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ECO-DESIGN OF ELECTRO-MECHANICAL ENERGY CONVERTERS: THE CASE OF THE THREE-PHASE SQUIRREL-CAGE INDUCTION MACHINE

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Abstract — This article provides the first results of the eco-design problematic on the single criterion of energy for electro-mechanical energy converters through the model of a three-phase squirrel-cage induction machine connected to a variable frequency and voltage power supply. Its sizes are computed through a genetic algorithm by minimizing two contradictory objectives: the mass of the active parts and the global energy requirement on life cycle. At first we compare these optimizations to more "traditional" ones in which only operating losses are considered. This brings us to identify in what circumstances life cycle assessment has an impact on electro-mechanical energy converters design. This impact is even more significant that the operating time of the machine at constant load power is short before the total time of use. Finally the sensitivity of the optimization's results to the elementary raw materials energy costs is considered.

Index Terms — Eco-design, three-phase squirrel-cage induction machines, electro-mechanical energy converters, life cycle assessment (LCA), multi-objective optimization.

I – Introduction

The first studies on aspects of the life cycle of products and materials take place in the late 60s, with a particular interest in energy efficiency. Gradually, other environmental impacts were incorporated such as wastes disposal, or different kind of pollution, but the complexity of impacts measurements and comparisons didn't help these studies to develop as fast as they should have.

This methodology has stayed in laboratories until the mid-90s where standardization was finally developed in 1996: ISO 14001 "environmental management". This standard, revised in 2007 [1], offers business management and organization methods to minimize the impacts of their activities or products on the environment, and to establish an action plan to improve their environmental performance.

This set of standards proposes a definition of the tool named life cycle assessment, which principle will be applied in our study [2]. With the increasing development of its application in business and in laboratories, life cycle assessment becomes the subject of working groups and scientific initiatives [3]. This tool is now mature enough to consider incorporating it into the design of electro-mechanical energy conversion systems.

II - Model and method

A. Eco-design

The energy management has become an alarming actuality. Therefore, the design of the electromagnetic systems has to be reconsidered on global energy basis preferably to the designs we know as power losses or investment minimization. The life cycle includes all the stages through which will pass the product from its manufacture (including raw material extraction, transport) at its last filing (dismantling and then recycling of materials)

Eco-design can have several definitions depending on the tools chosen to conduct the study. In our case we will expand a "classical" design method taking in account the energy criterion on the lifetime of the product.

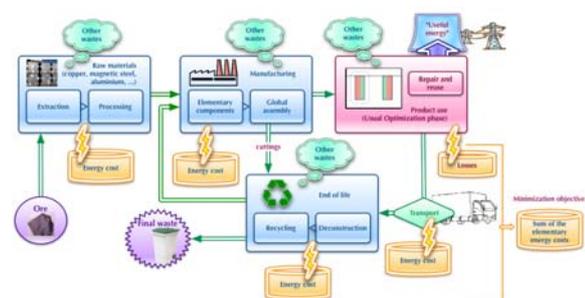


Fig. 1. The life cycle of a system and gross energy requirement

Indeed energy consumption represents one of the many environmental impacts generated by the

product on its life cycle. We believe more over that energy consumption represents, in the case of electro-mechanical energy converters, one of the major environmental impacts to be taken into account as a design's criterion really affecting the sizes of the machine. The methodology implementation remains independent of the considered impact, and can easily be extended to other environmental impacts in the future.

The two objectives to minimize in this study are the gross energy requirement on life cycle, W_{ACV} , and the mass of the active parts, M_a .

The optimization's tool used is an evolutionary multi-objectives algorithm. It operates then on the principle of Pareto front, which offers a range of intermediate structures minimizing conflicting objectives through successive iterations by using a genetic algorithm. The synoptic of these optimizations is proposed below. We chose to use the NSGA-II [4], [5].

