LIFE CYCLE ASSESSMENT OF DRY-TYPE AND OIL-IMMERSED DISTRIBUTION TRANSFORMERS WITH AMORPHOUS METAL CORE

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ABSTRACT

Increased energy efficiency has received high attention, not least because of increasing energy prices and global warming. Increasing the energy efficiency of a device may require a more complex construction, demanding an increased amount of materials. It is therefore not clear right from the beginning if an overall sustainable solution is achieved. Such a situation is encountered with new types of distribution transformers, which are using amorphous metal as core material, and allowing a very remarkable reduction of transformer losses by 50%-70%. A life cycle assessment (LCA) allows investigation of this aspect. The results show that the use of amorphous oil-immersed or dry-type distribution transformers is a sustainable solution with respect to all environmental criteria and considerably contributes to a cleaner and better environment.

INTRODUCTION

Increasing demand for energy and raw materials, the threat of global warming, and society's call for sustainable and environmentally friendly products ask for a comprehensive approach when developing new products. Energy efficiency and related energy savings are very important, often the dominating aspects.

Electricity is a form of energy carrier which allows versatile application and has globally a strongly increasing demand. In the chain from generation to consumption, it passes different components in an electric grid, like breakers, capacitors, meters, or transformers. Unfortunately, those components cause some energy losses, resulting in 9% of all the electricity generated worldwide getting lost in transmission and distribution.

Most of those individual components already have high energy efficiency. Nevertheless, improvements are possible. In general, there are two basic approaches for further developments: first, the energy or power handling capability of a device is increased, resulting mainly in reduced materials need or second, the losses are reduced, whereby the required amount of materials for the component may even increase. For very low loss components like circuit breakers, with losses in the order of 10^{-6}, or capacitors (10^{-4}) the first approach is the more straightforward one, but for transformers (10^{-2}) the second approach is more sustainable, as described in this document for amorphous metal distribution transformers (AMDT).

A life cycle assessment (LCA) provides a holistic view of the components total environmental impact. The goal and scope of this study is to compare the environmental impact associated with the life cycle of Distribution Transformers (DTs) using amorphous metal as core material with standard DTs. By doing this LCA we illustrate in which life cycle phase the largest environmental impacts are found. This can be used to optimize the trade-off between using more material in the transformer and lowering power losses during operation.

DISTRIBUTION TRANSFORMER (DT)

In the electrical power system, 2-3% of the total generated electric energy is lost in distribution transformers. In Europe alone, a reduction in the losses in the installed base of DTs by 50% is equivalent to the energy produced by 5 large nuclear power plants. Therefore, deferral of generation, especially from fossil fuel sources has a major impact on environmental sustainability. Energy savings is the name of the game for the future.

Mineral oil has been the dielectric fluid of choice in liquid filled DTs for decades, in spite of its known, undesirable impact on safety and the environment. Recently, vegetable oil based fluids have been developed as alternatives. Among these, the BIOTEMP® biodegradable fluid from ABB has a high flash point and provides a safe, environmentally friendly solution. Dry-type transformers are used in applications where safety is of major importance and in ecologically sensitive areas. Insulation needs are satisfied by air and by epoxy based solid materials.

Significant energy savings have been enabled with the availability of amorphous metal for cores of DTs. AMDTs offer up to a 70% reduction in no-load losses, have an identical functionality to conventional DTs, and a proven long lifetime. They require no modifications to the existing application environments.

Amorphous Metal

Amorphous metal (AM) for use in DT cores is a Fe-B-Si metallic alloy produced by solidifying alloy melts at very high cooling rates. Such rapid solidification leaves a vitrified solid with a random, amorphous atomic structure, essentially as in the liquid phase. Since the material is thin by its very nature, the application of amorphous metal is restricted to wound transformer cores.
AM offers the best of magnetic characteristics for application as a core material. Losses in AM cores are lower (by up to 70%) than in cores with regular grain oriented silicon steel (RGO) cores. On the other hand, the presence of boron lowers the saturation induction of AM to 1.56 T, compared to about 2.0 T for RGO. The design induction with AM is consequently lower, leading to slightly larger and heavier transformers.

