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► **To cite this version:**

Vincent Debusschere, Hamid Ben Ahmed, Bernard Multon. Eco-design of Electromagnetic Energy Converters: The case of the Electrical Transformer. IEEE IEMDC 2007, May 2007, ANTALYA, Turkey. pp.1599-1604. hal-00676233

HAL Id: hal-00676233

<https://hal.science/hal-00676233>

Submitted on 4 Mar 2012

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Eco-design of Electromagnetic Energy Converters: The case of the electrical transformer

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Abstract—This paper presents the first results of the eco-design problematic in case of one of the simplest electromagnetic energy converter: the single-phase electric transformer connected to a constant frequency and voltage power supply. The optimization of its sizes is led with the following objectives: the active mass and the global life cycle energy cost. We first compare optimization's results to those with "classic" mass versus power losses (copper and iron losses) optimization for several times of use ratio. This leads to recognition of the significant impact of the life cycle energy on the arrangement of the optimal Pareto fronts, explained by conflicting energy contribution in the life cycle global energy cost objective. Then we logically observe that the life cycle assessment impact is more significant when the real use duration is smaller than the lifetime. After that, the sensitivity of the optimization's results to the elementary raw materials energy costs is considered with the same times of use ratio. At last, some optimizations are run with a different raw material: aluminium instead of copper for the windings.

Index Terms—Eco-design, transformer, electromagnetic converters, life cycle assessment (LCA), multi-objective optimization.

I. INTRODUCTION

THE earliest forerunners of life cycle assessment (LCA) were in the USA the Resource and Environmental Profile Analyses (REPAs) of the late 1960s and early 1970s. As the term REPA suggests, these early studies emphasized raw material demands, energy inputs, and waste generation flows; attempts on more sophisticated analysis through environmental impact classifications would come later in the evolution of LCA methodology. Modern LCA methodology is rooted in the development of standards through the 1990s. In the late 1990s, the International Organization for Standardization (ISO) released the ISO 14040 series on LCA as an adjunct to the ISO 14000 Environmental Management Standards. These standards are applicable to any organization that wishes to implement, maintain and improve an environmental management system in order to decrease the environmental impact of their activity [1]-[2]. The LCA development is now encouraged in many ways, leading to complete studies and governmental initiatives [3].

Manuscript received March 1, 2007.
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Another early type of LCA emerged in the late 1970s in the form of net energy analysis. The life cycle energy analysis (LCEA) is an approach in which all the energy inputs to a product are accounted for: energy inputs needed to produce components, materials and services needed for the manufacturing process.

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. Economical optimizations of electric converters have already been done [4]. Their main criterion is the losses and the raw materials monetary cost. The global life cycle energy cost comes from a similar principle of single unit optimization, but with lower environment impact objectives.

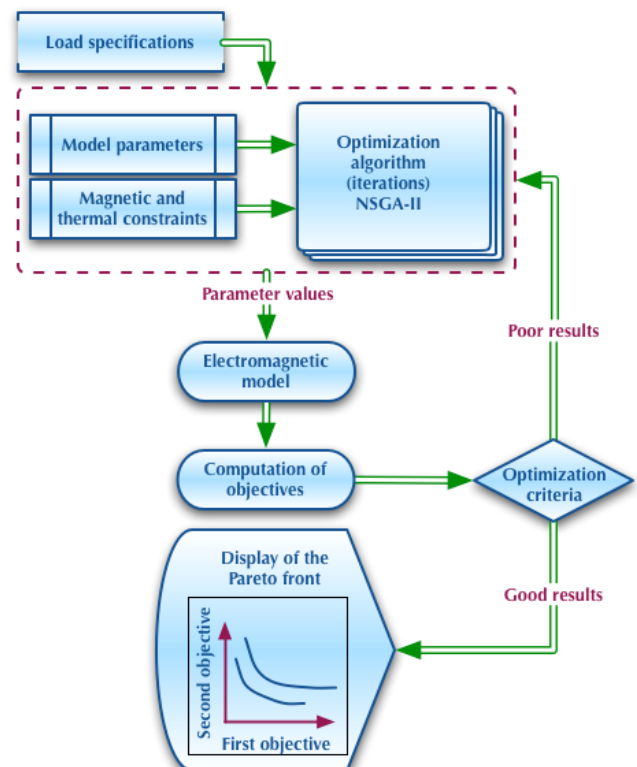


Fig. 1. Optimization block diagram.

