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AC magnetic circuits using non segmented shifted grain oriented electrical steel sheets: study of magnetic flux transition between sheets

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A new design of AC stator magnetic circuit using non segmented shifted grain oriented electrical steel sheets has been designed in order to reduce the iron losses and, consequently, to increase the AC machine efficiency. This paper analyses the magnetic behavior of this assembly, particularly the magnetic field transition between laminations.

Index Terms— grain oriented electrical steel, stator magnetic circuit, reluctance network, AC machine efficiency, magnetic flux transition, finite element analysis.

I. INTRODUCTION

IN RECENT years, reducing the energy consumption became a topic of great concern. The rotating electrical machine energy efficiency increase mandatory induces reduction of the losses. For that reason the ongoing research work is being concentrated on the development of these machines by using high quality materials.

The losses of AC electrical rotating machines are due in large part to the iron losses. Extensive research has been carried out in order to design new AC Stator Magnetic Circuit (SMC) using non segmented Grain Oriented (GO) electrical steel sheets. This structure is stacked by shifting the Rolling Direction (RD) of each successive lamination respectively by a constant spatial angle. Consequently, the easy magnetization directions of the SMC laminations are distributed helicoidally along its axis. Several preliminary tests performed on such SMC structure show an improvement in loss level when using 0.35mm thick GO sheets 60° shifted [1], [2]. In order to understand the behavior of this assembly, particularly the magnetic field transition between laminations, a mixed numerical analysis using a combination of Reluctance Network (RN) and Finite Element (FE) software is used.

The first part of the paper recalls the shifting principle and some results obtained on several motor yoke prototypes as well as real three phase induction machines build up with various Non-Oriented (NO) and GO shifted electrical steel materials.

In the second part, a RN is proposed in order to explain the involved phenomena taking place inside the proposed SMC structure submitted to a unidirectional field. The GO sheet layer has been represented as a circular array of non-linear reluctances. In the following the FE modeling shows that the magnetic path lengths across superimposed laminations of different relative orientations of the easy magnetizing direction are independent of permeability values.

The last part is dedicated to the presentation of simulated results.

II. NON SEGMENTED SHIFTED GO STRUCTURE

In industry the GO steel is used especially for manufacturing the transformer cores in order to decrease iron losses. It is well known that this material, due to the nature of the GOSS texture, exhibits a strong anisotropy. That means that the best magnetic properties are only found along the RD [3]. Consequently, the procedure of punching out GO stator foils from the strip and stacking them the same way as it is regularly done for NGO steels is not relevant for rotating machines because most of the time, the magnetic field inside the yoke is not lying along the RD. According to the $\hat{b}(\hat{h})$ curves obtained from Epstein frame tests (Fig. 1) on GO 0.35mm thick (denoted GO₃₅), the material exhibits an easy magnetizing direction for $\alpha=0^\circ$ and a difficult one for α close to 55° . The anisotropic angle α , corresponds to the deviation between the RD and the direction of the applied field.

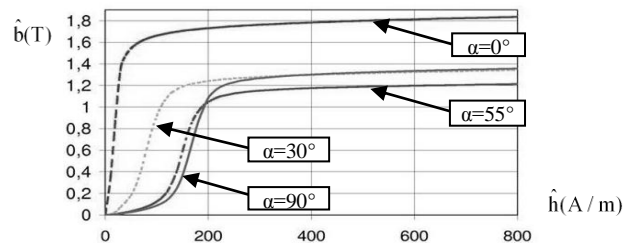


Fig. 1: GO₃₅ \hat{b} variations with \hat{h} for various α

A particular non segmented lamination assembly is suggested to use GO sheets in small and medium AC rotating electrical machine manufacture. The proposed principle offers the benefit of taking advantage from of the high saturation level and high permeability of GO steel when α equal to zero or nearby.