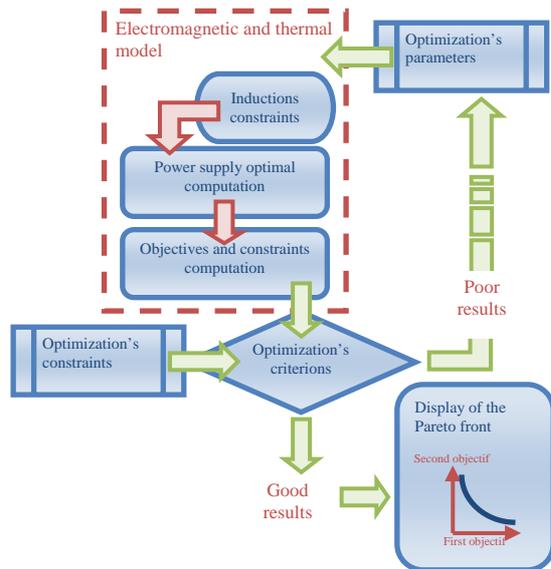


Fig. 2. Optimization's synoptic

Finally, the purpose of this study is to develop an eco-design methodology suited to the field of Electrical Engineering and not to obtain accurate quantitative results. Similar Studies have already been conducted but addressing the economic costs and not the energy [6]. We apply here these life cycle assessment principles on energy criteria

B. The induction machine model

We consider a three-phase squirrel-cage induction machine which includes a three-phase stator winding with $2p$ poles. The three-phase stator windings are powered by a balanced three-phase voltage system whose amplitude and frequency are variable and computed to minimize operating losses although the

power supply converter is not considered in our study.

The equations of one phase of the induction machine are reduced by using the electrical equivalent single phase scheme presented Figure 3, which will enable us to determine the torque's expression, so that copper and iron losses. The resistive and inductive components appearing on the scheme depend on the geometry of the machine. Mechanical losses are not considered here but could easily be incorporated in the simulations for example on the basis of speed function.

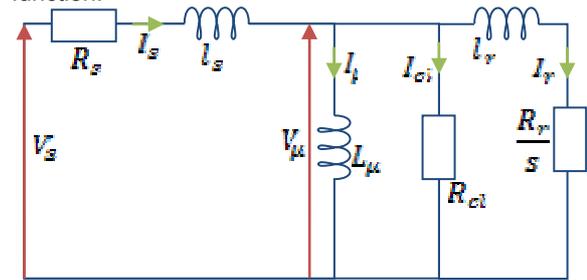


Fig. 3. Equivalent electric single phase scheme of the induction machine

$$T_e = 3 \frac{p R_r I_r^2}{s \omega_s} \quad (1)$$

$$P_{cs} = 3 R_s I_s^2, P_{cr} = 3 R_r I_r^2 \text{ and } P_{cl} = 3 \frac{V_{\mu}^2}{R_{cl}} \quad (2)$$

The geometric model used for the induction machine is proposed Figure 4. We choose to use trapezoidal slots within both the stator and the rotor, which allows us to keep a constant teeth's width.

The induction machine is reduced to a relatively simple geometric description made from blocks of basic untreated raw material, in order to easily find data's in the life cycle assessment inventory data bases.

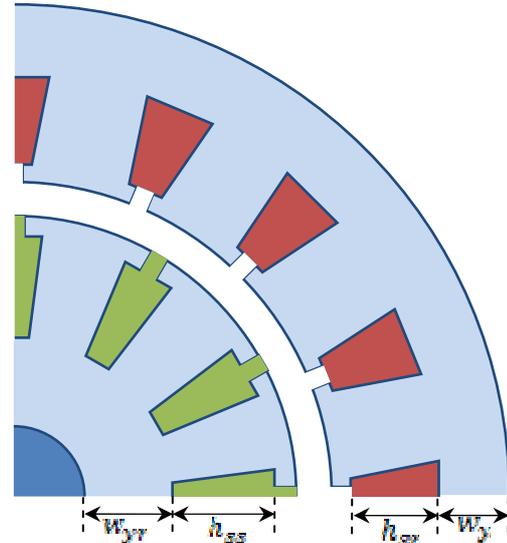


Fig. 4. Geometric model and optimization's parameters definition

The first two parameters are the active length of the machine and the number of pole pairs to which we add the stator and rotor yoke's width, as well as the stator and rotor slot's height. All other sizes are obtained by applied coefficients to these first parameters in order to stay with realistic induction machines structures and reasonable simulations times. The diameter of the rotor shaft is expressed from the constraint in torsion. For a circular cross section of diameter d , the maximal value of the torsion stress constraint is:

$$|\tau|_{\max} = \frac{16|T_e|_{\max}}{\pi d^3} \quad (3)$$

With σ_e the elastic limit of the steel from the rotor shaft. When assume, under the von Mises criterion, that this constraint is defined such as:

$$|\tau|_{\max} = \frac{\sigma_e}{\sqrt{3}} \quad (4)$$

C. Optimization's objectives computation

1) First objective: active parts mass

The optimal Pareto optimization allows competition of contradictory objectives. Our first objective is the active mass of the induction machine.

$$M_a = M_w + M_{sq} + M_{yts} + M_{ytr} \quad (5)$$

We have the stator windings mass M_w , the squirrel-cage mass M_{sq} and the yoke and teeth rotor mass M_{ytr} and stator mass M_{yts} . This calculation only depends on the geometry of the induction machine and will impose a minimal consumption of raw material resources so a reduced overall dimension. Besides this objective can be considered as relative to a purchase price of the induction machine. Indeed, low-power machines are often sold by weight.

