The circularity of medium-power electrical transformers

Evaluating design options based on an in-depth market survey

ABSTRACT

The Design-for-recycling of medium-power transformers is complicated by their long lifetimes. What will the recycling markets and technologies look like 50 years from now? We must be content with basing long-term predictions on the present-day situation. The Copper Alliance conducted an in-depth survey of the current state of transformer recycling. With their high metal content and straightforward disassembly, liquid-filled transformers score highly in terms of circularity. This can be further enhanced by using copper for the high voltage winding. Dry-type transformers are a different story; the lack of separability leads to a problematic end-of-life process.

KEYWORDS

recycling, design-for-recycling, circularity, copper windings, dry-type transformers

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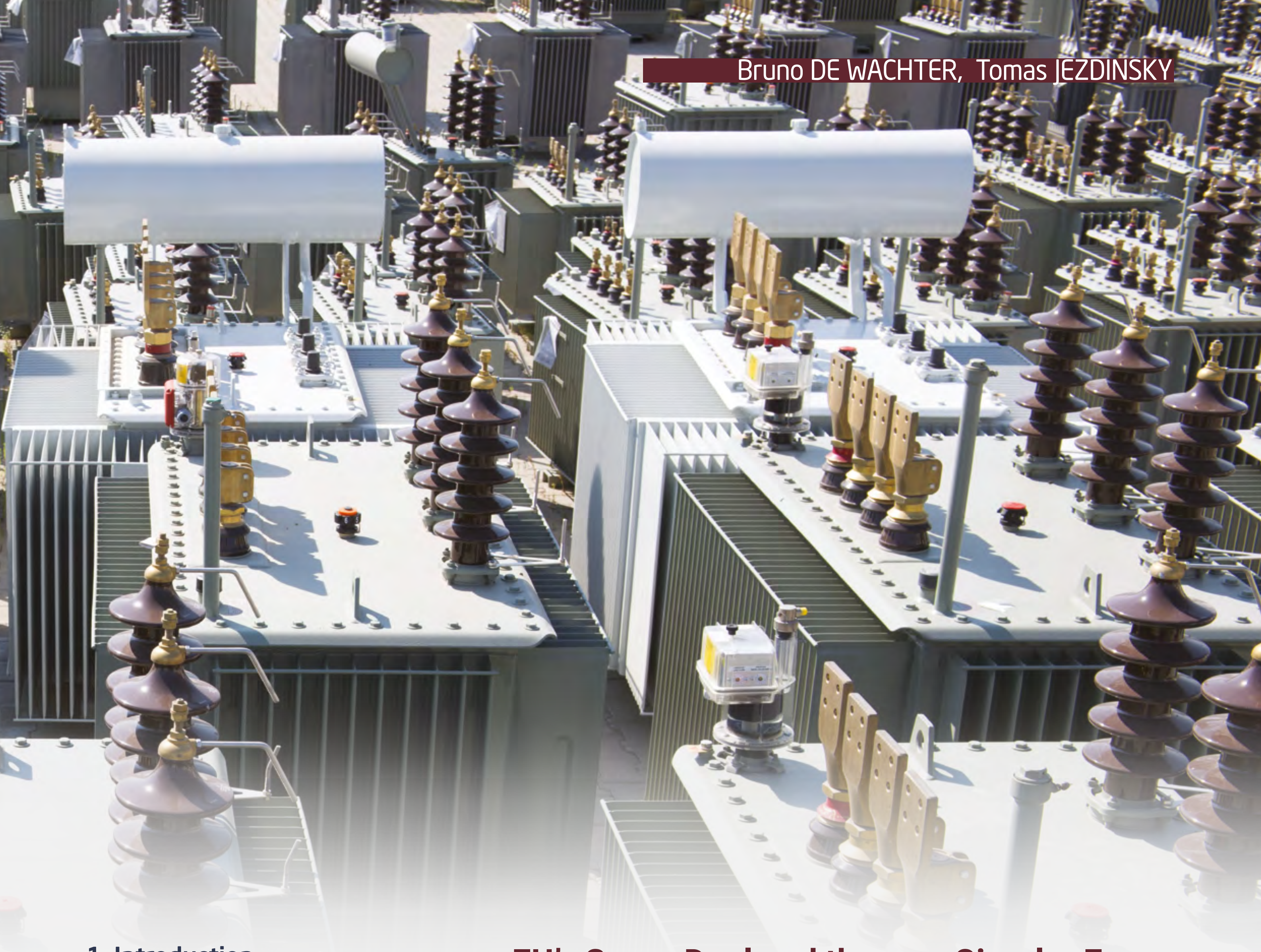

1. Introduction

In its *Green Deal* and the new *Circular Economy Action Plan*, the EU has been emphasising that the energy transition should be accomplished with maximum resource efficiency. The revised *Methodology for Ecodesign of Energy-related Products (MEErP)*, published in July 2021, translated this ambition into concrete decision-making instruments promoting the systematic assessment of material efficiency and recyclability in product design. The present article focuses on design-for-recycling for medium-power transformers.