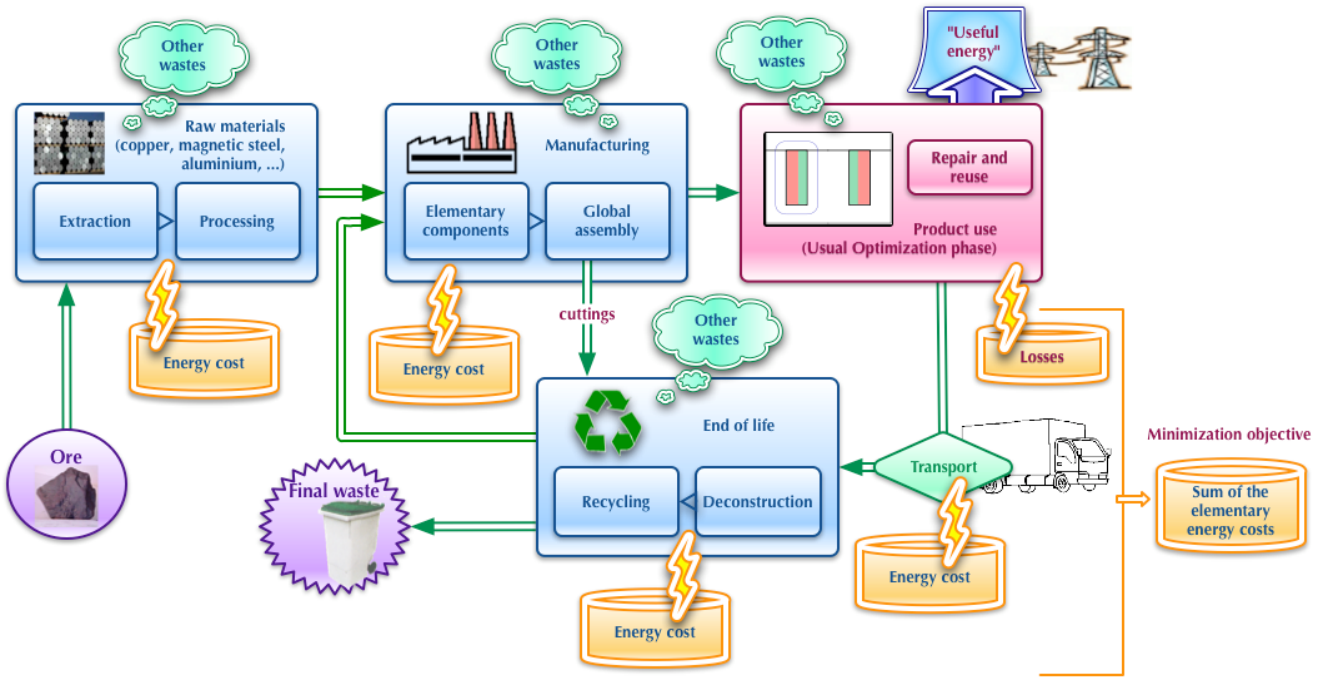


Fig. 2. Life Cycle of an electromagnetic system and global energy cost (main criterion optimization).

We choose then to work with the LCEA principle that means we extend the classic optimizations to the sum of the elementary energy costs during the entire life cycle of the product, as defined on Fig. 2.

We decide to minimize two objectives. The first one is the mass of the active parts M_a and the second is the global life cycle energy W_{LCA} . The transformer is reduced to its two active elementary components: the iron for the ferromagnetic circuit and the copper for the windings.