The winding overhang and the short-circuit ring are taken into account in the masses computations of the winding and the squirrel-cage masses.

2) Second objective: gross energy requirement on life cycle

The second objective is the sum of energy consumption related to the conversion of electrical energy into mechanical energy by the machine throughout its entire life cycle, which means according to its services specifications. In this global amount of energy appear two separate contributions with a contradictory behavior before the optimization's results.

The integration of operating losses on the life of the

machine gives us an initial energy cost which is usually the focus of efficiency optimizations. This cost directly depends on the load profile (i.e. the record speed-torque imposed on the machine in time) but also on the geometry of the machine that will act upon its performance (through the resistors and inductors of the equivalent scheme), so the level of its losses.

$$W_{fonc} = \int_{T_{use}} (P_{cs} + P_{cr} + P_{cl}) dt \quad (6)$$

The second contribution to the gross energy requirement on life cycle is calculated by adding all energy costs of the other stages represented in Figure 1 to W_{fonc} . There is the energy of raw materials manufacturing, products assembly, transport of the machine as well as its deposit, including a possible recycling of the constitutive materials. All these costs are presented in life cycle assessment databases (one excerpt is presented Table 1) and depend on the mass of material involved. This contribution to gross energy requirement depends only on the geometry of the machine and in any case on its operating load profile.

$$W_{mat} = \sum_{phases} \left(\sum_{elem} (M(elem)W_m(phase, elem)) \right) \quad (7)$$

The amount of energy for assembly and disassembly of the machine will not be taken into account. The main reason is the lack of data in this field. Furthermore in the case of large series machines whose assembly cost remains low due to investment in raw materials, this hypothesis remains acceptable.

Table 1 Elementary energy costs [7], [8]

| PARAMETER | VALUE |
|------------------------------------|------------------------|
| COPPER EXTRACTION AND PROCESSING | 100MJ.KG ⁻¹ |
| ALUMINUM EXTRACTION AND PROCESSING | 161MJ.KG ⁻¹ |
| STEEL EXTRACTION AND PROCESSING | 35MJ.KG ⁻¹ |

The low value of recycling energy consumption for any raw materials is explained by the assumption that only the deposit is taken into account at this stage of modeling, i.e. that the whole structure of the machine is considered as made only from primary raw material. To better stick to the industrial reality in Europe, we will take into account afterwards a certain percentage of recycled material in estimating of the active weight (for example the average European aluminum contains 30% of secondary raw material). We will later include these averages in comparisons of the results of optimizations.

D. Power supply computation

Although this is not often the case with low-power machines and rather large series (those whose dimensions are a priori the most sensitive to eco-design criteria as we have already seen it on earlier studies [9]), an electrical machine is now used in accordance with a specific power supply. The power supply converter is actually part of the machine's optimization.

To take this possibility into account in the eco-design methodology, we chose to include in the modeling of the induction machine a voltage power supply whose amplitude and frequency are variable.

Therefore, for each new geometry tested by the genetic algorithm, an adequate power supply needs to be computed. The main objective of these optimizations remains the overall minimization of the gross energy requirement. The optimal power supply is then computed in order to minimize the operating loss, within inductions constraints and the load profile specifications satisfaction.

E. Optimization's constraints

1) Inductions constraints

The first constraint concerns the magnetic induction in different parts of the magnetic circuit of the induction machine: the yoke and teeth, for the rotor and the stator. This constraint is involved in the linearity hypothesis for the magnetic modeling of the machine.

The induction's maximum does not appear as a constraint for the overall genetic algorithm, but in the optimal power supply of the machine computation. This represents then an internal optimization for the genetic algorithm. However, geometry that is not capable of achieving load profile specification without high saturation levels will be rejected later by the genetic algorithm.