EU's Green Deal and the new Circular Economy Action Plan emphasise that the energy transition should be accomplished with maximum resource efficiency

A first major observation is that medium-power transformers remain in use for a very long time. The depreciation period is typically 40 years, but their actual lifetime can be much longer — usually more than 50 years and sometimes even 80 years [1]. This long lifetime is a major strength in terms of material efficiency but comes with the complication that long-term recyclability assessment is a challenge. It is impossible to accurately predict where recycling markets, technologies, and regulations will stand 50 years from now. We have to make do with rough assessments based on today's market and technology, keeping in mind that the results should be viewed in light of an uncertain future.

With this goal in mind, the Copper Alliance carried out an in-depth survey of the current state of transformer recycling, conducting interviews at 20 stakeholder companies in Germany, Spain, Italy, France, and Serbia (a full list of the interviewed companies can be found in [2]). The data collected in the survey were processed and approved following the Delphi method. All statements in the chapters that follow in this article are based on the survey results, except where otherwise indicated.

Around 70 % of the transformer's mineral oil is recycled as first-grade for reuse in transformers, and the remaining 30 % is reused as second-grade oil in other applications — mainly as an industrial lubricant

The windings recycling requires shredding to filter out the small amounts of impregnated paper and lacquer, after which they can be almost 100 % recovered

2. The recycling of liquid-filled transformers

In recent times, end-of-life liquid-filled transformers have received major attention because of the presence of PCBs, which were judged toxic and banned by the EU in 1987. A positive consequence of the PCB crisis is that now only certified companies are allowed to handle oil-filled transformer recycling.

As a first step in the recycling process, the oil is analysed and pumped out of the transformer. Mineral transformer oil could, in principle, be recovered entirely through a filtering process. In practice, however, around 70 % of the oil is recycled as first-grade for reuse in transformers, and the remaining 30 % is reused as second-grade oil in other applications — mainly as an industrial lubricant. Natural esters could, in principle, be recovered in the same way as mineral oil, but there is no first-grade recycling process for natural esters yet because the market, equipment, and technical standards to cover it are lacking. An estimated 20–30 % of natural ester insulation is currently subject to second-grade recycling as vegetable oil, while the remainder goes for incineration with heat recuperation. A more efficient market for natural ester recycling and reuse is expected to develop as more of these transformers reach end-of-life.

In the next stage, the windings are removed from the transformer and shredded to filter out the small amounts of impregnated paper and lacquer. The shredded metals can be almost 100 % recovered.

The aluminium could, in theory, be recycled with purity levels of up to 99.7 % (Alu 7), which is the required level for reuse in new aluminium electrical wire manufacturing. In practice, however, the fact that it exists in many different alloys poses a serious barrier. The material should be subjected to laboratory analysis to detect the alloys and could then be recycled for use only in exactly the same kind of electrical application as previously. This is technically and organizationally complicated and is never carried out in practice. Because of the presence of the alloy materials and other contaminating metals (e.g., copper from connectors), the purity levels of the aluminium from transformer windings do not get any higher than 98 %. Therefore, the material is downgraded for use in second-life products for which this purity level is sufficient, such as building materials or non-electrical automotive parts.

Figure 1. Coils in the production line of three-phase oil-filled distribution transformers

Where high voltage windings are made of copper, the winding shreds are recycled at three different purity levels.

- Purity level 1A (> 99.9 %) has the same quality as copper cathodes. It can be melted and used again for electrical applications, including transformer windings, without further purification. This means that it follows a truly circular route that is highly efficient in terms of cost, energy use and environmental impact.
- Purity level 1B (> 99.7 %) has the same quality as copper anodes. It must be subjected to an electrolysis process to reach the purity level required for electrical copper.
- Purity level 2 (> 95.0 %) has the same quality as the copper concentrate sold by mining companies. It would need to undergo a thermo-chemical process to reach level 1B, and subsequently be subjected to an electrolysis process to reach level 1A, the purity level required for the electrical copper. In practice, it rarely follows this trajectory and is used without further purification in applications that require lower purity, such as copper alloys (e.g., brass) or additives in steel making.

How much of the copper exactly goes into each of those purity levels depends on the recycling company, but most (> 90 %) will be recycled at level 1A. One company has stated that it recycles 97 % of the copper from transformer windings at the highest purity.