The optimization tool is a multi-objective evolutionary algorithm, named NSGA-II [5]. This algorithm is capable of finding a well-distributed set of trade-off optimal solutions for two or more conflicting objectives of design.

The plot of the objective functions whose nondominated vectors are in the Pareto optimal set is called the Pareto front, which is obtained by computing a program in accordance with the block diagram represented on Fig. 1.

B. The transformer model

Before going on complex computation concerning a complete power transmission chain, the method principle has to be validated and the basis of the eco-design approach installed with a single-phase electric transformer connected to a constant frequency and voltage power supply. [6]

Its geometrical description is done with three parameters (a , b and c) and the coil windings number (n_l) as shown on Fig. 3.

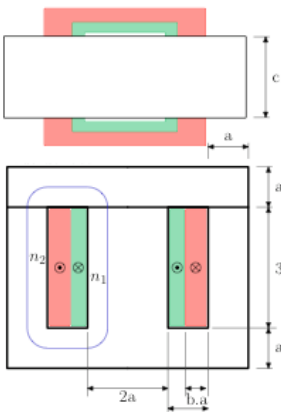


Fig. 3. Geometric transformer parameters.

1) *First objective (active mass)*: It is the sum of the masses of all active parts constituting the transformer.

$$M_a = M_{copper} + M_{iron} \quad (1)$$

For this computation we only need some physical data, such as the density m_v of the materials, the copper filling factor k_r and the geometrical parameters.

$$M_{copper} = (S_{w1} \cdot L_{w1} + S_{w2} \cdot L_{w2}) k_r \cdot m_{v,copper} \quad (2)$$

$$M_{iron} = V_{iron} \cdot m_{v,iron} \quad (3)$$

Where S_w is the windings section and L_w the windings average length. V_{iron} is the iron volume.

$$\begin{cases} S_{w1} = 3b \cdot a^2; L_{w1} = 2c + a(4 + \pi b) \\ S_{w2} = 3(1-b) \cdot a^2; L_{w2} = 2c + a(4 + \pi(1+b)) \\ V_{iron} = 24c \cdot a^2 \end{cases} \quad (4)$$

2) *Second objective (energy)*: The global life cycle energy W_{LCA} is the sum of the LCA energy W_{mat} (proportional to the materials' masses) and the power losses W_{losses} (depend on the load profile that defines T_{use} and load current amplitude). Global assembly and deconstruction energy are not included in W_{mat} , because they do not directly depend on the materials' masses. Indeed, these processes are generally designed for production lines and represent a fixed energy cost that is very specific to factories and not easily accessible.

As global cost on life cycle,

$$W_{LCA} = W_{mat} + W_{losses} \quad (5)$$

With:

$$\begin{cases} W_{mat} = \sum_{stages} \left(\sum_{elements} M_{element} \cdot W_{m,stage,element} \right) \\ W_{losses} = (P_{losses,iron} + P_{losses,copper}) T_{use} \end{cases} \quad (6)$$

$$\begin{cases} P_{losses_{copper}} = \frac{\rho_{copper}}{k_r} \left(\frac{L_{w1}}{S_{w1}} (n_1 \cdot I_1)^2 + \frac{L_{w2}}{S_{w2}} (n_2 \cdot I_2)^2 \right) \\ P_{losses_{iron}} = V_{iron} \left(k_h \cdot f \cdot (2 \cdot B_m)^2 + \alpha_p \cdot \left(\frac{2\pi f \cdot B_m}{\sqrt{2}} \right)^2 \right) \end{cases} \quad (7)$$

k_h and α_p are the hysteresis and eddy current losses factor; ρ_{copper} is the copper resistivity.

3) *Constraints*: The first constraint is about the flux density through the effective area of the central leg of the electric transformer. We choose a maximum flux density of $B_{sat}=1.5T$ in order to avoid saturations that are not reconcilable with our linear electric model.

$$\left[B_{max} = \frac{\sqrt{2}U_1}{2ac \cdot (2\pi f) n_1} \right] \leq B_{sat} \quad (8)$$

The second constraint restrains the iron and copper temperature: the maximum heating $\Delta\theta_{max}$ is equal to $100^\circ C$.

$$\begin{cases} \Delta\theta_{iron} \leq \Delta\theta_{max} \\ \Delta\theta_{copper} \leq \Delta\theta_{max} \end{cases} \quad (9)$$

These thermal constraints are computed from the expressions of the material's temperatures obtained from the scheme Fig. 4.

