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# Contribution of new electrical materials to the design of large induction motors

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**Abstract**—The aim of this paper is to present the possibilities for reducing the size of large induction motors with new electrical materials taken into account the thermal constraints. This paper highlights the possibilities for reducing losses, increasing the efficiency and decreasing the weight, by taking different grades of materials. A nonlinear multiobjective optimization is used to determine the best solution, by varying the internal and external geometric parameters.

**Index Terms**—Induction motor, magnetic circuit, insulation, motor design, electrical materials, magnetic sheets

## I. INTRODUCTION

A plenty of medium and large power Induction Motors (IM) made in the first half of the 1900s are still operating today [1] and improvement of the efficiency, volume reduction or even both is possible by using current materials like insulation or magnetic materials [2]. The aim of this paper is to quantify the influence of the materials in the dimensions of different IM at given rated power, from the 1950s to present days and to present the contribution of new materials on performance improvements.

The main dimensions of the IM are essentially related to the power density in  $\text{kW s/m}^3$  ( $C_{mec}$ ) [3]. This quantity depends on the specific current loading in  $\text{A/m}$  ( $A$ ), the air gap flux density in  $\text{T}$  ( $\hat{B}_e$ ) and the winding factor ( $K_{w1}$ ) in equations 1 and 2 which give the mechanical power in  $\text{kW}$  ( $P_{mec}$ ). Independently of the speed and thus the pole number, the constant  $C_{mec}$  provides the main dimension of the machine. Fig. 1 presents the evolution at different periods of this constant for pole pair numbers from 2 to 6. The curves allow one to deduce the evolution of the inner stator diameter and length at given speed [4] [5].

$$P_{mec} = \frac{\pi^2}{\sqrt{2}} \cdot K_{w1} \cdot A \cdot \hat{B}_e \cdot D^2 \cdot L \cdot n \cdot \cos\phi \cdot \eta \quad (1)$$

$$P_{mec} = C_{mec} \cdot D^2 \cdot L \cdot n \quad (2)$$

$$C_{mec} = \frac{\pi^2}{\sqrt{2}} \cdot K_{w1} \cdot A \cdot \hat{B}_e \cdot \cos\phi \cdot \eta \quad (3)$$

The first section of this paper deals with the improvement of IM motors with the details of the impact of electrical insulation

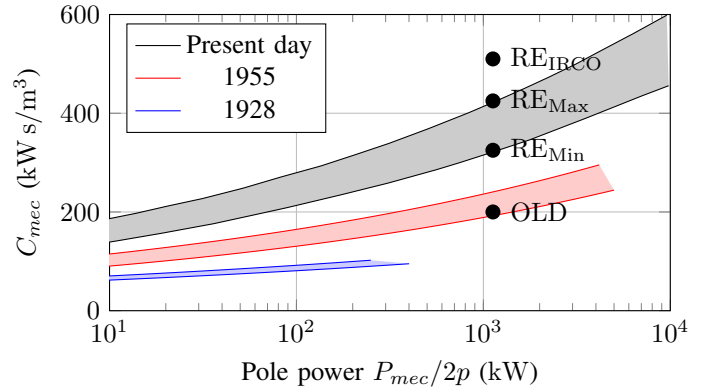


Fig. 1. Evolution of machine sizing constant  $C_{mec}$  based on empirical knowledge and a traditional know-how, for pole pairs 2 to 6.

$\cos\phi$ : power factor       $\eta$ : efficiency  
D: inner diameter (m)      L: length motor (m)  
n: speed revolution (rps)      p: pole pair number

and magnetic circuit quality. The second section presents the simplified thermal circuit model. The third shows the main dimensions chosen and the first results. The fourth presents the optimization and dimensions of the best case and a conclusion for the last section.