A. New GO Stator Magnetic Circuit Structure

The proposed SMC structure is assembled by shifting the RD lamination from the previous one by a constant β spatial angle [2]. In consequence, the easy magnetization direction is radial distributed across the successive layers of the SMC on its height. This principle makes the magnetic field circulate from one lamination to another in a consistent way with the

principle of energy minimization. Previous studies led on staked rings pointed out that the most efficient β value was 60° .

If the first sheet RD is the spatial reference, when $\beta=60^\circ$, the second sheet RD is shifted by 60° compared to the reference. This shift is 120° for the third sheet RD. The fourth sheet RD relative to the reference is shifted by 180° , identical to the reference situation; the spatial period along the SMC axis is three sheets.

B. Validation of the new SMC structure

First, the shifted assembly technique was tested on motor yoke prototypes submitted to a unidirectional magnetic excitation [4], [5]. Two different steel qualities are tested: GO₃₅ and NO₆₅ (NO 0.65mm thick). The NO₆₅ steel can be considered as isotropic. The geometry of the laminations is close to the real machine and the two SMCs are made up of different sheet quantities in order to reproduce the same SMC length (50mm). The obtained results show a significant iron loss reduction for the GO₃₅ 60° shifted compared with the NO assembly mainly because of high static loss decrease.

Second step was to test this particular structure inside a real rotating electrical machine. A number of identical 10kW squirrel cage induction machines of stator and rotor initially made of NO₆₅ were modified. The stator of two machines were replaced respectively by GO₃₅ 60° shifted sheets and NO₅₀ sheets. As NO₅₀ steel presents a low anisotropy, the corresponding sheets have been also 60° shifted. The comparisons were made on the basis of the NO₆₅ original machine, by supplying the machines from the grid (50Hz). The results show that even under rotational magnetic field, the most efficient assembly is GO₃₅ followed by the NO₅₀ one. GO₃₅ gives the best performances concerning the magnetizing current, the iron core loss amount, the relative permeability and the reactive power. For example the GO₃₅ efficiency increase is close to two digits for rated operating conditions. In addition, under Pulse Width Modulation supply, a high magnetic noise decrease relatively to NO₆₅ machine was identified, attributed mainly to the switching magnetic noise component decrease. Consequently, this new sheet combination offers the double advantage of efficiency increase and magnetic noise decrease. These results emphasize the interest for a better understanding of magnetic flux transition between sheets.

III. SIMULATIONS

A. Discretization of the GO sheets

Tests results are not sufficient to understand how the magnetic flux establishes through adjacent laminations and why the 60° shifted structure gives better results. The simplest method would be to model the shifted GO structure using a 3D FE software. But 3D anisotropy associated to local saturations, considering air-gaps between sheets due to the insulation, constitutes a too complex numerical problem. The rotational field increases the difficulty. For that reason only a simple model involving a motor shifted yoke submitted to a unidirectional field is considered.

As the presence of teeth can be ignored, the simplicity of the magnetized area makes it possible to realise a model of the SMC by using non-linear variable reluctances. The advantages of using a RN model are the relatively low computing time, the high accuracy and, consequently, it can be considered as a compromise between FE and lumped parameter models. [6], [7], [8].

Assuming the magnetic flux distribution being homogeneous on the w (Fig. 2a) sheet width, the RN assembly representing a sheet can be made considering n identical segments each covering an angle of $360^\circ/n$. The different segments are denoted $S_{x,y}$ where x locates the sheet and y the segment. For the first sheet, these segments are denoted: $S_{1,1}, S_{1,2}, \dots, S_{1,j}, \dots, S_{1,n}$. Let us assumed that the $S_{1,1}$ axis is 90° shifted with the RD (Fig. 2a). Assuming the magnetic field circulation to be circular, $S_{1,1}$ can be characterized by the mean α value, denoted $\langle \alpha_{1,1} \rangle$, equal to 0° . For $S_{1,j}$, $\langle \alpha_{1,j} \rangle = (j-1)360^\circ/n$.