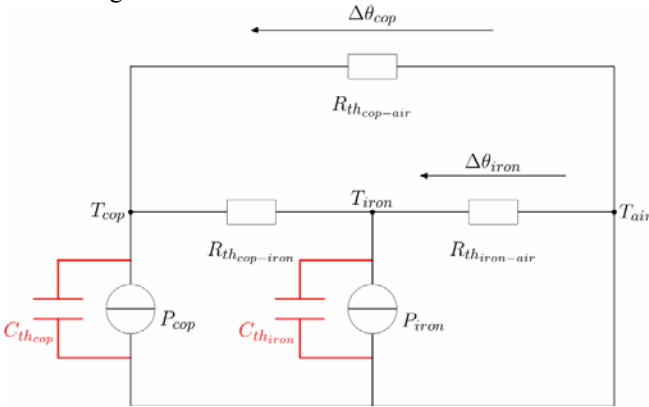


Fig. 4. Equivalent electric scheme of the thermal transformer's modeling.

Finally a maximum value is fixed for the geometrical parameters in order to restrict the maximum size of the transformer. We choose to limit the excursion of the geometrical parameters because we do not use to consider a huge power range of transformer's solutions (see Table I in Appendix for parameter ranges).

C. Load profiles

The objective's computation is based on different load profiles. These profiles are defined on a one-day time basis repeated five days a week and ten month a year over fifteen years.

These fifteen years constitute the maximum lifetime value for the transformer. It is not always equal to the life cycle's time, and depends on the ageing of the constitutive components of the transformer as well as in some cases on the user's sociological behavior. Indeed, some products are

replaced before their real end of life that means even if they are still functional.

Neither an ageing modeling nor a premature end of life will be used in our simulations.

The simplest load profile uses the transformer at its nominal power within duration T_{use} of 24 hours.

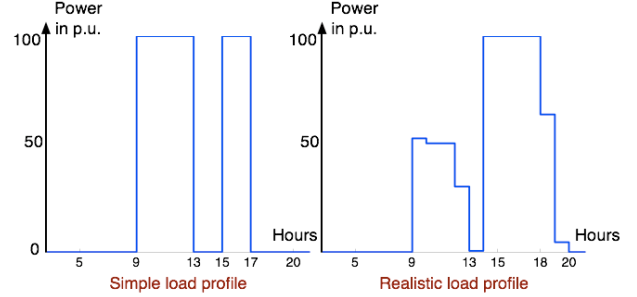


Fig. 5. Load profile examples.

The second load profile introduces pulses from which we modulate the width. This profile allows us to analyze the impact of the transformer's thermal response (by variation of the width modulation) over the optimization's results. If the running time is long enough compared to the thermal time constants, the hypothesis of steady state represents a significant simplification in the computation process and then a definitive time gain. Indeed, temporal simulation is not necessary in that case since we just stack already known steady state losses.

These width variations of the pulses change above all the proportion of W_{losses} before W_{mat} in W_{LCA} . We will come on this subject later.

The last load profile is power graduate. This type of profile is more realistic and will be used for further simulations.

Let us note that when not used, the transformer is still connected to its power supply. That means there are still iron losses. On the other hand; the losses modeling do not depends on temperature variations.

III. RESULTS

A. First simulations

1) W_{mat} contribution

Our first simulations concern the comparison between two different optimizations opposing mass and energy. One optimization minimizes W_{LCA} , leading to LCEA studies and the other minimizes only W_{losses} , which is one of the most classical optimization criterions.

On every type of load profile presented on Fig. 5, the divergence between the two Pareto fronts is similar to curves represented on Fig. 6.