2) Thermal constraints

The second constraint concerns the thermal field and is defined as a global optimization's constraint. Indeed, the temperature is computed at different places in the induction machine, limiting the temperature rise of the winding to 130 ° C (Class B insulation) and ferromagnetic plates at 100 ° C (not accessible). These increases in temperature are obtained from the power flows of operating losses (copper and core losses) that we consider to be evenly distributed among the materials in which they appear.

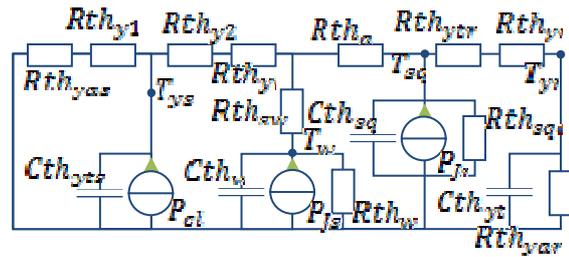


Fig. 5. Equivalent electrical Scheme of the thermal transient model of the induction machine

As exposed thereafter, we can choose between thermal models under transient or permanent state. This choice depends on the load profile imposed on the machine (its operating specifications) and will play an important part on the variation of modeling parameters and on the computing time, which is very much reduced in steady state. The difference between these two models is the additional thermal capacities of the different parts.

F. Load profile

Optimizations with the genetic algorithm are based on different load profiles. They represent the evolution over time (over five years in the case of these simulations) of the record torque and speed required of the induction machine. For practical reasons of simulations, a daily cycle is set throughout these years. It consists of constant stage of speed and torque (which gives us the nominal size of the machine) from which we vary the duration's time.

Through the width of requests we highlight several fundamental facts of the eco-design problematic for electro-mechanical converters. Through this process, we vary the importance of an energy contribution in gross energy requirement, promoting operating losses or energy consumption of other stages of the machine's life cycle.

III - Results

A. First result

1) Importance of the mass of the machine

The first simulations are designed to qualify the introduction of the life cycle of the machine on the results of optimizations. In this context, the comparison of two types of optimizations opposing energy to mass is conducted. The first one concerns the gross energy requirement on life cycle and the second one the only operating losses. The gross energy requirement is calculated as the sum of operating losses and the total energy consumption due to other stages of the induction machine.

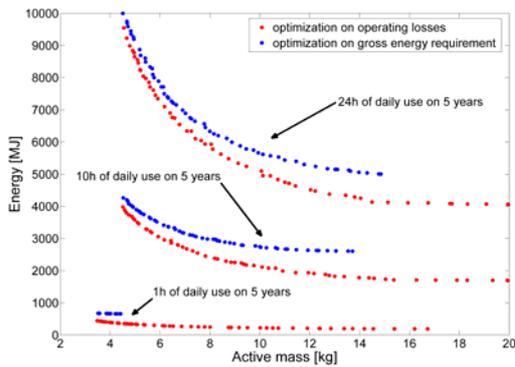


Fig. 6. Comparison of optimizations opposing mass and energy for several operating time. (1Nm and 3000tr.min⁻¹)

It appears a divergence between each pair of Pareto fronts presented Figure 6: it is not possible to achieve technological solutions with as heavy masses by minimizing gross energy requirement that only by minimizing the operating losses. This comes from the life cycle assessment inventory databases, which are expressed in energy per mass unit. The distribution of basic energy costs Table 1 gives us a gross energy requirement roughly proportional to the total mass. Therefore, the genetic algorithm spontaneously eliminates solutions whose mass makes the gross energy requirement too important, which is confirmed by the increasing gap between the two optimization's front.

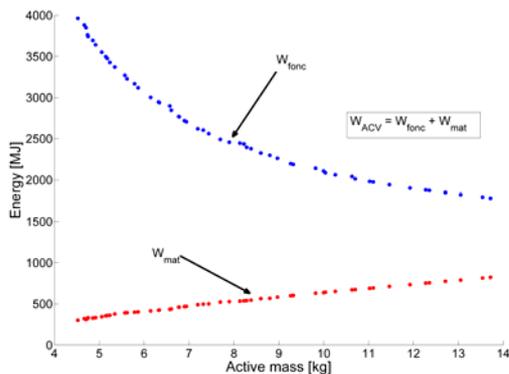


Fig. 7. Distribution of contributions to the gross energy requirement according to the active mass optimization's results (1Nm 3000tr.min⁻¹, usage time 10h per days on five years)

In this same spirit, when we value the mass objective at the expense of the gross energy requirement, the two types of optimizations return relatively close structures because the contribution of operating losses before the other stages energy consumption becomes dominating.

