COMPARISON OF VARIOUS TECHNOLOGIES USED FOR DISTRIBUTION TRANSFORMERS FROM AN ECO STANDPOINT

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ABSTRACT

This paper provides some elements of a life cycle analysis for distribution transformers manufactured in different technologies. The detailed study was made for three phase 2.6 MVA, 36 kV transformer commonly used in wind turbine application in three design options: dry-type cast resin, conventional liquid-immersed and compact liquid-immersed (such as commercially available SLIM® transformer).

As a part of the study described in the paper, the methodology and tools were developed to analyze main activities in transformer manufacturing process and main components of transformer design responsible for eco-footprint. Comparative exploratory Life Cycle Impact Assessment was made. Rather significant difference was observed between cast resin transformer and liquid-immersed options. This was mainly related to the weight of transformer components. Resulting losses are also higher for cast resin transformer; hence the use phase of this type of design has more environmental impact, too. The conclusions may become a guideline for selection of transformer technology at procurement stage in case environmental aspects are to become more and more critical.

INTRODUCTION

There are different technologies available for manufacturing of distribution transformers. The two most common are: liquid-immersed transformers and dry-type cast resin transformers. Depending on the technology, the equipment has different characteristics and is typically used in different applications. While liquid-immersed transformers are common at power distribution utilities, the dry-type cast resin transformers are more common in special applications, like buildings, marine or industrial installations.

More recently, step up transformers of both types have become integral part of distributed “green” energy generation. They are integral parts of photovoltaic generation sites and wind turbines, including offshore installations. A wish for complete eco-friendly solutions to be provided for these installations created a need for comparative analysis of environmental impacts of these different transformer technologies.

Both technologies use different range of materials for transformer construction, manufacturing processes are different, and performance characteristics are not always equivalent. In conventional liquid-immersed transformers the cellulose based paper and pressboard materials are used in majority as insulation in the windings and within core/coil assembly (known as “active part”). The winding conductors can also be insulated with enamel. Entire active part assembly is then dried, closed in a steel tank and immersed in mineral oil acting as dielectric and cooling medium.

Modern compact designs of distributed power generation systems may require transformer designs where focus on limited size and weight of the design is critical. For example, in wind turbine construction it is common to use liquid-immersed transformers utilising alternative insulation materials. Cellulose based paper and board can be then replaced with aramid insulation and mineral oil can be replaced with silicone or ester fluids. Higher operating temperature allowed for these materials, allows for reduction of cooling systems of transformers. As a result, the active part and overall dimensions of the equipment are reduced. This translates to less material used for these designs.

The concept of cast resin technology is different. Instead of cellulose other materials are used, suitable for operation at higher temperatures. Transformer windings instead of being immersed in oil are encapsulated as solid blocks in moulded epoxy resin forms. Spacing between windings or between active part components and external enclosures are not filled with oil but are provided with appropriate large clearances in the air.

The differences in materials used and their quantities may translate into different environmental impacts of each solution.

EVALUATION METHODOLOGY

The study was made together with Association de Recherche Technologie et Sciences in Chambery, France – an institute experienced in life cycle analysis [1].

As a part of the study described in the paper, a methodology was developed to analyse main activities in transformer manufacturing process and to analyse main components of transformer design responsible for eco-footprint. The life cycle assessment covers:

- extraction and production of raw materials (conductor, core steel, insulation, tank or enclosure),
- manufacturing of main parts,
- transformer assembly,
- painting,
- transportation,
- use of product,
- dismantling and disposing after end of life.

It includes consumption of material and energy resources as well as emissions and waste generation.

The life cycle inventory (LCI) process was performed for quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of the product. Materials, weights of components, transport and energy consumption were collected. The Simapro 7.1.8 software was used with the EcoInvent 2.0 database, which contains data on materials, industrial processes, energy, transports and waste treatment. For materials or processes not existing in the EcoInvent database, like aramid insulation or magnetic transformer steel, the usable data was created based on detailed information provided by the manufacturers.