First of all, it is not possible to reach the same weight of technological solutions with the W_{LCA} optimization than with the W_{losses} optimization. Indeed, the mass increase has a direct energy cost and it compensates the reduction of W_{losses} part in W_{LCA} .

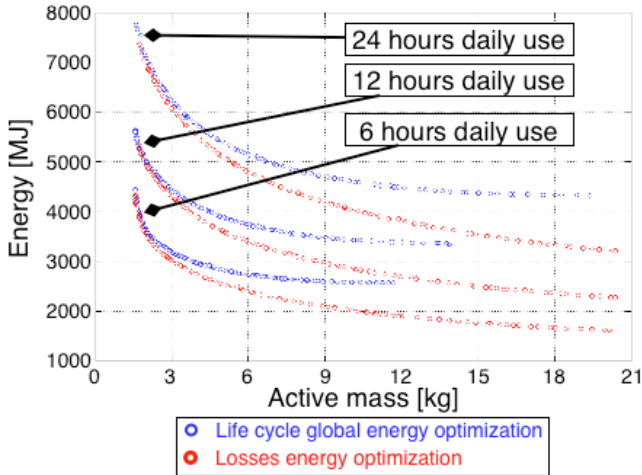


Fig. 6. Case of a 230VA transformer. Comparisons of optimization results.

This is a totally new mechanism brought by the LCA in the optimization's results. The W_{LCA} optimization concerns the real energy cost of the transformer. Choosing a heavy solution in order to decrease to energy losses is not interesting anymore because of the raw materials energy cost. The evolutionary algorithm does not retain these solutions in the life cycle global energy optimization.

The energy difference between two optimizations on a same time basis comes also from the elementary energy cost of the raw materials. Indeed, the energy gap is growing in the same way that the active mass of the transformer. The lightest solutions tend as well to be identical in the two optimizations (W_{mat} becomes insignificant).

As an illustration, energy distribution is represented on Fig. 7 in the case of a 12 hours daily use load profile. There is clearly a conflict between W_{mat} and W_{losses} , which explains the final optimal Pareto front limitations on Fig. 6.

The difference between iron and copper losses when the life cycle global energy cost goes past 5000MJ comes from the thermal constraint that limits the maximum current (and then the copper losses) in the windings.

2) T_{use} contribution

The comparison of the three different daily use times on Fig. 6 brings another comment. Equation (6) shows that W_{losses} increases directly with T_{use} but W_{mat} only depends on the geometrical parameters. An idea of W_{mat} and W_{losses} contribution in W_{LCA} in function of the total time use is proposed on Fig. 8 in the case of a fixed structure of transformer.

W_{LCA} optimization can reach bigger weight solutions when T_{use} increases because W_{mat} proportion in W_{LCA} declines. On the other hand, LCEA study may become of secondary importance in these optimization's cases (W_{losses} becomes dominating).

