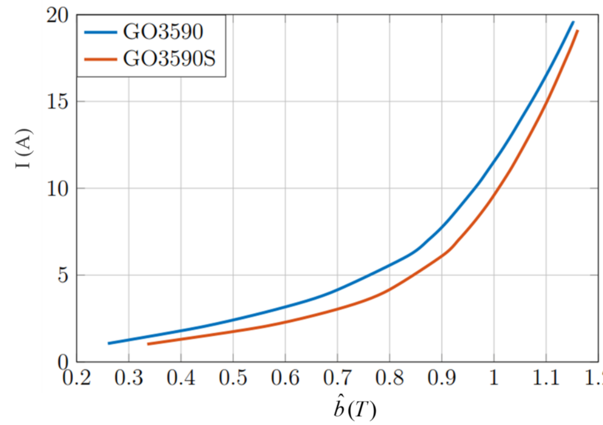

Figure 3: Comparisons of $I^s_{(s)}$ RMS values

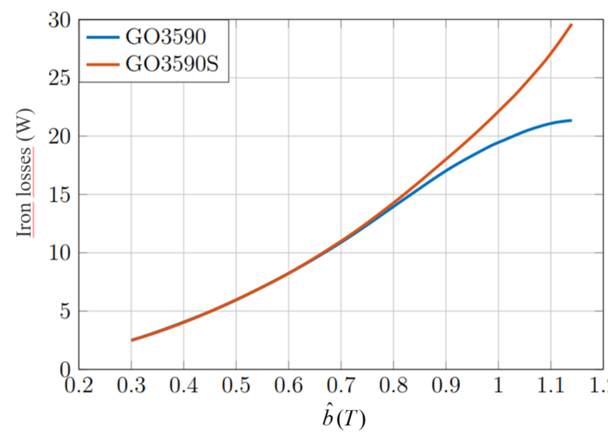

Figure 4: Comparisons of iron losses values

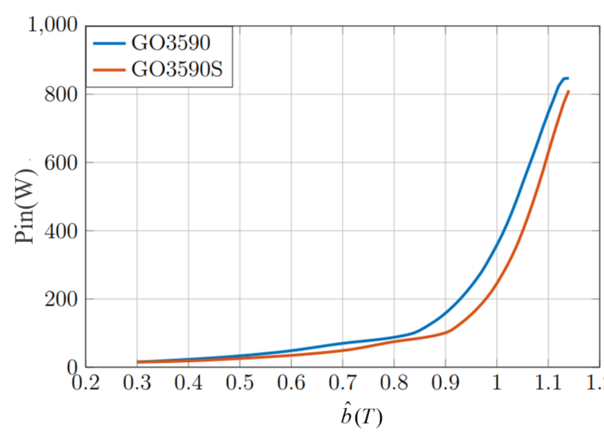

Figure 5: Absorbed power

As can be observed, overall, the total losses are considerably reduced (ratio 1.5 to 2) with $CGO_{35}90S$ structure.

In an attempt to justify this rather surprising result, the identification of the path followed by the field line in both SMC is made using finite element analysis.

4 Finite element analysis

4.1 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 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 for the phenomena that take place inside the structure. Thanks to the symmetry, in Z axis (Figure 1) 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 a 5 μm air-gap 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].

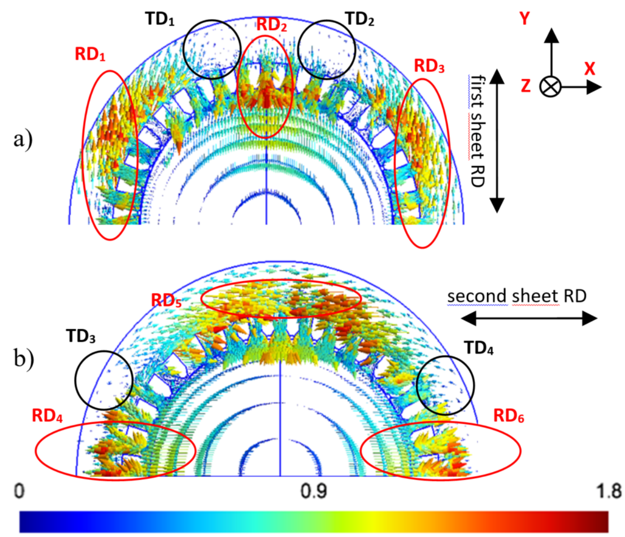

Figure 6: Distribution of b in the plane of the sheet for a) first sheet and b) second sheet

