LIFE CYCLE ASSESSMENT AND INRUSH CURRENTS MEASUREMENT OF AMORPHOUS TRANSFORMERS

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ABSTRACT

This paper deals with EDF Research and Development work for ERDF needs in terms of energy efficiency, focused on Amorphous Metal Distribution Transformers (AMDT). The first part is dedicated to evaluate the life-cycle assessment (LCA) of amorphous technology compared to silicon steel technology. It is shown LCA of amorphous units, from raw materials till the recycling, is the most ecofriendly one compared to traditional technology.

The second topic is about inrush currents. These currents, measured after re-energization, reach very higher values for amorphous technology than those of conventional technology. The reason for this difference is explained by analyzing magnetic properties of the core and the moment when the transformer is switched in.

INTRODUCTION

The overall losses in the European Union (EU) distribution transformers are estimated at 33 TWh per year [1]. Energy losses in distribution network can be mainly divided into no-load losses, which probably account for about 63% of total losses. Considering the potency of losses generated in transformers, ERDF, French national distribution company, has decided to reduce no-load losses in order to fulfill EU policies and its environmental commitment.

The energy efficiency of a distribution transformer, in terms of losses, is fundamentally dependent on the type of material used for building the transformer core. Amorphous ribbon units represent a significant new advance in transformer technology. Amorphous core distribution transformers allow more than 60% reduction in no-load losses compared to standard grain oriented silicon steel (GOSS) transformers [2]. Under the present environment of high concerns for climate change, ERDF is working to improve its distribution system efficiency and focusing on employing efficient transformers, such as amorphous units.

The aim of this paper is double:

- Comparative LCA between amorphous and conventional transformer technologies. LCA will be presented in order to ascertain which one of these 2 transformers has the least impact on the environment.
- Investigations on inrush currents carried out on 250 kVA amorphous and conventional distribution transformers.

LCA BETWEEN AMORPHOUS AND TRADITIONAL TECHNOLOGY

What is LCA?

LCA is an analytical tool specifically designed to assess the environmental impacts from the extraction of raw materials till the recycling of a product. The evaluation framework most commonly applied in LCA involves the following steps [3]:

- Goal and scope definition: this phase involves defining the purpose of the study. A functional point, serving as a reference point, is defined to be able to compare products.
- Inventory: a system with boundaries is defined that include all relevant process chains of the product in question. For each process, the relevant environmental interventions are inventoried in relation to the process' contribution to the product function.
- Impact assessment: the purpose in this phase is to compile information obtained in the inventory and to convert the relevant interventions into scores on each impact category, reflecting a common mechanism of environmental threat.

The goal of this study is to compare the LCA of both transformer technologies, e.g., amorphous and silicon steel. In that purpose, a functional point has to be defined. The magnetic materials used in both transformers are mainly iron-based alloys; therefore one ton of iron alloy is the functional unit. The system boundaries for both LCA evaluations are as below:

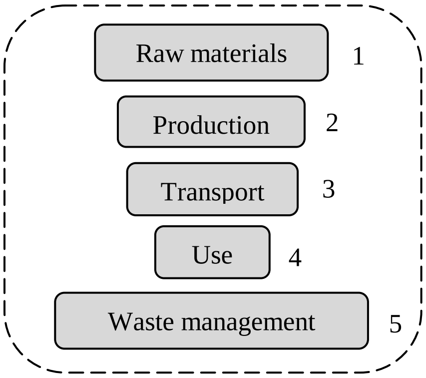

Fig.1: System boundaries of the study

Inventory of amorphous technology

Phase 1
The LCA of manufacturing iron ore is scrutinized by calculating the amount of CO_2 produced per ton of iron. This value is specified in a study done on a typical integrated iron making blast furnace [4]. The amount of CO_2 produced is approximately **1544 kg** per ton. This value is the same for the silicon steel because iron bars are the primary materials.

Phase 2
One of the techniques for producing amorphous ribbons is called the melt-spinning. Alloy ingots are melted and forced onto a rapid rotating copper wheel by an argon blast. The energy required to produce one ton of amorphous ribbons is evaluated through the calculation of heat of fusion during melting and the enthalpy of rapid solidification. These values are:

- $\Delta U_{melt} = 0.96$ GJ/ton
- $\Delta H_{sol} = 0.46$ GJ/ton

It is estimated the energy dissipated through heat is equal to energy supplied. The auxiliary energy (wheel, ribbon cutting...) is estimated around 1.5 to 2 GJ/ton. The whole process needs **5 GJ** for producing one ton of amorphous ribbon.

Phase 3
This part will determine the impact of transporting the materials, from production till recycling, by evaluating the emission of CO_2 per km. Commercial alloys are produced by Hitachi Metglas, situated in the US. These ribbons are then sent to China where they are made into cores. These cores are dispatched to manufacturers in EU in order to be assembled. On the whole, amorphous materials travel 30000 km by ship and 3000 km by truck. The environmental print (CO_2/km) of each mode of transportation is given in [5]. The total emission of CO_2 for transporting one ton of amorphous materials is equal to **562 kg**.