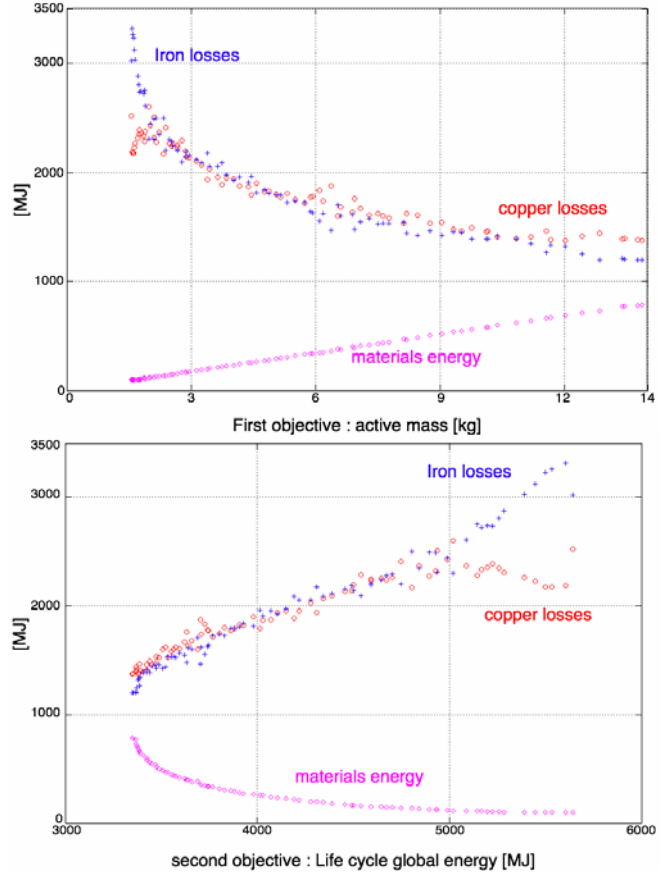


Fig. 7. Energy repartition inside W_{LCA} in function of the two objectives in a 12 hours daily use load profile.

In a first conclusion, LCEA study has an impact on the optimization's results that depends on the elementary materials energy costs and the load profile. Therefore an eco-design method tends to be very specific to any case to which it is applied.

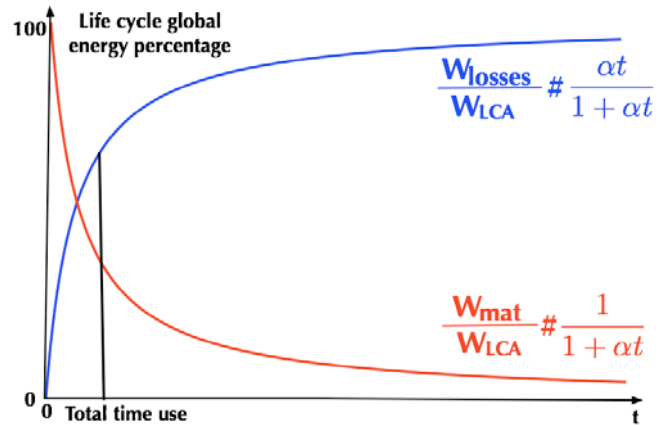


Fig. 8. Energy contributions in W_{LCA} in function of time use. ($\alpha = P_{losses}/W_{mat}$)

Moreover, the relevance of such a study before the already known "classic" optimizations has to be validated particularly towards energy contributions.

B. Sensitivity study

The elementary material's energy cost measurement depends on local and technological conditions. For that reason the data used here are only considered as an order of magnitude. Table I compiles the elementary energy costs used in our computations [7].

Our final aim is actually to set up an eco-design method, and not to obtain an optimal structure of electric transformer for a specific load profile.

TABLE I
ELEMENTARY ENERGY COST

Parameter	Value
Copper's extraction and processing	107.7 MJ/kg
Iron's extraction and processing	35.7 MJ/kg
Aluminium's extraction and processing	188.7 MJ/kg
Copper's recycling	0.01 MJ/kg
Iron's recycling	0.01 MJ/kg
Aluminium's recycling	0.01 MJ/kg
Transport	5.14 MJ/kg/m

Besides, we are doing fifteen years projections. The increased scarcity of energy and construction's raw materials makes the transport and extractions energy costs grow up.

We must then be acquainted with the sensitivity of the optimization's results to the energy cost of every material and in every life cycle stage. Equations (5) and (6) bring the sensitivity expression:

$$\Delta W_{glob} = \sum_{stages} \left(\sum_{elements} M_{element} \cdot \Delta W_{m_{stage_{element}}} \right) \quad (10)$$

On the Fig. 9, we present Pareto fronts for the sensitivity study of the extraction and processing energy for both copper and iron, and of the transport energy. All the simulations are done with the 12 hours daily use load profile, changing one of the elementary energy cost within $\pm 20\%$ of its initial value.