For use of product phase the expected lifetime of transformers, average loading and losses were considered, including detailed aspects like origin of energy used for manufacturing and origin of energy used for losses during operation.

Life cycle impact assessment (LCIA) was performed by use of Eco-Indicator 99H evaluation method. In this method the results are normally characterized and normalized for various damage categories and impact categories. The damage categories include ecosystem quality and resources. The impact categories fall in the following groups:

- emissions (carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, acidification/eutrophication, ecotoxicity),
- land use,
- resource depletion (minerals, fossil fuels).

Additionally, the carbon footprint was evaluated exploratory with the method IPCC GWP 100a.

STUDY DETAILS – OBJECT MODELLING

The exploratory study using the methodology described above was made for representative 3-phase, 2.6 MVA, 36 kV transformers - a quite common medium voltage rating in wind turbine applications. The comparison was made between:

- dry-type cast resin transformer in IP23 housing,
- conventional liquid-immersed transformer filled with mineral oil and with insulation system based on cellulose paper and board,
- compact liquid-immersed transformer designed for tight dimensional limitations specific for wind turbine application (SLIM®), filled with alternative less flammable fluid and with high temperature insulation system based on aramid materials.

The detailed transformer design data was based on products manufactured by CG Power Systems (or formerly Pauwels). Specifications of the three selected designs are shown in Table 1. The bill of major materials for each type of transformer was used. The simplified list of materials used in the evaluation is shown in Table 2.

According to the life cycle analysis methodology, the “functional unit” has been set as a reference. It was set to 1 MVA. Transformer operational life was assumed to be 20 years with an average load of 65%.

Table 1. Specifications of three analysed products

		Cast resin	**Conventional liquid-immersed**	**SLIM® liquid-immersed**
No load loss	W	3900	2500	2500
Load loss @ 75°C	W	-	20500	-
Load loss @ 120°C	W	20500	-	20500
Impedance	%	8	6	6
Sound level	dB(A)	74	74	70
Length	mm	2800 (in IP23 housing)	2185	2315
Width	mm	1400 (in IP23 housing)	1010	770
Height	mm	2900 (in IP23 housing)	2075	2110
Footprint	m²	3.9	2.2	1.8
Volume	m³	11.4	4.6	3.8
Fluid weight	kg	--	1185 (mineral oil)	990 (silicone fluid)
Total weight	kg	8075 (in IP23 housing)	5700	5375
Top oil rise	K	-	60	80
Average winding rise	K	100	65	120

Table 2. Simplified list of major materials used in different transformer technologies

Function	Cast resin	Conventional liquid-immersed	SLIM® liquid-immersed
enclosure	galvanised steel	-	-
tank	-	mild steel	mild steel
windings	copper	copper	copper
bus bars	copper	copper	copper
core	magnetic steel M5	magnetic steel M140	magnetic steel M140
insulation	PET	cellulose	aramid
insulation	polyester	-	-
insulation	epoxy resin	-	-
dielectric liquid	-	mineral oil	silicone
clamping	mild steel	mild steel	mild steel

Table 3. Energy consumption due to losses for compared transformers

	Cast resin	Conventional liquid-immersed	SLIM® liquid-immersed
No-load losses calculated [W]	3900	2500	2500
Load losses calculated at nominal load [W]	20500	20500	20500
Load factor	0,65	0,65	0,65
Hours per year	5694	5694	5694
Years	20	20	20
Load losses [kWh]	2334540	2334540	2334540
Total losses [kWh]	**3017820**	**2772540**	**2772540**

The definition of the origin of energy was critical for production phase and the use phase. For liquid-immersed transformers Belgian energy was used for energy consumption during the manufacturing phase and a European mix of energy has been selected for energy losses during use. In the adopted scenario, the transformers were used in the European Union. In case of cast resin transformers, the coils are produced in Italy. That is why the Italian pattern for energy at manufacturing was used. Additionally, the transport of coils from Italy to Belgium for complete transformer assembly was included in considered inputs.

