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Non-Segmented Grain Oriented Steel in Induction Machines

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Abstract—This paper presents a technique which improves energy efficiency of AC rotating machines by using Grain Oriented (GO) steel at stator core instead of Non Oriented (NO) steel. The losses of GO steel are lower than the NO ones, but only when the magnetic flux circulates along the rolling direction; consequently it is rarely used in AC machines where the magnetic flux rotates. By stacking many shifted GO laminations of AC machine stator, the flux pass from one lamination to another, and the core losses are reduced. A lot of experimentations have been done with unidirectional field, rotating field and with real induction machines. They show important improvements with GO shifted steel. The efficiency difference between a classical 10 kW induction machine and a modified machine with GO stator is more than 2 points. Moreover, the no-load current, and so the reactive power are smaller. This technique creates environmental and financial gains.

1. INTRODUCTION

Fossil fuels (coal, gas, and oil) account for 85% of the energy consumed on Earth. Their production will not always increase [1]. In addition, their use emits CO_2, widely recognized responsible for the greenhouse effect and global warming. In the coming decades, other sources of energy such as nuclear and renewable will not be enough to replace fossil energies. So it is necessary to reduce energy consumption. This could come from improvements of energy efficiency.

About 20% of the energy consumed on earth is used to produce electricity. This percentage could increase in the future: with less gas and oil, a part of consumption for heating and transports could come from electricity (heat pump, electrical public transport, electrical cars...). On the other hand, alternative energy sources to fossil fuels (renewable and nuclear) allow to generate electricity.

The majority of electricity consumption in industrialized countries is due to electric motors. Electric motor applications in industry consume between 30% and 40% of the generated electrical energy worldwide [2]. Electric motors with improved efficiency in combination with frequency converters can save about 7% of the total worldwide electrical energy. Roughly one quarter to one third of these savings could come from the improved efficiency of the motor [3]. Consequently, it is very important to reduce losses of electric motors.

This paper presents a method to reduce losses of AC rotating machines by using Grain Oriented steel. First, reminders about AC machines and electrical steels are given. Then, the use of shifted Grain Oriented steel is presented, with many experiments. Finally, the results of experimentations with real machines connected to the network are shown.

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2. ELECTRICAL AC MACHINES AND STEELS

2.1. Electrical AC Machines

In a rotating electrical AC machine, the flow of electrical currents generates magnetic fields which are canalized by laminated magnetic cores. Those last are generaly built with a stack of thin Non Oriented steel sheets. Figure 1 shows a wound stator (without frame) and a steel sheet of an 11 kW induction machine.

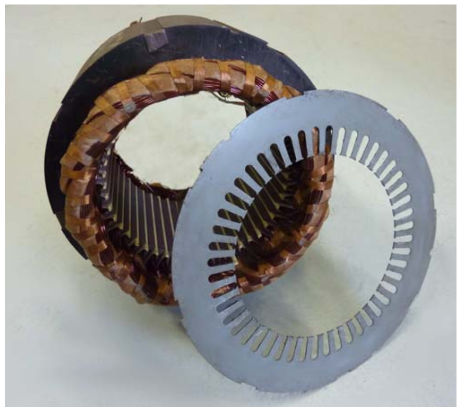

Figure 1. Wound stator and steel sheet from an induction machine.

The International Electrotechnical Commission defined in the international standard 60034-30 [3] the efficiency of three-phase induction motors: there are 4 classes from IE1 (standard) to IE4 (super premium, the best). In Europe the class EFF1 (the best) is equivalent to IE2, and EFF2 is equivalent to IE1.

Losses of electrical rotating machines come essentially from [4]:

- friction and windage loss,
- Joule effect losses tied to the windings heating, they represent approximately 30% of the losses at no load and 70% at full load,
- iron core losses due to the magnetic flux variation in the magnetic circuits; they represent, in a classical induction machine, approximately 50% of the losses at no load and 25% at full load.
- stray load losses tied to complex phenomena [5].

Majority of machines work rarely at full load. As iron losses are practically not in relation with the load-state, it is very important to reduce them. They are largely influenced by the steel quality. Many electrical steels exist.

2.2. Electrical Steels

The magnetic properties of GO steel are better than NO steel in the lamination direction. But this anisotropy is a problem in AC machines because of the rotating magnetic field. Only a few special machines, big turbo-generator particularly, use GO segmented steel [6].