## II. IMPROVEMENT OF THE IM

### A. Presentation of the discussed examples

The paper focuses on the design of a 4.5 MW IM, with a 6.6 kV voltage supply, two pole pairs. This is a squirrel cage machine with 72 stator slots and 62 rotor slots. Four different configurations with the same airgap width have been studied :

- 1) Old electrical insulation and old magnetic circuit  
 $C_{mec} = 200 \text{ kW s/m}^3$  (named=OLD)
- 2) Recent (RE) materials, minimum value of  $C_{mec} = 325 \text{ kW s/m}^3$  (named=RE<sub>Min</sub>)
- 3) Recent materials, maximum value of  $C_{mec} = 425 \text{ kW s/m}^3$  (named=RE<sub>Max</sub>)
- 4) Recent materials, iron cobalt electrical steel sheets, and high value of  $C_{mec} = 510 \text{ kW s/m}^3$  (named=RE<sub>IRCO</sub>)

TABLE I  
OLD ELECTRICAL INSULATION.

Localisation	Years	width (mm)	Composition
Flat copper	1926 / 1928	0,4	Coton wrapping or tape paper
	1955	0,3-0,4	
Winding / Groundwall	1926 / 1928	2,5-4	Micanite sheath / tube
	1955	2,5-3	

TABLE II  
RECENT ELECTRICAL INSULATION.

Localisation	width (mm)	Composition / laminating
Flat copper	0.3	Mica tape with polyester film
Winding	0.15	Mica paper with metallic salt accelerator and zinc naphtanate
Groundwall Corona effect	0.085	Conductor tape with polyester tape
Groundwall Finish tape	0.18	Glass and polyester and polyester felt with epoxy resin
Total Winding + Groundwall	0.415	Total insulation for the coil winding and groundwall

The three values of  $C_{mec}$  come from usual design, whereas the last one corresponds to the size reduction target.

### B. Impact of electrical insulation

The electrical insulation evolution allows the increase of the voltage supply, the dielectric strength and the acceptable temperature. This concerns the high voltage insulation and the fill factor improvement of copper in the slots [1] [6].

Tables I and II give an overview about the improvement of electrical insulation. It can be seen in table I that before 1960s the groundwall insulation was essentially made of micanite tube which is an assembly of thin flakes of mica stuck together with a flexible varnish, the tube thickness depends on voltage supply. The conductor insulation was composed of various papers and cotton. A few turns around the conductors were necessary.

The new electrical insulations presented in the table II, are composed of several types of thin materials, each serves to protect the IM (turn-to-turn insulation, corona effect, mechanical protection). To the nearest of the conductor, the turn-to-turn protection is a base of mica paper with epoxy resin impregnation.

### C. Impact of magnetic circuit quality

The electrical steel sheet quality has been improved through better building process. About the non-oriented steel sheet, three categories based on datasheet have been considered : old iron silicon sheets (thickness 0.5 mm or 1 mm) are taken as a reference, recent iron silicon sheets (thickness 0.5 mm) and recent iron cobalt sheets (thickness 0.35 mm) in Fig.2 and 3 [7] [8].

Among the electrical steel sheets qualities used in the paper, the lowest losses are for iron cobalt called IRCO with 1.4 W/kg at 1.5 T and 50 Hz. This steel sheet is characterised by a high saturation induction at 2.3 T, whereas the others have a weaker saturation at 1.8 T, but the difference in the bend of the curve is more important for the old characteristics. Moreover the old sheets have specific losses between 6 W/kg and 8 W/kg at 1.5 T and 50 Hz.

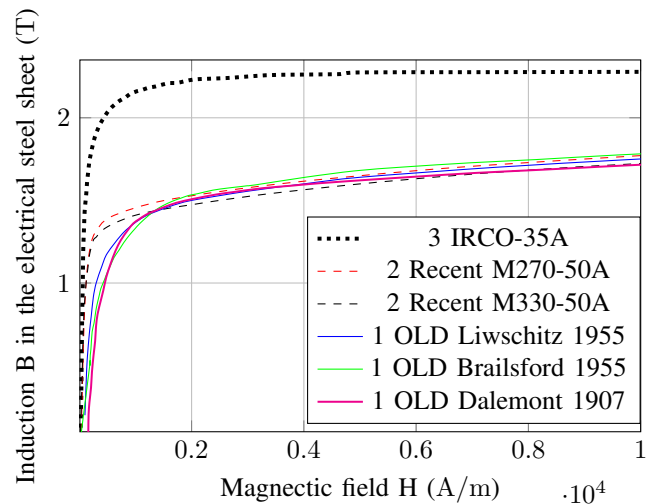


Fig. 2. Several electrical steel sheets quality comparison of B-H curves.