For each $\langle \alpha_{1,j} \rangle$ can be assigned a specific $\hat{b}(\hat{h})$ magnetizing curve as presented in Fig. 1. According to the α definition, the possible α values lie between 0 and 90° . To reduce the RN complexity, n must be a multiple of 4. So, $n=16$ is selected to define this RN as to make it possible to satisfy the spatial periodicity. It results that each segment covers sectors of each 22.5° angle opening (Fig. 2a). The Fig. 2b presents the RN for the first sheet pointing out the α practical values.

To characterize the α mean values for the other sheets, let us consider, for example: $\langle \alpha_{1,2} \rangle = 22.5^\circ$. The segment of the second sheet superimposed to $S_{1,2}$, denoted $S_{2,2}$, has, for $\beta=60^\circ$ counted positively as pointed out in Fig. 2, a value $\langle \alpha_{2,2} \rangle = 60^\circ - 22.5^\circ = 37.5^\circ$. For the third sheet, it comes: $\langle \alpha_{3,2} \rangle = 120^\circ - 22.5^\circ = 97.5^\circ$. That corresponds to a theoretical value which has to be converted in a practical one which is equal to equal to: $\langle \alpha_{3,2} \rangle = 180^\circ - 97.5^\circ = 82.5^\circ$. For the fourth sheet one can obtain: $\langle \alpha_{4,2} \rangle = 180^\circ - 22.5^\circ = 157.5^\circ$. That leads to a practical value equal to 22.5° which corresponds to $\langle \alpha_{1,2} \rangle$.

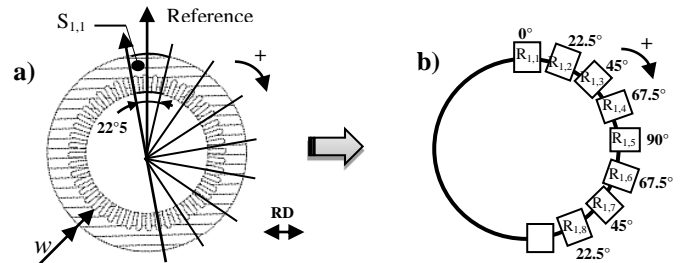


Fig. 2. Modeling one GO sheet (a) into a reluctance network (b)

B. Matlab Reluctance Network

Considering the structure presented in Fig. 2 in its developed form, a Matlab-Simulink RN model of the SMC is proposed in Fig. 3. According to the software notations, the reluctance elements are denoted $R_{x,y,\alpha}$. x and y are defined as previously and α corresponds to the α mean values just defined.

The \mathcal{R} reluctance value specific to each element is given by $\mathcal{R} = l/\mu s$. μ is the permeability of the material which constitutes

a given segment. l is the mean length of a segment, s its cross-sectional area given by the product wt where t represents the sheet thickness. l , w and t are constants. A controlled ϕ flux source is used to impose the flux level inside the yoke. μ is defined as: $\mu = \hat{b}/\hat{h}$. In order to determine μ for the different α mean values, an interpolation method is used taking account the magnetization curves given in Fig. 1.

Since the laminations are separated from each other by around 3 μm insulation, reluctances R_g are introduced to allow for filed circulation across the adjacent layers. R_g takes also into account the sheet reluctance across the sheet thickness assumed to be constant and equal to 60 times the air permeability [3].

ϕ is subject to a linear variation from zero to the saturation level at about 1.8T. In these conditions, for low ϕ , the μ values are known because they correspond to the linear part of the \hat{b}/\hat{h} curves. When ϕ increases, the μ values are adapted taking into account the saturation in each sheet that leads to a change in the ϕ repartition between sheets. The simulation is made for an elapsed time of one second.