Electrical steels can essentially be characterized by their magnetic permeability and their losses. In a general way the losses are in relation to the thickness of the sheets, but the steel quality is also important. The Table 1 shows the losses of some NO and GO steels at 50 Hz, $\hat{b}$ is the peak flux density value. It can be seen that three different steels with the same thickness 0.35 mm don't have the same losses (the losses of NO M 235-35A are given at 1.5 T, they would be more important at 1.7 T).

Among the iron losses, the static, dynamic and excess losses can be distinguished [7, 8]. At 50 or 60 Hz, most of the losses of classical NO machines are static losses (often called "hysteresis losses").

Table 1. Examples of characteristics of NO and GO steels.

Name	Thickness	Magnetic losses at 50 Hz	
		$\hat{b} = 1.7\,\mathrm{T}$	$\hat{b} = 1.5\,\mathrm{T}$
GO M 80-23 P	0.23 mm	0.8 W/kg	
GO M 125-35 P	0.35 mm	1.25 W/kg	
GO M 140-35 S	0.35 mm	1.4 W/kg	
NO M 235-35A	0.35 mm		2.35 W/kg
NO M 400-50A	0.5 mm		4 W/kg
NO M 700-565A	0.65 mm		7 W/kg

2.3. Anisotropy

Sheet strips have been cut at an angle α with respect to the Rolling Direction (RD) as shown on Figure 2, and their dimensions are 30×300 mm.

Measures were performed at Epstein Frame at 50 Hz [9]. The losses (in Watts/kg) versus the peak flux density $\hat{b}$ (in T) are in Figure 3 for GO M 140-35 and Figure 4 for NO 400-50A. The strong

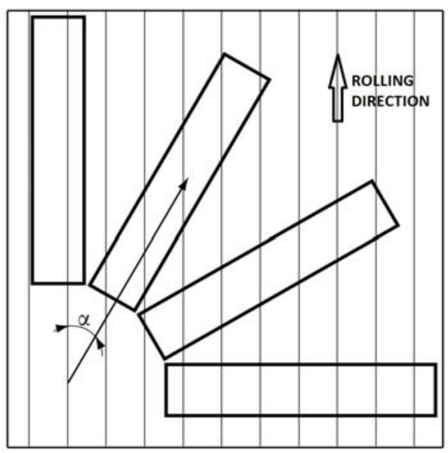

Figure 2. Epstein strips cut with an angle α (from S. Lopez's thesis [9]).

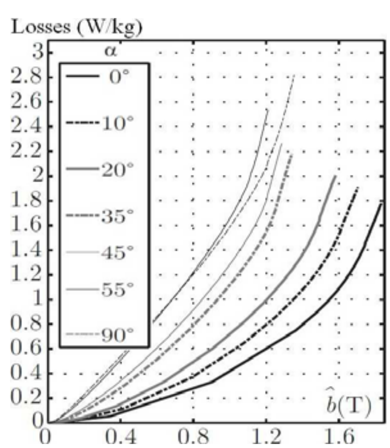

Figure 3. Losses of GO M 140-35 steel at 50 Hz (from S. Lopez's thesis [9]).

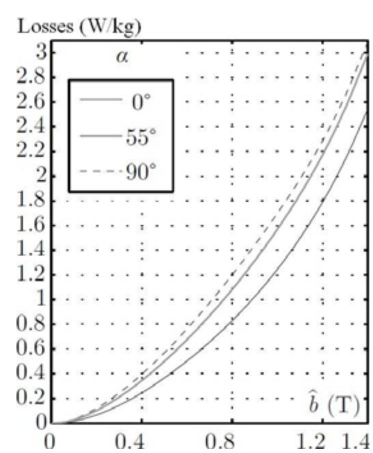

Figure 4. Losses of NO 400-50A steel at 50 Hz (from S. Lopez's thesis [9]).

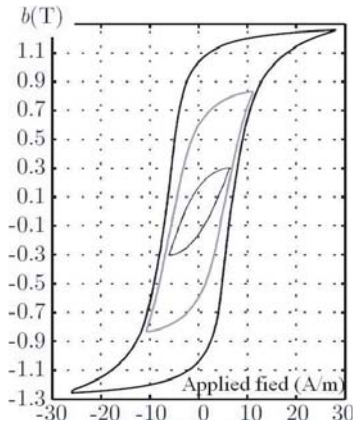

Figure 5. Losses cycles for GO steel at 2 Hz, $\alpha = 0°$ (from S. Lopez's thesis [9]).