Phase 4
The environmental impact of using amorphous materials is evaluated through the calculation of no-load losses generated by the amorphous transformer in its lifetime (30 years). These losses are calculated from an $A_0/2$-C_k 250 kVA rated amorphous transformer:
$P = 110 \times 24 \times 365 \times 30 = 28908$ kWh

The no-load losses level (110 W) differs from $A_0/2$ level (210 W) because 110 W corresponds exactly to iron losses measured on the transformer and $A_0/2$ is the maximum allowed level.
An amorphous transformer produces **29 MWh** of no-load losses per year.

Phase 5
The environmental impact of waste management is evaluated through the calculation of energy required for recycling one ton of amorphous materials. Hitachi Metglas takes charge of this process. The amorphous cores are crushed and cut down. Then the epoxy resin is separated from the metal by a solvent. The remaining metal pieces are dried and will be used in another melt-spinning process. The total energy required is equal to **3 GJ/ton**.

Inventory of conventional technology

Phase 2
GOSS materials are produced from iron bars. These metal bars (10-20 cm thick) go through a lot of processes (rolling, annealing...) in order to be manufactured into electrical steel (0.23-0.30 mm thick). The amount of energy required for manufacturing GOSS materials has been evaluated by Arcelor Mittal engineers [6-7]. To produce one ton of GOSS, we need 12 GJ of energy. The dissipated heat is estimated to be equal to energy supplied. The auxiliary energy (rolling wheels, cutting, cooling system...) are roughly estimated in the range of 3 GJ. In total, **27 GJ** is required to produce one ton of GOSS.

Phase 3
The electrical steel industry is very much developed within EU (Thyssen Krupp, Arcelor Mittal, and Corus) than amorphous technology. So the environmental impact due to transport is very much less than amorphous one. In case of Thyssen, the iron bars are produced in Germany then shipped to France (Isbergues) to be made into GOSS. The final product is then dispatched to transformer manufacturers who assemble the active part. In total, **52 kg** of CO_2 are released per ton of GOSS.

Phase 4
The no-load losses are calculated from a C_0-C_k 250 kVA rated conventional transformer. The total losses are:
$P = 425 \times 24 \times 365 \times 30 = 111690$ kWh

A 250 kVA C_0-C_k conventional transformer generates approximately **112 MWh** of no-load losses per year.

Phase 5
Steel is the most recycled material worldwide. One of the processes used for recycling is the electric arc furnace. Recycling steel requires 60% less energy than producing steel from iron ore [8]. Recycling one ton of steel needs **11 GJ** of energy.

With the inventory phase done, the impact assessment of each process should be analyzed regarding an environmental parameter. From several indicators (CO_2, SO_2, NO_x...), the CO_2 equivalent basis has been chosen as it is one of the most sought-after environmental indicators.

Now, values given in GJ and kWh have to be converted to CO_2 equivalent as it would be easier to compare both technologies.
The conversion factor of energy in GJ into CO_2 eq. is given in [9]. This factor is equal to 93 kg CO_2/GJ.
Regarding the CO_2 equivalent for kWh, it depends greatly on the specific electricity grid mix. In France, 1 kWh of electricity power produces 0.09 kg of CO_2 [10].

In order to be correct in the comparison between amorphous and conventional technologies, they should be judged at equal function. To explain, silicon steel transformers function at an induction level around 1.5-1.6 T, whereas amorphous transformers operate at 1.2-1.3 T. The induction level of core material influences directly the weight of the core. For instance, GOSS core weighs 420 kg but an amorphous core weighs 604 kg for a 250 kVA rated transformer. A factor, considering the weight difference, should be applied to values reported in the inventory for the amorphous technology. This factor is equal to:
604/420 = 1.4

Table I gives the overall environmental interventions converted into CO_2 eq.
It is clearly observed amorphous technology is twice less polluting, in terms of CO_2 emissions, than conventional GOSS technology. It is also noticed emissions during the "use" phase (losses) represent a major part in environmental impact.

Unit : tons of CO_2/ton of iron alloy		
LCA	Technology	
	Amorphous	**GOSS**
Manufacture	1.544	1.544
Production	0.651	2.511
Transport	0.787	0.052
Use	3.654	10.080
Recycling	0.391	1.023
TOTAL	7	15

Table 1: Results of amorphous and conventional LCAs

INRUSH CURRENT MEASUREMENTS

Inrush current is a large transient current which is caused by cycle saturation of the magnetic core during energization. These currents can reach 10 times the rated nominal current. For its high value, the magnetizing current upsets the balance between the currents at the transformer terminals, and can be therefore experienced by the differential relay as a false current. The relay, however, must remain stable during energization. It is therefore desirable to evaluate the magnitude of inrush currents in order for relays to properly differentiate between inrush and other incidents.

Two different inrush currents were measured on 250 kVA amorphous and GOSS transformers:

- Inrush currents during energization of an unloaded transformer.
- Inrush current during re-energization of a de-energized transformer.