Economical considerations in transformer selection

The losses of transformers consist of two parts: the no-load loss, P_0, generated in the core and the load loss P_k occurring mainly in the transformer windings. P_0 is always present as soon as a voltage is applied to the transformer and of constant value, whereas P_k only occurs during transformer operation and is load dependent

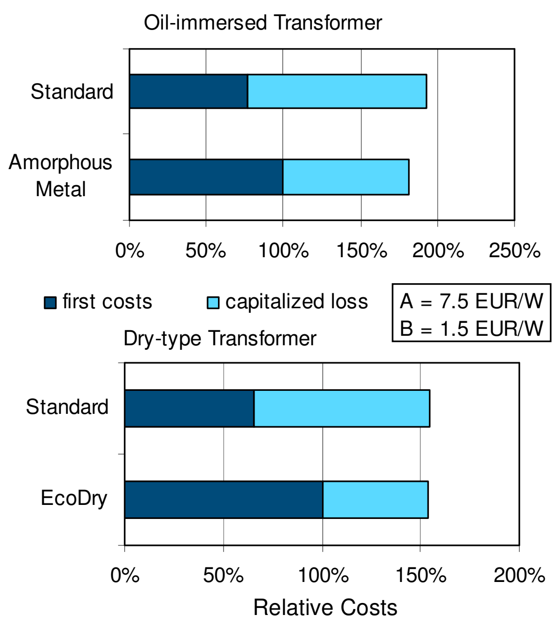

Fig. 1: Comparison of total ownership costs of oil-immersed and dry-type transformers with cores made of RGO steel and amorphous metal. A and B are the capitalization factors for no-load loss and load loss, respectively. All costs are normalized to the first cost of the AMDT. EcoDry is ABB's ultra-efficient dry-type transformer family. The data is for 1000 kVA transformers

For maximum efficiency under normal operating conditions, DTs are optimized to have the lowest P_0, since they are typically only lightly loaded (<50%). For utilities, the reduction of no-load loss is therefore a major focus and AMDTs are the perfect choice.
While a variety of costs may be considered: first costs, life cycle costs, additional infrastructure costs, etc. in selecting a transformer, a most important consideration is that of the cost of losses during its lifetime. In calculating total ownership cost (TOC), the losses are accounted by their financial impact, capitalized for an expected payback period for the transformer (Fig. 1). Although first costs of AMDT are higher, they often become the preferred choice if TOC is considered. Furthermore, since they help mitigate emissions related with generation, additional cost savings are realized from associated costs such as taxes for CO_2 emission.

THE LCA METHODOLOGY

Life Cycle Assessment, LCA, is a tool to calculate the environmental impact of a product or system during its different life cycle phases. The LCA methodology framework according to ISO 14040 [1] is presented in figure 2. An LCA consists of four iterative steps; goal and scope definition, inventory analysis, impact assessment and interpretation.
The depths, focus and results from a LCA may shift largely depending on the goal and scope definition and intended use. To assure quality and consistency in LCA studies, the ISO 14040 and ISO 14044 [1,2] have been developed to guide the practitioner conducting the LCA. The basic principle for an LCA is to relate the technical system over its' life cycle phases to different types of environmental impacts.

THE LCA STUDY FOR DISTRIBUTION TRANSFOMERS

The LCA includes the raw material manufacturing, operation for 30 years, end of life handling and transports, see figure 3. The environmental impact from the assembly and disassembly of the DTs is minimal and not included. Calculations are based on 1000 kVA DTs.
The LCA is based on two load cases; 1) normal operation at 20% constant load, and 2) peak load at 50% load for 50% of the time and 20% load for the remaining time. These load cases have been selected based on the outcome of an EU funded project, which investigated the energy saving potential of DTs [3]. According to that study, the average load of utility DTs in the European grid is 19% and the average load at peak load is 53%. Note that for industrial applications the transformer load is typically 50% or higher. An operational lifetime of 30 years is considered.
The loss values of the conventional transformers are selected according to CENELEC EN50464-1 [4] and HD538.1 [5], the respective standards for oil-immersed and dry-type transformers specifying loss values. The no-load

loss values are shown in figure 4. Identical values for load loss for conventional and amorphous are used.