To illustrate this principle, we represent Figure 7 the

distribution of the two opposite contributions to the gross energy requirement depending on the mass objective optimization's results. This figure illustrates the contradictory behavior of the two contributions W_{fonc} and W_{mat} , which allows us to draw the initial outlines of an eco-design methodology in the field of electro-mechanical energy converters.

2) Importance of the load profile

The equation (6) shows that W_{fonc} grows directly with the operating time of the induction machine (at constant load power). W_{mat} contribution in the gross energy requirement depends only on geometric parameters. It appears then Figure 8 three distinct areas in which we should place our methodological work.

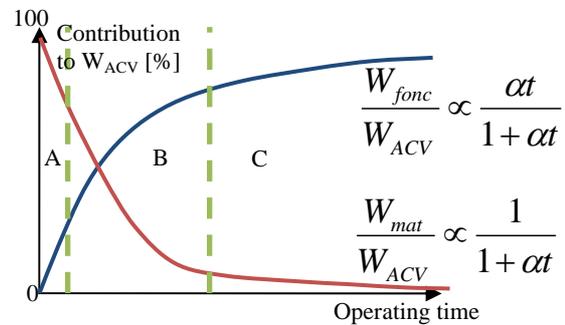


Fig. 8. Energy contributions as a function of operating time

The introduction of the life cycle assessment significantly impacts the optimizations results as long as the operating time of the machine is located in zones A and B, i.e. when the complete operating losses remains negligible before the rest of the energy consumption on life cycle. In the case of Zone A, it becomes unnecessary to use a life cycle optimization taking into account operating losses. Indeed, the term W_{mat} is predominant; simply minimizing the mass of the machine will minimize its global energy consumption on life cycle. Note that this scenario does not allow a Pareto front like representation; at least with the objectives described above (they are no longer strictly contradictory).

Zone C represents where the cumulate operating losses become dominant before the other contributions to the gross energy requirement. It is therefore unnecessary to go through a life cycle assessment; the results are very similar to those obtained with the only losses computation.

In the end eco-design criterion will be applied to load profiles placing optimization's results in zone B. Studies involving time analysis are usually very specific to the cases to which they are applied. Eco-

design is no exception. Thus the relevance of such studies greatly depends on the application's target (power levels and operating time) and on other energy elementary costs of different raw materials (their geometric distribution).

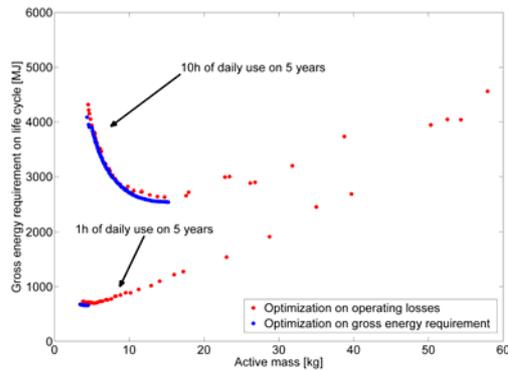


Fig. 9. Gross energy requirement calculated for the two types of optimization. ($1\text{N.m } 3000\text{tr.min}^{-1}$)

Figure 9 emphasizes the influence of solicitation time duration of the induction machine on the distribution of solutions according to a Pareto front. To do this the gross energy requirement is calculate afterwards for solutions obtained by optimizing their only operating losses. We then compare these results to optimizations that lead directly on W_{ACV} (with an equivalent load profile specification). We see at first that the obtained solutions are relatively close but that the genetic algorithm has rejected all solutions which a too much massive structure penalizes gross energy requirement. Moreover, when W_{fonc} and W_{mat} are of an equivalent order of magnitude (10 hours per day operating time), minimization of the mass remains inconsistent with the minimization of gross energy requirement. This is less and less true with the decrease of the operating time (1 hours per day operating time), and eventually get, hypothetically, a quasi-linear relationship between mass and gross energy requirement with a no use operating specification.

3) Thermal Model

We have seen that machines which can offer fertile ground for the implementation of an eco-design methodology show low cumulated operating losses or in the same range as other contributions to the gross energy requirement, i.e. load profiles with short operating time of use (with a constant load power). Such demands, short and spaced in time (a typical example would be motors for gate or garage doors) may present operating times close to the thermal time constants of the machine. It is therefore imperative to introduce a transient thermal model. However, the difference in computing time (one to five) let use still

consider the use of a steady state thermal model in relative continuous operating time.