During the use phase, the environmental damages are resulting from the energy consumption which is related to losses of the transformer. Some additional energy is required for periodic cleaning of cast resin transformers, while the liquid-immersed transformers are assumed maintenance free in this study.

Various environmental impacts from different technologies are then related to different loss levels of transformers used for comparison (Table 3). It was assumed in the study that load losses are supplied by the wind energy, while the no-load losses are supplied by European electricity mix (various sources of energy generation).

RESULTS

Based on the data collected and using the evaluation methods described before, the exploratory LCIA was performed translating the data into the established damage and impact categories. It allows for comparison of the technologies used from the perspective of environmental footprint.

Fig. 1 shows comparison of impacts on ecosystem quality and resources for all three technologies. Significant difference can be observed between cast resin transformer and liquid-immersed options. This is mainly related to the weight of transformer components. Larger dielectric distances in cast resin transformer are a driver for larger core and coils (more raw materials needed). Resulting losses are also higher for cast resin transformer; hence the use phase of this type of design has more environmental impact. Different types of materials were used for analysis of conventional and SLIM® type liquid-immersed units. Although the SLIM® is more compact and uses less materials for its active part, the overall eco-footprint is calculated very similar to conventional design. This may be related to the fact that use phase is the most significant in impacts calculated, and both transformers having the same losses fall very close in total

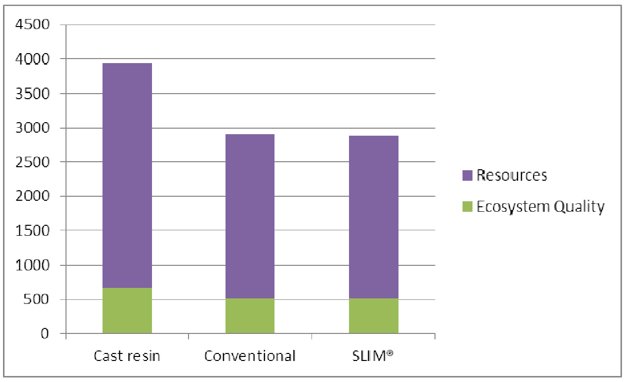


Figure 1. Comparison of impacts on ecosystem quality and resources for different transformer technologies

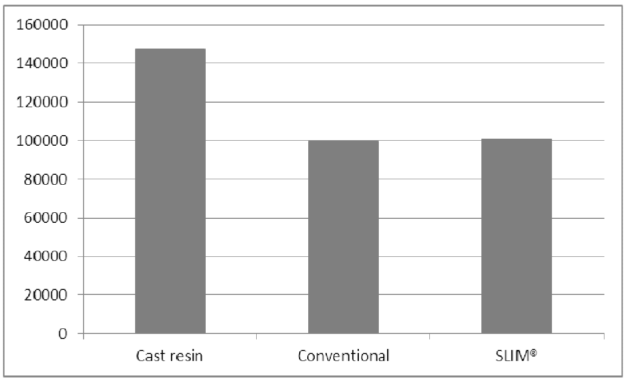
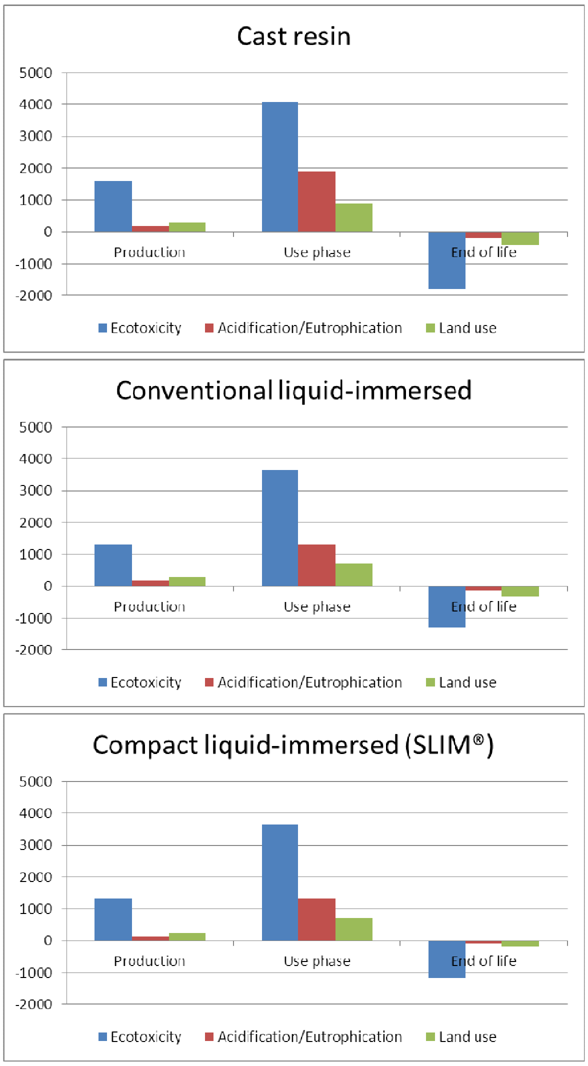