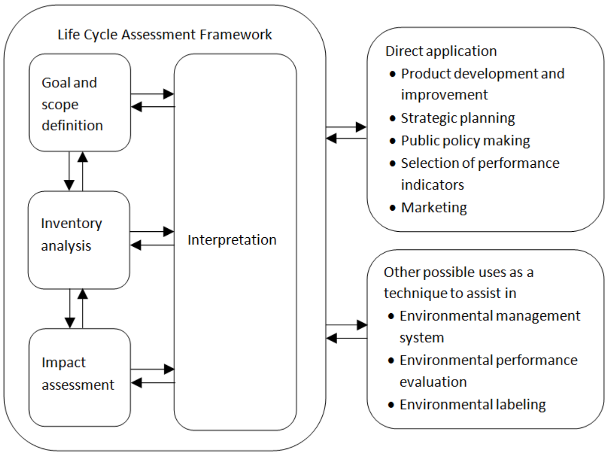

Fig. 2: LCA methodology and framework modified from ISO 14040

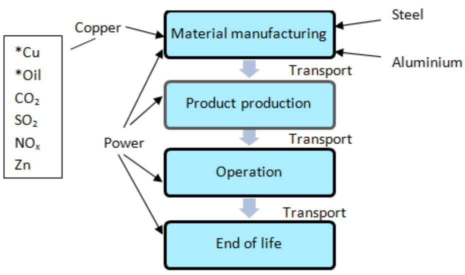

Fig. 3: In the Inventory analysis the different raw materials, energy carriers and transports are summarized. The energy and emissions to produce these are then also added

The typical weight of a core of a conventional dry-type transformer as considered is in the order of 2 tons, whereby the weight of an amorphous core increases by 25%-30%, corresponding to a substantial requirement in additional core material.

The main impact assessment method used is global warming potential (GWP) since climate change is a problem of increased concern in the society. In addition five other impact categories have been used to confirm the selection of GWP as the main indicator [6].

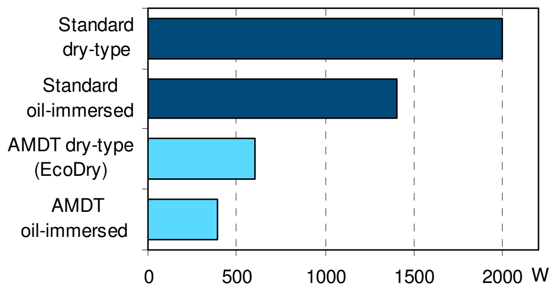

Fig. 4: No-load loss values of the 1000 kVA distribution transformers used in this study

Inventory analysis

The LCA data were retrieved from the GaBi v.4.3 and EcoInvent databases [7, 8]. Additional LCA data for the amorphous metal was obtained from other sources [9, 10]. Specific design data (materials, power losses, transports) for each transformer was retrieved from the local ABB factories in Germany and Poland.

The indirect environmental impact from the power losses was calculated based on an average power grid mix based on national statistics reports from 25 EU countries, with approximately 0,5kg CO_2 corresponding to the production of 1kWh electric power [7, 8].

At end of life the following assumptions are made: main materials (copper, steel, aluminum) are recycled at a rate of 95 %, plastic, oil and other insulation materials are incinerated, remaining materials are deposited at a safe landfill.

RESULTS

DTs with amorphous metal cores have significant lower impact for all environmental impact categories regardless of investigated load case, figure 5-7.

Figure 5 and 6 represent the typical average load of European DTs at 20%. At this load the total environmental impact is approximately 60% lower for dry and oil-immersed AMDT compared to the respective standard transformers.

Figure 7 represents the high load case at 50%. At this load the total environmental impact is approximately 40-50% lower for the dry and oil-immersed AMDT compared to the respective standard transformers.

A more detailed analysis of the impact of the different life cycle phases (manufacturing, operation and end-of-life) is shown in figure 8. Manufacturing stands for only a minor part (2 to 10%) of the total environmental impact for all studied DTs. Recycling of the metals gives a positive contribution (negative bar) to the total environmental impact since they are returned to the global metal reservoir and thus outweigh parts of the manufacturing bar. The relative contribution of the environmental impact from power losses then becomes even larger since material can be recycled but not energy.