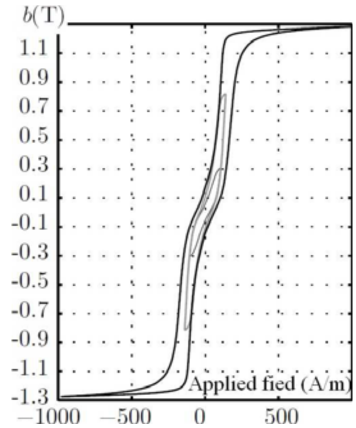

Figure 6. Losses cycles for GO steel at 2 Hz, $\alpha = 55°$ (from S. Lopez's thesis [9]).

anisotropy of GO appears clearly: the performances are better when the magnetic flux circulates in a direction near the RD. Anisotropy of NO exists but is not important. This explains why GO steel is essentially used in transformers where the main field direction is the rolling one.

The static losses can be estimated by measurements at low frequency: the losses cycles for GO M 140-35 at 2 Hz appear in Figures 5 and 6 for the best and the worst values of α (0 and 55°). As the scales of these figures are different, the necessary amperes-turns to have the same flux density are largely higher with $\alpha = 55°$; the magnetic permeability is smaller in this direction.

3. SHIFTED GO STEEL SHEETS

3.1. Principle

The stator magnetic circuit is assembled shifting each lamination from the previous one with a constant spatial angle β as shown in Figure 7. So the easy magnetization direction appears in different parts of the magnetic circuit. This principle forces the magnetic flux to pass from one lamination to another, along the z axis, in order to satisfy the principle of energy minimization [10, 11]. This particular circulation of magnetic flux has been confirmed by 3D Finite Element simulations [12]. Another important result of this study is that the air-gap between sheets (due to the insulated coating which thickness is 6 to

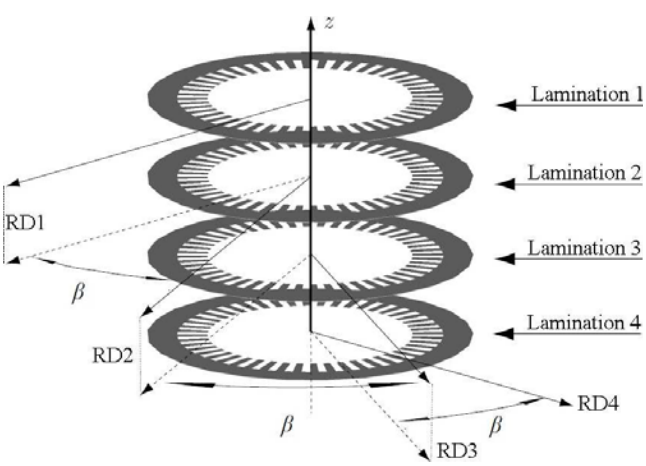

Figure 7. Shifted and stacked sheets (from S. Lopez's thesis [9]).

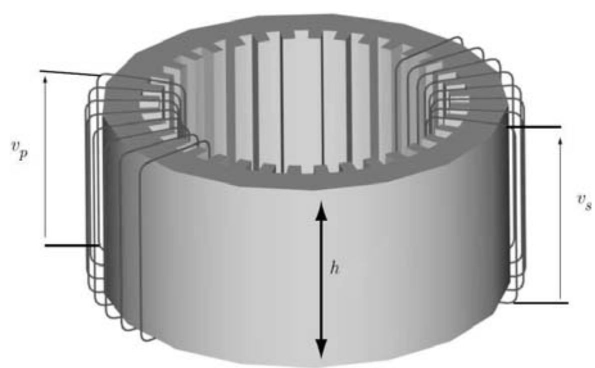

Figure 8. Magnetic circuit for unidirectional field tests (from S. Lopez's thesis [9]).

8 µm) has a very low influence on the flux repartition.

In the following the notation $GO_{35}\beta$ is used for example with 0.35 mm GO steel shifted with β degrees.

3.2. Experiments with Unidirectional Field

Several magnetic cores were built as shown in Figure 8 with different qualities of electrical steel and different β shift angle. Each core has a primary 100 turn winding, supplied with a sinusoidal voltage. A secondary 100 turn winding allows appreciating the magnetic behavior and calculating the flux density by measuring the induced voltage. In this way the teeth are not magnetized. The cores contain 100 laminations if their thickness is 0.5 mm, or 143 if their thickness is 0.35 mm; so the total core length h is always 50 mm and the masses are the same. The external diameter is 200 mm and the internal one is 163 mm. By measuring the primary current and the secondary voltage, it is possible to deduce the active and reactive power as in a transformer and so the iron losses and the magnetic permeability [13].