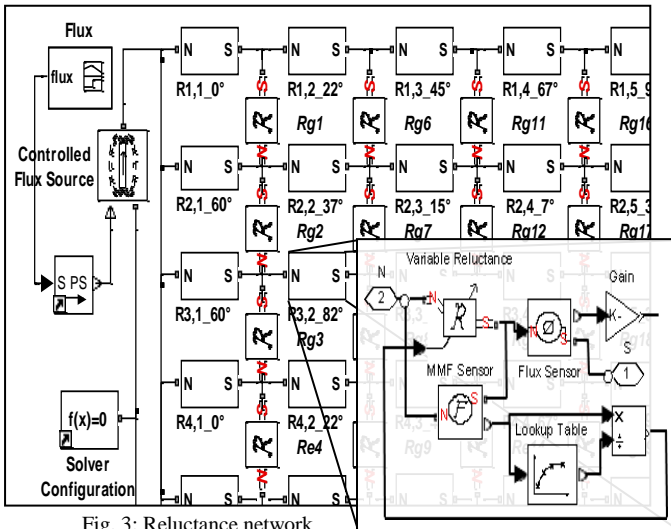


Fig. 3: Reluctance network

C. Finite element analysis

In the above mentioned simulation, the assumption of a magnetic path length across the SMC laminations independent from permeability values has been made. In this part, a FE model is set up to verify the relevance of this assumption.

The presented system (Fig. 4) is made of two concentric cores, separated from each other by an air-gap. The internal core is made of a unique material, with a constant relative magnetic permeability $\mu_{r1}=3000$, whereas the other one is made of two parts. The first part is made of the same material as the internal core, but the second part is made of another material, with a higher relative permeability μ_{r2} .

The procedure for the evaluation of the magnetic path length is the following: a magnetic flux density, equal to 1T, is set in the left part of the system, where the relative magnetic permeability is equal to μ_{r1} in both the internal and the external cores.

Hence, the resulting magnetic flux density is computed in the whole studied domain.

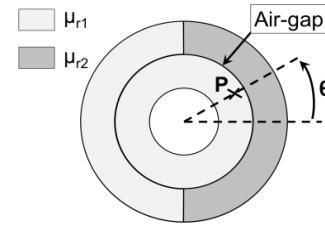


Fig. 4: The FE principle system of two concentric cores

As an example, Fig 5 shows the repartition of the magnetic flux density in the internal core for several values for μ_{r2} with respect to the angle noted θ in Fig. 4. One can see the expected evolution of the magnetic flux density vs. θ , which is a high value where the permeability is equal to μ_{r1} in both cores, and a low value where the permeability is equal to μ_{r2} in the external core.

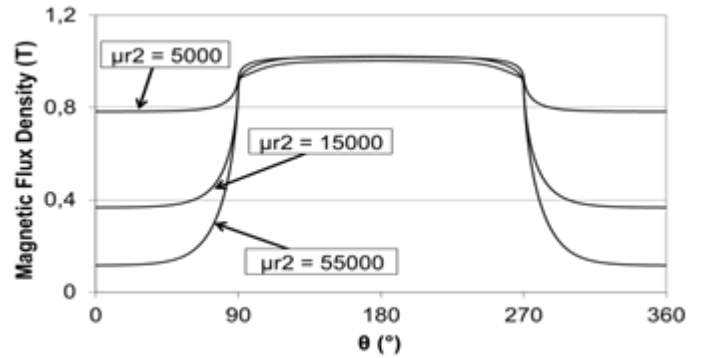


Fig. 5: Repartition of the magnetic flux density in the internal core

Fig. 6 shows the evolution of the θ angle where the transition between the two cores is done. As it can be see, the higher μ_{r2} , the lesser its influence on the magnetic path length. Hence, in case of a high ratio between μ_{r2} and μ_{r1} - like in the above study - the magnetic path length can be considered as independent of permeability.