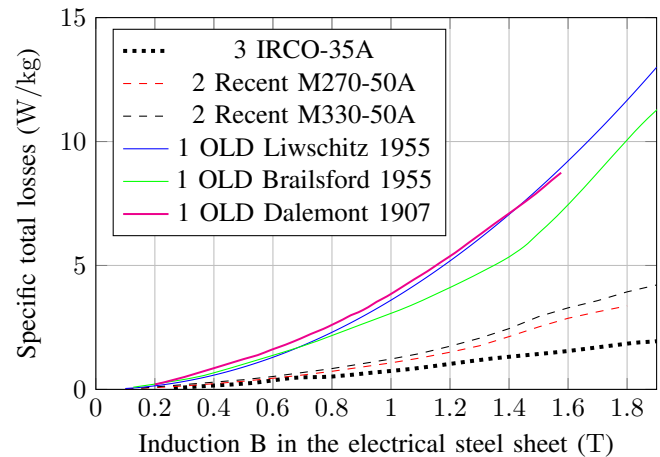


Fig. 3. Several electrical steel sheets quality comparison of specific total losses.

### III. SIMPLIFIED THERMAL CIRCUIT MODEL

In the aim to optimize the size of IM machine, the thermal circuit model will allow to check the temperature within the IM. It is well known that the critical temperature point are inside the stator conductors and the winding heads. Joule and magnetic losses will be the main cause of temperature increase in the machine.

The selected thermal model considers only the transfers of heat by radial conduction within the machine. The use of thermal potential differences will allow to evaluate the temperature increase. The thermal model Fig. 4 and 5 will be in a steady state operating condition of the machine. [9]

In this thermal network, two power sources are considered in this circuit, the Joule and iron losses in the stator. The variables  $T_i$  correspond to the temperature at different points in the stator. The thermal resistances of this network are calculated from the analytical equations of the heat equations at the areas borders defined by the radius  $Rad_i$  in the Fig. 5. They depend on geometrical parameters and the materials thermal conductivity. The resistances are calculated at different points of the winding, insulation, stator yoke and the frame in contact with the ambient air. The thermal conductivities used in the model are [9] :

- Winding copper 5 W/(m K);
- Winding insulators 0.20 W/(m K);
- Iron and silicon magnetic circuit 25 W/(m K);
- Cast-iron housing 52 W/(m K).

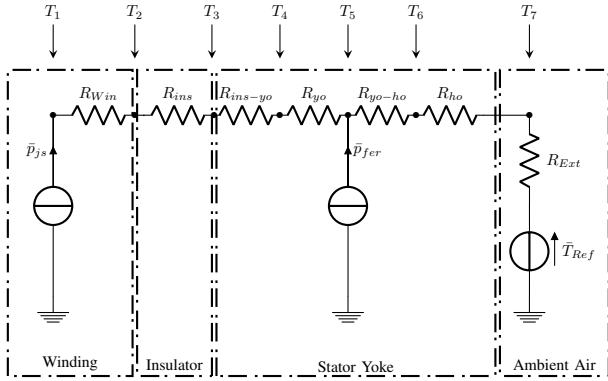


Fig. 4. Simplified thermal circuit model.

### IV. MAIN DIMENSIONS AND RESULTS

The analytical calculations are based on the usual equations of large IM design [4] [5], and the characteristics given in Fig.1. Partial results are presented in table III that gives the main dimensions for each configuration, based on Fig. 1 for  $C_{mec}$  and considering materials characteristics.

For  $RE_{IRCO}$  the constant is chosen at 510 kW s/m<sup>3</sup> higher than the present day area of Fig. 1 corresponding to the gray area between  $RE_{Min}$  and  $RE_{Max}$ . The results of the design process shows that for the same rated power, the air gap flux density is slightly more important for the machine with IRCO

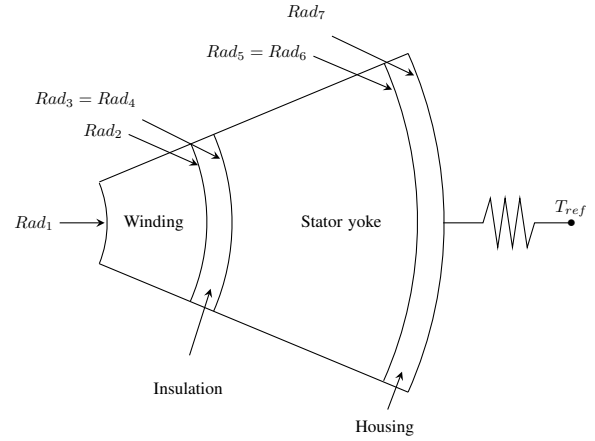


Fig. 5. Simplified stator for the thermal model.

because the magnetomotive force losses in the material are lower.