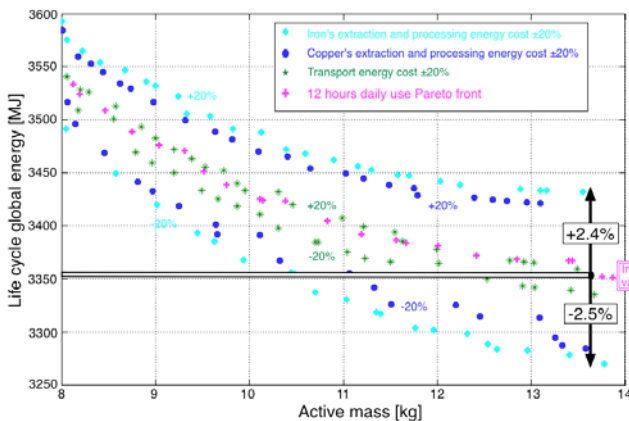


Fig. 9. Sensitivity study. Variation of the material's energy cost.

The maximum variation of W_{LCA} is under 5% in the worse case and this variation decreases when the proportion of W_{mat} in W_{LCA} decreases (i.e. with the lighter solutions of transformer).

The variations of the optimization's results are not identical for every elementary energy cost. Indeed, a 20% variation on the iron extraction and processing energy cost gives a higher

life cycle global energy cost than the same variation on the transport energy cost. It is then more important to concentrate our optimizations on the first elementary energy cost than on the second one in that case.

In the same way, the energy cost of one of the life cycle stage can be insignificant and neglected, but always with strictly defined hypothesis. This is another point where eco-design method greatly depends on the study's object.

As an example, we propose the value of the two extreme optimizations for a 13kg transformer taken from the Pareto fronts of the Fig. 9 in Table II.

TABLE II
PARAMETER VALUES FOR A 13KG TRANSFORMER

Parameter	Copper extraction energy +20%	Copper extraction energy -20% ^a
a	28.5mm	28.0mm
b	43.2%	43.7%
c	68.3mm	70.8mm
n_f	614 coil windings	593 coil windings

The parameter's dispersion is not significant in that case. We should however be aware of the sensitivity dependence on the materials masses and on the load profile.

Indeed, when the transformer time use decreases, the proportion of W_{mat} in W_{LCA} increases. The optimization's results are then more sensitive to variations of the materials energy costs. For example, with the same simulations as shown on Fig. 9, the 6 hours daily use load profile gives a maximum variation for W_{LCA} of 5.5% and the 24 hours load profile of under 4.5%.

C. Influence of coil material

Eco-design leads to new solutions, and new structures that include different raw materials compositions. Changing copper into aluminium or iron sheets into iron powder for different criterions of optimization is an example of what should automatically propose an eco-design method in electromagnetic energy converters.

On a same 12 hours daily use load profile (the simple load profile Fig. 5), the optimization's results are quite different whether the windings are made of aluminium or copper.

Choosing for example a life cycle global energy cost objective of 4000MJ brings a solution with aluminium windings twice as heavy as the one with copper windings, and this affects the dimensions of the solution too (Fig. 10).

On the other side, choosing an active mass objective (for example 4kg) only affects the global energy cost (4800MJ with aluminium windings and 4100MJ with copper windings) and few the dimensions (not represented on Fig. 10).

Depending on which objective is chosen, the transformer optimal solutions on the Pareto front are very sensitive or not to the change of windings raw material.

The objective and specification's choices have a huge impact on optimization's results in these simulations even more that eco-design runs lifetime predictions.