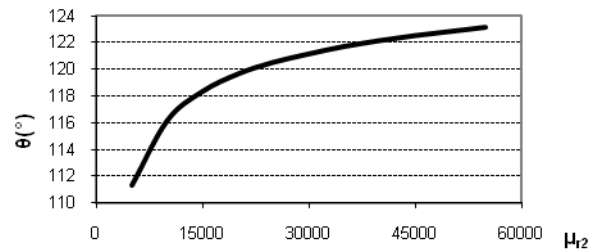


Fig. 6: Evolution the magnetic flux density in the internal core

D. Results and discussion

The results presented in the Fig. 7 give the flux density variations calculated in every element of the structure (0 to 90°). This makes it possible to understand how the GO structure allows the magnetic flux establishing mainly in areas of high permeability throughout the magnetic circuit. Due to the spatial periodicity the results for only three sheets are presented.

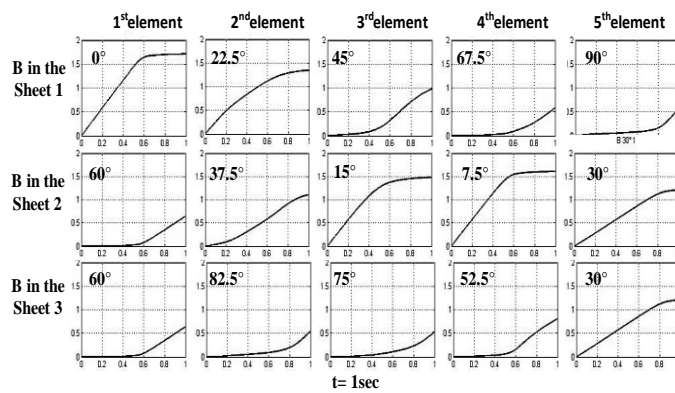


Fig. 7: The flux density timevariations inside every segment

First it can be observed that the easy magnetization direction appears in different parts of the SMC. Indeed, the flux density levels in the 1st segment of every sheet, show that until the sheet is saturated, at about 1.6T, only the first sheet is working. For the two others, because the RD are in the hard direction ($\alpha=60^\circ$) the local flux density is zero. At 0.5s the first sheet is saturated and second and third sheets start to work in a similar way. That means that reluctances between sheets do not affect in a significant way, in this case, the flux density distribution in sheets. In the same moment, for the 3rd element it can be observed that the second sheet start to work first. Because of the α value (15°) the saturation level is about 1.5T.

In Fig. 8, the global results for 6 sheets are presented for the maximum flux level. What can be observed is that the magnetizing process is not homogeneous across the SMC stack. The shift principle leads to an increase of the local flux density in the sheets those are well oriented. This allows the flux finding the high permeable directions in different parts of the magnetic circuit, channeling it, which gives a local and global reduction of the iron losses.

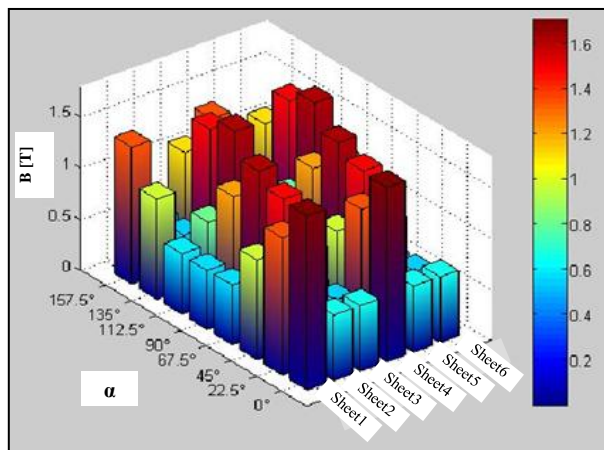


Fig. 8: Global results

IV. CONCLUSION

The study presented in this paper concerns the use of GO steel for the manufacture of high-efficiency motors. Indeed, the market for this type of machine is becoming wider as the performance standards are becoming more demanding, some

are mandatory in several countries, representing a potential market for this type of machine.

The internal phenomena of the shifting structure were analyzed, showing that this structure makes it possible for the magnetic flux to establish efficiently in areas of high permeability throughout the magnetic circuit. That leads to a reduction of the level of the flux density in local areas that has worse magnetic characteristics 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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