Fig. 6 gives the efficiency of each machine resulting from analytical calculations. The results show an improvement of efficiency between the old and the new materials. The results in Fig. 7 show a decrease of 52.3 % for the iron weight, 15.8 % for the copper weight and 0.54 point efficiency rise, between the OLD and the best IM configuration (IRCO). However, for usual applications the economic criteria lead to take an iron-silicon magnetic circuit (cases  $RE_{Min}$  and  $RE_{Max}$ ) instead of IRCO. Concerning the efficiency, the improvement is roughly the same but the iron weight and volume are more reduced with IRCO.

The table IV shows the iron and copper losses in the stator, that can be used for the thermal model. Then, the thermal circuit model gives the temperature  $T_1$  for each machine which corresponds to the critical point located around the conductors. Table IV also presents the temperature  $T_1$  for each machine. This table shows a reduction of local heating at the critical point, between the old and new configuration, caused by an insulation thickness improvement. The results at the main losses and the temperature  $T_1$  are consistent.

### V. OPTIMIZATION OF IRCO CASE

The previous configurations are stem from datasheet curves of Fig. 1. Especially, in the recommended area between  $RE_{Min}$  and  $RE_{Max}$ , the design will insure acceptable temperature. The

TABLE III  
PRINCIPAL INTERNAL DIMENSIONS FOR 4.5 MW IM.

IM	Inner diameter (m)	Outer diameter (m)	Iron length (m)
OLD	1	1.57	0,9
RE Min	0,8105	1.19	0,90
RE Max	0,737	1.08	0,82
RE IRCO	0,68	1.05	0,76

TABLE IV  
MAIN SOURCES OF THERMAL MODEL AND TEMPERATURE OF CONDUCTORS INSIDE THE STATOR.

IM	OLD	RE Min	RE Max	RE IRCO
$P_{js}$ (kW)	28.8	24.4	22.4	27.2
$P_{fer}$ (kW)	38.4	12.85	16.6	11
$T_1$ (°C)	127	82.7	75.8	83.6

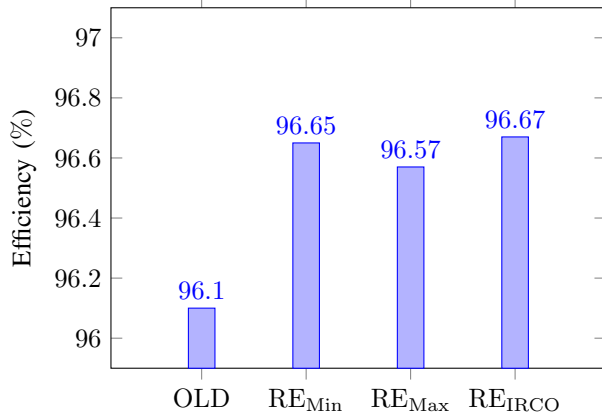


Fig. 6. Efficiency of each configuration.

aim of this section is to calculate and control the case IRCO outside this area.

In order to obtain optimized results for iron cobalt case, a nonlinear multiobjective optimization with the analytical calculations is used [10] [11]. This optimization makes it possible to vary the main dimensions of the machine (diameter and length) and the sizes of stator slots. The main objective is the smallest dimensions with equivalent efficiency to this range of motors. The constraints used in this optimization define the physical limits that can be taken into account. These limits are: the saturation of the magnetic induction at