The gap between the simulation results based on either transient or steady state thermal models is even more pronounced as time solicitation of the machine is short: under transient thermal model, the machine does not have the same temperature levels, allowing the genetic algorithm to seek solutions with lower mass than by using a steady state thermal model.

B. Sensibility study

Life cycle assessment inventory databases elementary energy costs are very different from one database to another. Indeed, they may represent the primary energy, the non renewable part, and the estimates from the country's energy mix measurement, etc. On the other hand, processes differ from one production plant to another, the methods of measurement and accuracy too. In addition, we simulate an induction machine on its entire life cycle. We are then working on projections over several years, which do not take into account changes in the elementary energy costs. These findings lead us naturally to a study on the sensitivity of the optimization's results changes before elementary energy costs variation.

$$\Delta W_{mat} = \sum_{phases} \left(\sum_{elem} M(elem) \cdot \Delta W_m(phase, elem) \right) \quad (8)$$

We are particularly interested in the sensitivity of the results in the case of structures with a minimal gross energy requirement, i.e. when dispersions are most pronounced. In the end, this sensitivity is strongly influenced by the proportion of the material involved in the geometry of the machine. The data used here are the total mass of material associated with the elementary energy cost and the value of the cost itself. We get Figure 10 relatively low variations on Pareto fronts in case of the copper production elementary energy cost. This remains in the same order of magnitude for other materials constituents of the machine.

This type of sensitivity studies conducted before a more complete eco-design study, allows avoiding the assessment of certain phases of the life cycle by knowing that the results of optimizations have low sensitivity to the phase's costs. These sensitivity studies lead us in the choice of optimization's criterions and phases that require further analysis.

Note that the results sensitivities to changes in elementary energy costs also depend on the load profile. Indeed, an induction machine with dominant operating losses before other contributions to the

gross energy requirement will see its dimensions less sensitive to changes in energy costs as a machine with the opposite energy properties.

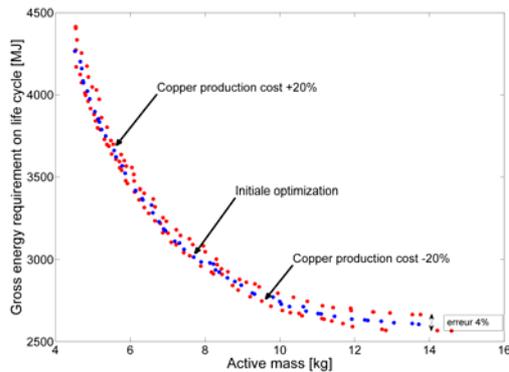


Fig. 10. Comparison of optimizations with different copper production costs. ($1\text{Nm } 3000\text{tr}\cdot\text{min}^{-1}$, usage time 10h per days on five years)

IV - Conclusion and perspectives

The main result of this study is that life cycle assessment is likely to propose different sizing results from those obtained through more traditional optimizations. However, the real impact on the results of optimization depends on the conditions of electro-mechanical energy converter use, in our case the load profiles, as well as the relative importance of different elementary energy costs.

The chosen eco-design methodology, directly linked to the load profile, requires in some cases transient thermal modeling at the expense of computing time. In the case of load profiles presenting low cumulated operating losses, it is better to stack sequences of permanent thermal steady states, allowing a very fast and sufficient computation.

The second part of our study concerns the sensitivity of the optimization's results to elementary energy costs. This point is fundamental regarding the accuracy and origin of the life cycle assessment inventory databases, and leads us, in the restrictive framework, of our simulations, to a sensitivity of the results to changes of elementary energy costs strongly linked to the final volume of the material involved. Note that this sensitivity is variable depending on the chosen load profile, as well as the importance of the energy costs before the gross energy requirement. A change of material winding would also give significant differences on the results of optimization. However, the impact of these changes is difficult to separate from the manufacturing process of the electrical machine.

The modeling of asynchronous machines by multiplying the geometric and power supply parameters, materials and number of constraints can quickly become difficult to handle in terms of results readability and especially binding in terms of computing time. However, there remain fundamental points on which a prospective eco-design method in the field of electrical engineering has to search. The "inactive" parts should be included in the mass calculating so that energy costs of manufacturing processes and dismantling of electromagnetic systems. The choice of the power supply of the machine, required as part of an overall optimization of electrical machine, must also become part of the life cycle assessment. Finally, in simulations including several years' projections, it becomes necessary to introduce in the computation materials aging through for example a behavioral model linked to temperature variations, to mechanical stress, etc.

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