Figure 9 shows the core losses and Figure 10 the permeability μ_r at 50 Hz for different steels versus the flux density: NO_{50} concerns non shifted NO M 400-50A, GO_{35} concerns GO M 140-35 S with several shift angles. It appears clearly that the performances of the GO core are better than those of the NO one, and that the best shift angle is near than 90°.

AC machines use generally 0.65 mm NO steel; so the tested NO M 400-50A which thickness is 0.5 mm is a better one. Nevertheless some calculations have been done to estimate the losses if the NO thickness was 0.35 mm, as the used GO. The static, dynamic, and excess losses were separated

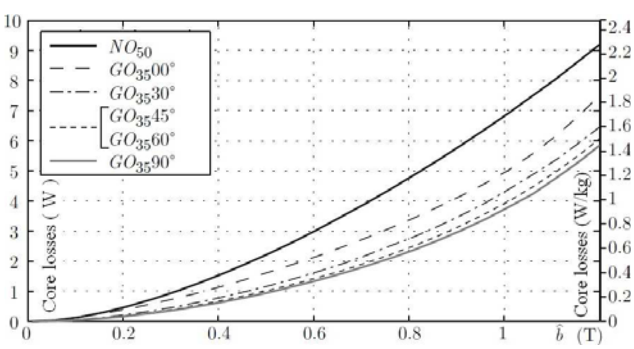

Figure 9. Core losses for different configurations of GO and NO steel with 50 Hz unidirectional field (from S. Lopez's thesis [9]).

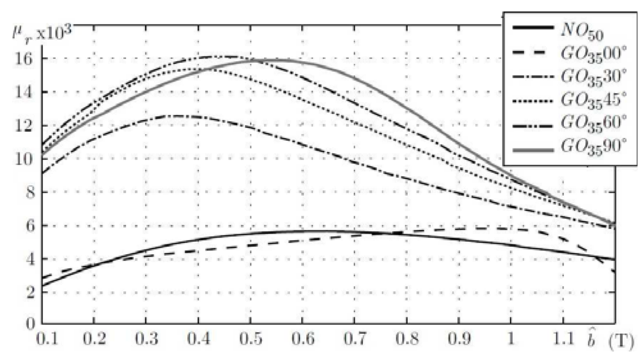

Figure 10. Magnetic permeability for different configurations of GO and NO steel with 50 Hz unidirectional field (from S. Lopez's thesis [9]).

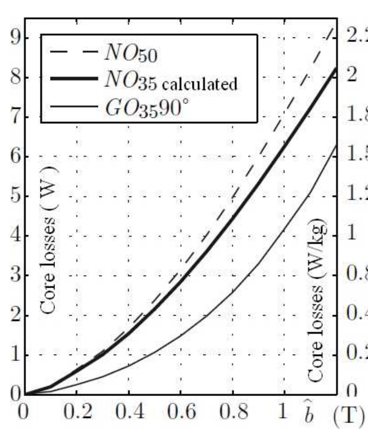

Figure 11. Core losses for NO 0.5 mm, NO 0.35 mm and GO 0.35 mm with 50 Hz unidirectional field (from S. Lopez's thesis [9]).

with measurements at low frequency; then the estimated losses of a fictitious 0.35 mm NO core were calculated [13]. The results are given in Figure 11: the performances of the GO core are better than those of the NO core even if the thicknesses of the laminations are the same. This principle has been patented [14].

3.3. Experiments with "Static Motors"

The previous experimentations have to be confirmed with rotating field [15]; consequently "static motors" were built. The principle consists of stacking some laminations especially laser cut: they are similar to real ones but the rotor circuit is included and attached to the stator by 3 small joints. Figure 12 shows one lamination and a static motor. The total core height is 8 cm. Two three-phase windings are placed in the slots. The primary one is electrically powered and creates a rotating field as in a real machine. The auxiliary one is used to measure the induced voltage: it allows to estimate the air-gap flux density and, measuring the primary current, to calculate the core losses without Joules losses. Moreover there are no mechanic losses because there is no rotation, and it is relatively easy to create a lot of configurations with different steel qualities and shift angles.

A lot of measures were done with static motors [16] with NO M 400-50A and GO M 140-35 S. Figure 13 shows the core losses versus the air-gap flux density. The conclusions are similar to the previous ones: shifted GO are largely better than non-shifted GO and NO steel.

Figure 12. Static motor: one sheet and a wound stack.