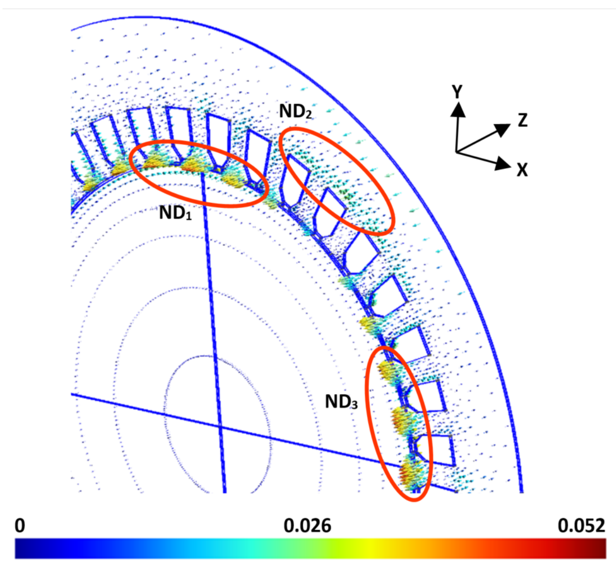

Figure 7: Distribution of *b* in the interlaminar air-gap

4.2 Non-Segmented shifted structure

The results of the FE simulations for this configuration are presented in Figures 6 and 7. Is interesting to note the distribution of induction *b* into the plane of two superimposed sheets (Figure 6) and into the interlaminar air-gap between two laminations (Figure 7).

According to the shifting principle the angle between the RDs of two consecutive sheets is 90°. As foresaw, the magnetic flux prefers to use RD areas where the material grains are conveniently oriented (Figure 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 (Figure 7, zones ND_{1-3}).

This phenomenon is similar to those been described in the literature [10] and can be explained as the magnetic flux prefers to follow the RD as long as possible in order to respect the principle of energy minimization.

4.3 Segmented shifted structure

In such configuration, the segments have the RD either in the direction of the stator yoke (Figure 8a) for the first sheet or in the direction of the teeth for the second sheet (Fig-

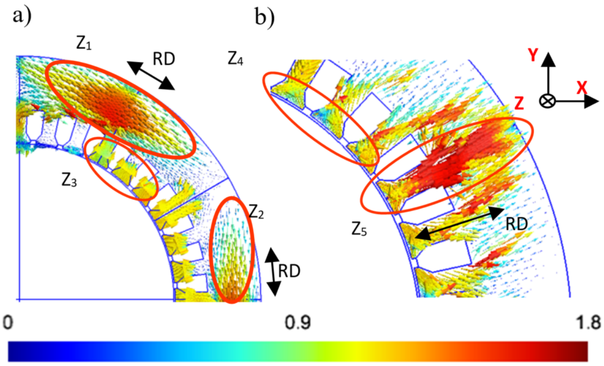

Figure 8: Distribution of b in the plane of the sheet for: a) first sheet and b) second sheet

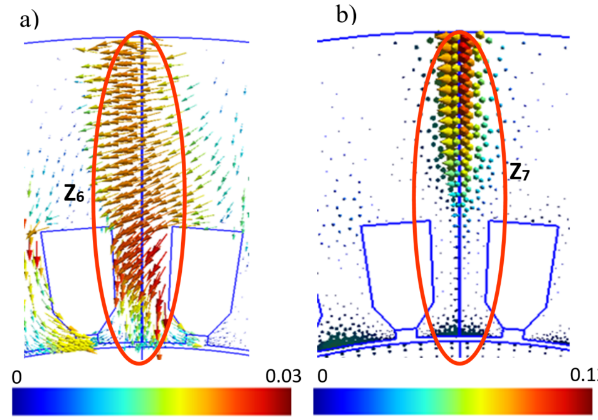

Figure 9: Joining zone of the two segments. Distribution of b in: a) the plane of the sheet and b) the interlaminar air-gap

ure 8b). The FE simulation results, show that the induction is distributed mainly in the easy magnetization 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 cause more iron losses.

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 (Figure 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 magnetization direction and at the end, to enter into the adjacent segment.

5 Magnetic behavior of SMC

For given $\hat{b}_{ag}$, the teeth are practically used in the same way. Regarding the yoke, considering $GO_{35}90S$ 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 $GO_{35}90$ structure, the magnetic field circulates from one lamination to another mainly following the principle of energy minimization while for the $GO_{35}90S$ 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 $GO_{35}90S$, leading to increasing iron losses for this configuration. For $GO_{35}90$, the iron losses at high magnetic flux density tend to decrease. This phenomenon is similar to [13].

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 $GO_{35}90$ structure show that there are 2 saturated areas for every non-segmented lamination corresponds to the hard magnetization direction.

For $GO_{35}90S$ 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 $GO_{35}90S$.

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 $GO_{35}90$.

6 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.

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