Figure 2. Exploratory carbon footprint of transformers as per IPCC GWP 100a method (in kg CO_2)



a) b) c)

Figure 3. Impact on ecosystem quality from transformer production, usage phase and its end of life (a - cast resin, b - conventional liquid-immersed, c - compact liquid-immersed (SLIM®))

score. The same explanation can be given to the calculated carbon footprint (Fig. 2). Again, both liquid-immersed options are very similar and get better score than an equivalent transformer in cast resin technology.

Split of selected environmental impacts on ecosystem quality between transformer production phase, usage and its end of life is presented in Fig. 3. The main impact comes from the use phase and is related to production of electricity to cover transformer losses. This has its impact also on the use of natural resources needed for producing the power for losses. The impact on ecotoxicity at production stage is due to the production of copper (especially use and emissions of nickel and chromium). What is remarkable, significant part of impact at the production stage can be later compensated at the end of life, when significant portion of materials could be recycled (e.g. copper).

As can be seen in Fig. 3, the pattern of impacts in specific stages of transformer life is very similar for all the technologies. Only the values are different (a bit higher for cast resin than for liquid-immersed solutions).

CONCLUSIONS

The use phase is the main source of environmental burden in terms of energy losses. CO_2 emissions, from the generation of electrical energy to cover the losses of transformer, score the highest. To improve the environmental performance of transformers, the designs have to focus on this point. This is currently under consideration in several working groups within the European Community in defining directives for low loss eco-designed transformers.

Considering the production phase only, the most important impact comes from the copper of the windings. Copper has a relatively big environmental load because of its production (involving nickel and chromium) and of its scarcity (impact on resources). Use of aluminium would end up in a lower total eco-impact, but that would only influence the end-value, not the relative impact when comparing the different technologies.

The end-of-life phase almost balances the production phase because of the recycling of all metallic parts. Although it should be noted that it is easier to recuperate the valuable base materials from liquid-immersed windings than from resin-encapsulated.

Proposed evaluation method indicates that the difference between compact liquid-immersed transformer (such as commercially available product SLIM®) and the conventional liquid-immersed transformer is not significant regarding eco-footprint. The cast resin technology seems to be the most affecting the environment due to higher mass of components and higher losses. And if on top of the eco-footprint, also compactness and reliability are decision drivers, then SLIM® type transformer seems to be the best choice. These conclusions may become a guideline for selection of transformer technology at procurement stage in case environmental aspects are to become more and more critical.

ACKNOWLEDGMENTS

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SLIM® is a registered trademark of CG Power Systems.

REFERENCES

[1] Association de Recherche Technologie et Sciences, Delegation de Chambery, 2009, *Life cycle analysis of transformers, Dossier No 15092.*