Simple energization

In this part, 10 consecutive measurements of inrush current were carried out on an unloaded transformer. Each measurement was spaced out with a gap of 2 ms, so an entire voltage period is covered (f=50 Hz/T=20 ms). The maximum inrush currents measured are given below for both transformers:

	Amorphous	Conventional
Max inrush current (A)	74	66

The primary nominal current is calculated as follows [11]:

$$I_N = S/\sqrt{3}.U_1$$

with S, the rated power and U_1, the primary voltage.

$$I_N = 250.10^3/\sqrt{3}.20.10^3 = \mathbf{7.2\ A}$$

The inrush currents measured are typical values, corresponding to approximately $10I_N$.

Energization of a de-energized transformer

In this part, the transformer is energized then it is switched off and finally re-energized after 300 ms interval. Indeed, in operating conditions, after a fault, a transformer is switched off for 300 ms and turned on automatically. If the fault persists, the device is shut off again. Taking into account this procedure, inrush currents of 1st and 2nd energization were measured for both transformers. In order to observe the influence of switching time on inrush current, 5 measurements were carried out when U=0 and 5 measurements when $U=U_{max}$. The results are given below:

	Amorphous		Conventional	
Max inrush current when U=0 (A)	83	197	45	41
Max inrush current when $U=U_{max}$ (A)	21	162	35	33

It is noticed amorphous transformers command higher inrush currents when re-energized than conventional GOSS ones. These currents can reach more than $25I_N$.
In fact, the magnitude of inrush currents depends on the following parameters [12]:

- Switching time of the transformer
- Residual fluxes in the core
- Hysteresis characteristics such as permeability.

When the connection happens at the instant at which the flux would equal zero, i.e. at the voltage's maximum, this does not give rise to any exceptional current or flux. The flux is the integral of the applied voltage and is exactly equal to what it would be if this had not been the first period of the applied voltage.

However, when the transformer is connected at the moment the voltage equals zero, the flux will reach twice its normal height when integrating the voltage (see Fig. 2). Much more current is needed to increase the flux and the current can easily reach higher levels. The presence of remanent magnetism can increase this effect, leading to even larger inrush currents.

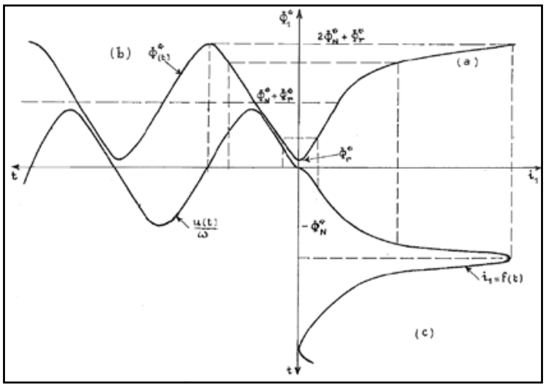

Fig.2: Illustrations of: first B-H loop (a), flux Φ (b) and current i (c) [13]

These two parameters are common to both technologies but then how come amorphous transformers exhibit higher inrush currents?

This can be explained by studying the hysteresis curves of both materials (see Fig. 3)

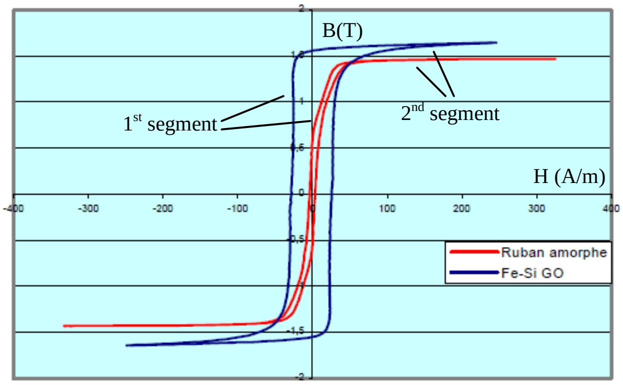

Fig.3: Hysteresis curves of amorphous ribbon (in red) and GOSS (in blue)

The hysteresis curve can be described as 2 segments, one linear and the other representing the saturation. The permeability μ of amorphous ribbons is equal to 100000 whereas it is only 42000 for GOSS. Amorphous ribbons saturate around 1.5 T but GOSS saturates at 2 T.

Because of high permeability, the amorphous core is driven into saturation quicker than GOSS. Therefore, the 2nd segment, in case of amorphous ribbons, is flat reaching the real saturation level. As a result, the inrush current reaches very high levels. In case of GOSS, the saturation is not totally attained. This is why AMDTs, in certain conditions, demand high inrush currents than conventional units.

CONCLUSION

LCA of AMDTs, from raw materials till the recycling, is the most ecofriendly one compared to GOSS technology.

Inrush currents measured after re-energization for amorphous technology reach very higher values than those of conventional technology. The reason for this difference is explained by the high permeability of amorphous ribbons compared to GOSS.

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