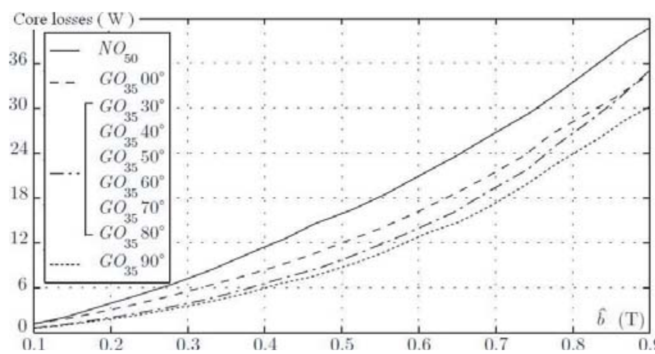

Figure 13. Core losses for different configurations of GO and NO steel with 50 Hz rotating field (from S. Lopez's thesis [9]).

4. APPLICATION TO INDUCTION MACHINES

Real induction machines have been realized with shifted GO steel.

4.1. Practical Realization

Many three-phase induction machines have been modified. New GO and NO laminations have been laser cut, annealed, and placed into stator frames with different shift angles.

The initial machines had the following characteristics: 10 kW, 230/400 V, 36.5/21 A, 1440 rpm, 50 Hz, $\cos\varphi = 0.81$, iron length 0.179 m, external diameter of the laminations 200 mm, 48 stator slots. One machine wasn't modified; its laminations are NO M 700-65A (0.65 mm). A machine with NO M 400-50A (0.5 mm) were built with $\beta = 60°$ (the NO sheets were shifted, in the case where the small anisotropy of the NO steel would ameliorate the performances). Two machines with GO M 140-35 S (0.35 mm) were realized, one with $\beta = 60°$, the other with $\beta = 90°$. In each machine, a small auxiliary stator winding allows to estimate the flux density in the air-gap by measuring the induced voltage. The masses of the different machines are the same. The rotors have not been modified.

4.2. Results

The machines were powered by a system of 50 Hz three-phase balanced voltage.

4.2.1. No Load Experiments

The no-load tests are important because a lot of electrical machines in industry work often at no load or low load. Moreover the iron losses are practically independent of the load state. The active power and the current absorbed by the different machines were measured.

The results concerning the no-load active power and the no-load R.M.S. current are given in Table 2 for three configurations: NO_{65}, $NO_{50}60°$, $GO_{35}60°$. The no-load losses include not only the iron losses, but also Joules and mechanical losses, which are not influenced by the change of sheets. Despite this, the GO core is largely better. The difference between the machine with GO core and the original machine is 38%. Furthermore the no-load current is 14% lower with GO core although this quantity is largely influenced by the air-gap thickness (which is the same on all the machines). This reduction of no-load current means a better power factor and so, less reactive power and less line losses.

Table 2. No load losses and current for different machines.

	$GO_{35}60°$	$NO_{50}60°$	NO_{65}
Losses (W)	396.2	444.2	548.7
Stator current (A)	8.6	8.85	9.8

4.2.2. Characteristics with Load

The currents, the different losses and so the efficiency are calculated for all the machines as recommended by the standard IEC-60034-2 [17, 18]. The parameters of the single-phase equivalent scheme are separately determined by practical classic tests (no-load, blocked rotor...). Then it's possible to calculate the characteristics at different operating points [9].

For example, the calculated stator current versus slip is presented in Figure 14, and the calculated iron losses in Figure 15. The difference between NO and GO is approximately constant concerning the iron losses, but it increases with the slip concerning the stator current. Consequently the differences concerning the joules losses increase with the slip, which influences the efficiency.

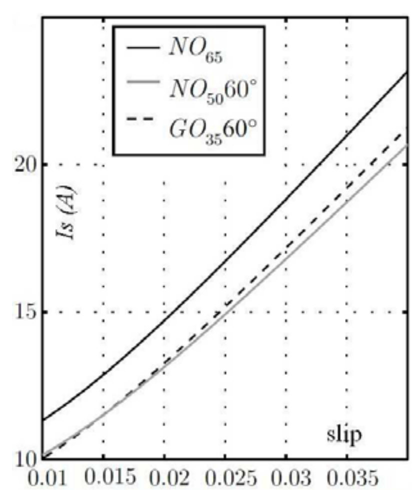

Figure 14. Stator current for different machines (from S. Lopez's thesis [9]).