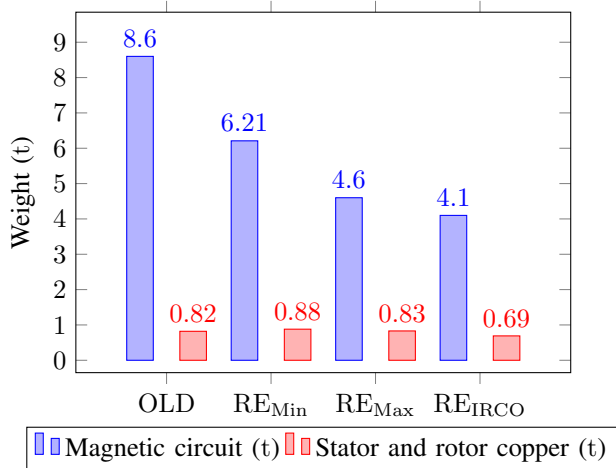


Fig. 7. Weight of magnetic circuit and stator and rotor copper of each configuration.

2.2 T for iron cobalt electrical steel sheet, the magnetizing current, the current density in the winding, the maximum temperature inside a conductor and one mechanical constraint, corresponding to the shaft diameter chosen at 0.25 m for this power.

The variation of the input parameters in the genetic algorithm returns a matrix with several results depending on the objectives. This matrix shows a result set in Fig 8 in the form of a pareto curve.

Based on this curve, it is possible to calculate the volume and choose a pareto optimum. This point gives a length higher than diameter : the inner diameter is 0.684 m, the outer diameter 1.05 m, and the length 0.66 m. The efficiency is slightly less than the previous design with 96.65%. The magnetic circuit weight is of 3.37 t and 0.6 t for stator and rotor copper.

TABLE V  
COMPARISON BETWEEN TWO IRCO CONFIGURATIONS.

IM	RE IRCO	Optimization IRCO
$\eta$ (%)	96.67	96.65
Weight iron (t)	4.1	3.4
Weight copper (t)	0.69	0.6
$T_1$ (°C)	83.6	90
$P_{js}$ (kW)	27.2	31.8
$P_{fer}$ (kW)	11	11.7

If we compare this solution with the previous RE<sub>IRCO</sub> one (Table V), it can be noted that the lowest weight and dimensions are obtained with the same efficiency. The temperature increase but is still acceptable. (This new optimized design leads to  $C_{mec} = 580 \text{ kW s/m}^3$ ).

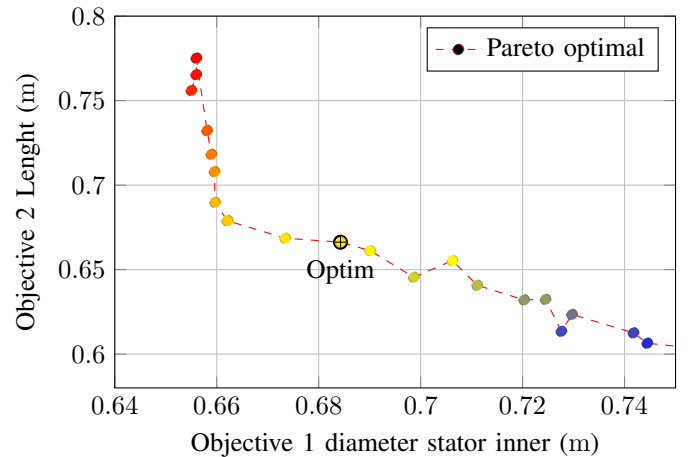


Fig. 8. Pareto curve for two objectives about a design motor with iron cobalt electrical sheet steel.

## VI. CONCLUSION AND DISCUSSION

This paper presents a study about the building of IM at different periods. It shows how the electrical material ameliorations have an impact on the main dimensions, the weight

and the efficiency. The results show that for the best case with the iron cobalt magnetic circuit, an important reduction, of internal diameter, length and weight, and a 0.54 point efficiency improvement can be obtained. To specify the results, and validate the IM reduction, a thermal circuit model is exploited to check the temperature at the critical point  $T_1$  located inside the stator conductors. To improve the IM design, a genetic algorithm is used to find the best solution using the analytical relations and considering the thermal constraints. The geometric parameters of IM can be changed for different objectives, as minimising weight with better efficiency. The optimization allows to find the best solution into the Pareto matrix. The optimal weight reduction is a 60.8 % for magnetic circuit and 26.8 % for total copper.

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