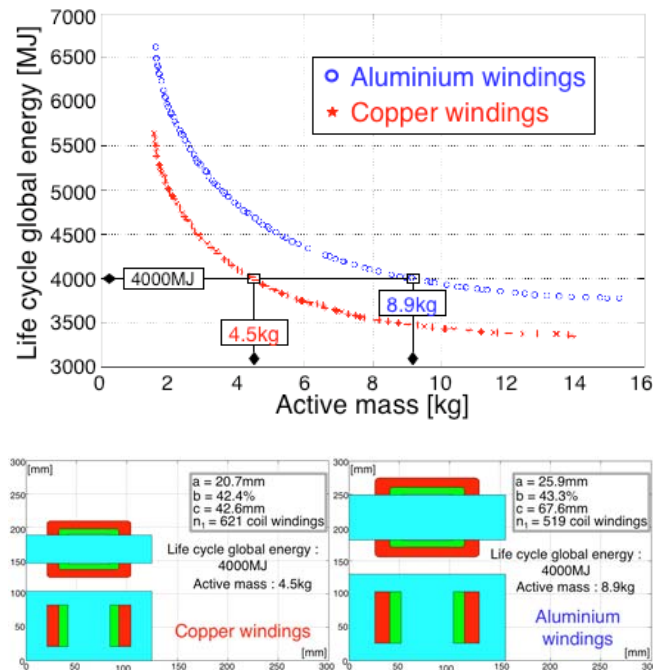


Fig. 10. Optimization comparison on the same load profile with two different windings materials and example of identical W_{LCA} solutions

IV. CONCLUSION AND PERSPECTIVES

The primary result of this study is that the LCEA has a real impact on the design of electromagnetic systems and this impact particularly depends on the load profile.

The method that we choose is then directly linked to the load profile, especially to the possibility that one of the energy contributions to the global life cycle energy cost is dominating or not. Besides, we have seen that the thermal transient state modeling can be avoided in some cases when the transformer is used for a long time at the same power rate. In that case, optimization programs only need a sequence of steady states calculated ones for all that means a very short time of total computation.

The second part of our study concerns the sensitivity of the optimization's results to the elementary materials energy costs. This is a primary point especially regarding the precision's uncertainty (and their evolution) of the life cycle analysis databases. The simulations indicate that the optimization's results present a weak sensitivity to the elementary energy costs and that this sensitivity depends on the elementary energy cost, i.e. its magnitude in the life cycle energy cost.

Sensitivity study for the material themselves (aluminium instead of copper) reveals that a change of raw material brings entirely different solutions. Such changes will depend on specific needs for materials or objectives.

The electric transformer case is a first step in the progress that leads us to an eco-design method for electromagnetic systems. We should naturally turn to the electric machines, by multiplying the parameters, materials and constraints number.

The eco-design method will also include the electric power

supply, which represents a complete optimization's study for the actual electric machines.

APPENDIX

TABLE I
OPTIMIZATION'S PARAMETER RANGES

Parameter	Minimum value	Maximum value
a	5mm	30mm
b	0.001%	100%
c	5mm	100mm
n_1	1 coil windings	10000 coil windings

TABLE II
DATA VALUES USED TO COMPUTE THE OPTIMIZATIONS

Parameter	Description	value
U_1	Tension at the primary of the transformer	230V
U_2	Tension at the secondary of the transformer	9V
S	Nominal power	230VA
f	Frequency	50Hz
e_{iso}	Thickness of the windings insulant	1mm
λ_{iso}	Thermal conductivity of the insulant	$0,29W.m^{-1}.K^{-1}$
h	Thermal convection factor	$7W.m^{-2}.K^{-1}$
$\Delta\theta_{MAX}$	Copper and iron maximum heating temperature	100K
$C_{Thaluminium}$	Aluminium thermal capacity	$904J.kg^{-1}.K^{-1}$
$C_{Thcopper}$	Copper thermal capacity	$385J.kg^{-1}.K^{-1}$
C_{Thiron}	Iron thermal capacity	$460J.kg^{-1}.K^{-1}$
B_{max}	Maximum flux density	1,5T
$m_{Valuminium}$	Aluminium volume mass	$2702kg.m^3$
$m_{Vcopper}$	Copper volume mass	$8860kg.m^3$
m_{Viron}	Iron volume mass	$7600kg.m^3$
k_h	Hysteresis losses factor	$90 A.m V^{-1}.s^{-1}$
α_p	Foucault current losses factor	$0,065 A.m.V^{-1}$
$\rho_{aluminium}$	Aluminium resistivity	$1,7e-8 \Omega.m$
ρ_{copper}	Copper resistivity	$1,7e-8\Omega.m$
k_r	copper filling factor	0,4

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