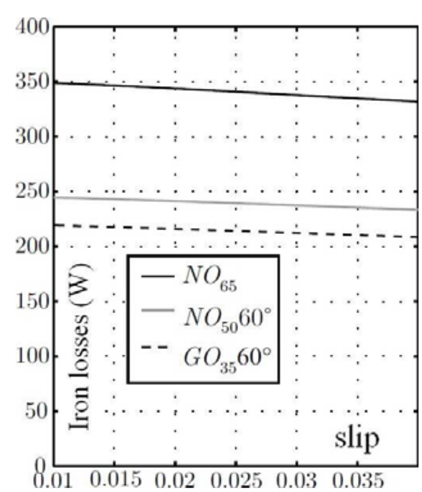

Figure 15. Iron losses for different machines (from S. Lopez's thesis [9]).

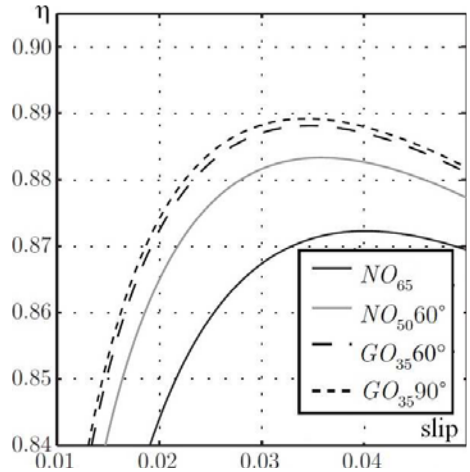

Figure 16. Efficiency for different machines (from S. Lopez's thesis [9]).

The efficiency η versus the slip s has been calculated in four cases: NO_{65} (original machine), $NO_{50}60°$, $GO_{35}60°$, $GO_{35}90°$. The results are given in Figure 16 and Table 3. The machines deliver their rated power when the slip is about 3%, then the efficiency difference between the original machine and the best one is 2.16 points. This difference is important because, in the IEC 60034-30 standard, only 1.6 points separate the efficiency of an 11 kW IE2 machine from an IE3 one. The gain is mainly due to iron losses (80%), and more particularly to static losses. Winding Joules losses represent the other part of the gain.

Table 3. Efficiency for different machines.

	$GO_{35}90°$	$NO_{35}60°$	$NO_{50}60°$	NO_{65}
η for $s = 3\%$	88.86%	88.7%	88.2%	86.7%
η for $s = 2\%$	87.5%	87.3%	86.55%	84.45%

4.2.3. Environmental and Financial Gains

This study shows that, compared to a classical machine, the consumption of a 10 kW machine with GO shifted laminations is 150 W less. The gain, approximately 2% at full load, increases to 30% at no load. A lot of electric motors are always connected to the grid, often at low load. In those conditions the gain of 150 W represents 1314 kWh per year, the financial gain varies approximately from 100 to 350 in Europe, from 70 to 500 US$ in North America, and more than 800US$ in some islands (2013 rates). In addition the line losses are reduced because the power factor of such a machine is better.

The additional cost to build such a machine will not be important because only the stator laminations are different. As an electrical machine can work tens of thousands of hours, it will be easily amortized.

A Life Cycle Analysis was realized [19]. The additional energy consumption necessary to build the machine was estimated at 40%. 2000 hours of operation are sufficient to compensate the additional energy consumption. Ten environmental criteria have been studied such as greenhouse gas emissions, eco-toxicity, depletion of natural resources, water consumption... The balance is always positive or neutral.

5. CONCLUSION

The losses of induction machines can be reduced by using GO electrical steel instead of NO steel. The stator laminations have to be shifted. Experiments have been done with single-phase magnetic core, three-phase "static motors", and real 10 kW induction machines, and show that the performances are better with GO shifted. The best shift angle is 90°. The efficiency of a GO modified machine was increased by more than 2 points.

These results can probably be improved by using a better GO steel quality. Moreover, the energy gains would be greater with a more powerful and higher efficiency machine (designed to work at low flux density).

Furthermore, it is likely that the conclusions would be similar to other AC machines (synchronous, switched reluctance...). Possible applications therefore concern a lot of motors whose uses are very different (pumping, ventilation, cold production, transport...) but also electricity production. Many big alternators already use GO steel with a cut sheet metal into segments, but this is not the case of medium power alternators used, for example, in wind turbines. They could produce more electricity with this technique.

Another positive point concerns the magnetic noise: electromagnetic phenomena in the air-gap of the machine produce forces, stator vibrations, and noise. Some ongoing studies suggest that shifted laminations have a positive influence on vibrations and noise [20, 21].

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