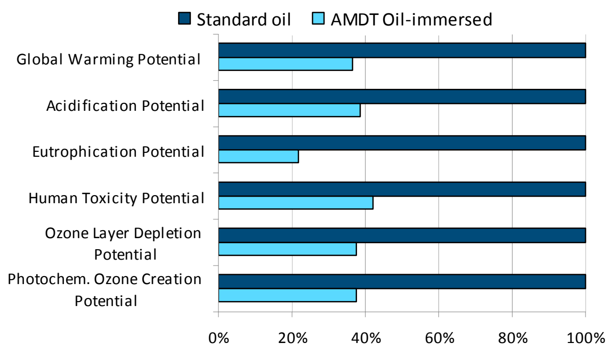

Fig. 5: Relative environmental impact of oil-immersed transformers with amorphous metal cores compared to standard ones at a load of 20%

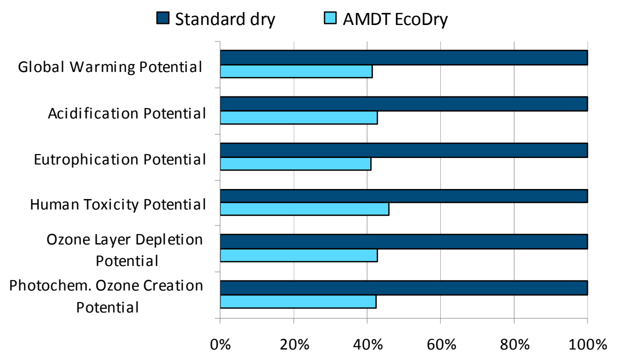

Fig. 6: Relative environmental impact of dry-type transformers with amorphous metal cores (EcoDry) compared to standard ones at a load of 20%.

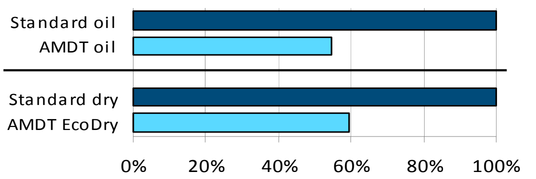

Fig. 7: Relative Global Warming Potential (GWP) for oil-immersed and dry-type transformers with amorphous cores in relation to their corresponding standard transformers at high loading of 50%

CONCLUSIONS

By doing this LCA we clearly demonstrate how the trade-off between material in the product and power losses during operation looks like. It is beneficial for the environment to "invest" in more material in order to decrease power losses during the products operation. A common perception is that increased material use is bad from an environmental perspective since once can directly see it, contrary to power losses that results in an indirect environmental impact caused by energy generation and thus is difficult to visualize in the same way as material.

The larger material use in AMDTs compared to conventional DTs is therefore well motivated from an environmental point of view as the reduction of power losses during operation dominates the life cycle impact. The life cycle assessment shows that the amorphous oil-immersed or dry-type DTs are more sustainable solutions with respect to all studied environmental impact categories. In relative terms, the effect is larger at low average load which represents the typical average load of European DTs, where no-load losses dominates and where the use of amorphous metal core decreases the no-load loss. At higher transformer loadings the relative differences become smaller, but nevertheless also in this case the amorphous oil-immersed or dry-type DTs are still the most sustainable solutions and give, in absolute terms, rise to a significant environmental improvement.

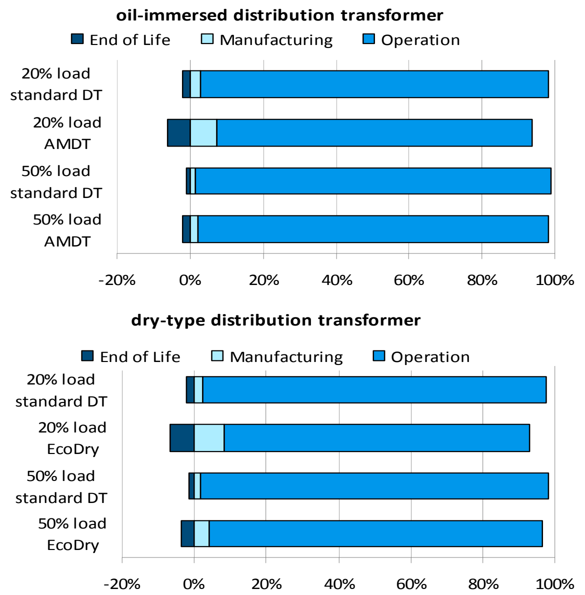

Fig. 8: Relative contributions from the product phases to the total environmental impact. The end of life treatment (recycling) results in a negative impact. Data presented for oil-immersed and dry-type standard and amorphous DT and a load of 20% and 50%

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