Magnetic steel from the transformer core and structural steel parts are almost 100 % recovered. Magnetic steel laminates can, in principle, be cleaned and reused in a new transformer. However, the transformers currently being taken out of service in the EU have laminate thicknesses of 0.3 mm and above, which no longer comply with the current Ecodesign regulation. Some go to be stamped out to make laminates in Asia and Turkey, where smaller transformers are not subject to loss restrictions [3]. The process of stamping out smaller laminates from the original piece also has the advantage that potential damage from the dismantling process at the laminate edges is not an issue. The proportion of magnetic steel following this route depends on prices in the Asian market.

Figure 2. Copper granulates at a recycling plant

Magnetic steel from the transformer core and structural steel parts are almost 100 % recovered, and magnetic steel laminates can, in principle, be cleaned and reused in a new transformer

Porcelain elements used for electrical insulation in various parts of the transformer are sorted, cleaned and shredded. Almost 100 % is used in construction, mainly as hardcore in road construction.

About 3–5 % of a transformer is organic material such as wood, paper, or corrugated cardboard. Much of this has been impregnated with oil by transformer end-of-life. This liquid could, in principle, be separated from the solid waste for reuse, but this is not economically viable. As a result, these materials, with the oil they contain, go to waste incineration plants with energy recovery. This means that they are used as a combustion material to generate heat or electricity. In some EU countries, a lack of incineration plants or legal constraints means that these elements end up in the landfill.

A small proportion of the transformer (1–2 %) cannot be reused, recycled, or incinerated and has to be disposed of in the landfill. This includes plastic joints and buffers and silica connectors.

Table 1 illustrates typical recycling and circularity levels for a 400 kVA distribution transformer containing PCB-free mineral oil, M0H magnetic steel, aluminium low voltage winding, and either aluminium or copper for the high voltage winding.

3. The recycling of dry-type transformers

Cast-resin dry-type transformers pose a major difficulty for recycling. The windings, which in the case of oil-filled transformers can be extracted easily and recycled, are entirely over-moulded with an epoxy or quartz resin. Separating this resin from the metal coils takes time and energy and is not economically viable within the EU. It would require powerful machines for pre-cutting the material into smaller pieces (typically 1000 kN) and several rounds of milling and grinding with high-powered shredders (typically 4500 kN). Even then, the metal can only be recovered at low purity (< 95 %) for use only in secondary applications. Moreover, more than 80 % of dry-type transformers use aluminium as a winding material rather than copper, which limits the scrap's economic value. If separation were possible, the economically worthless resin parts would still make up about 40–50 % of the material weight in the case of aluminium windings and 30–40 % of the material weight in the case of copper windings. Since the resins are chemically diverse and recycling is highly complex, they cannot be recovered and have to be disposed of in the landfill.

These findings are supported in an Italian University thesis [4] which states that full separation of the resin and coil today is "highly costly, time-consuming and an economic nonsense". Even the special-

About 3–5 % of a transformer is organic material such as wood, paper, or corrugated cardboard, mostly going to waste since it is not economical to reuse it

Figure 3. Transformer magnetic steel laminates

Figure 4. A new cast-resin dry type transformer

ised cryo-grinding process is not seen as a solution according to the thesis since it would require an excessive quantity of liquid nitrogen for the separation (120 litres of liquid nitrogen to recover 300 kg of resin).

As a result, the coils still entirely covered with cast resin are sold together with other electromechanical scraps for export outside the EU. It is assumed that most of them end up in India, where a low-paid workforce separates the resin from the metal coils in semi-automated processes. The recovered metal is sold to foundries as low-grade scrap, with the remainder ending up in the landfill.

Other parts of cast-resin dry-type transformers, including the magnetic steel in the core, structural steel parts in the frame, and ceramic components, follow the same recycling path as in the case of liquid-filled transformers.

Conclusion

The circularity assessment of medium-power electrical transformers is striking for the sharp contrast between liquid-filled and dry-type units. The first sets the example, with its straightforward disassembly and a high degree of recyclability, while the second shows how a lack of separability in the conception of a device can lead to a problematic end-of-life process. Their application areas partly overlap, so there is often a choice between the two types, and, until now, circularity has seldom been a decisive argument in making this choice. With increasing attention on the circular economy in business and policy-making, this is soon likely to change.

In the case of oil-filled transformers, about 75 % of the material can be reused or is

Cast-resin dry-type transformers are difficult to recycle since their windings are entirely over-moulded with an epoxy or quartz resin, and their separation requires time and energy that is not economically viable within the EU

Table 1. Typical recycling and circularity levels for a 400 kVA transformer

End-of-life material	400 kVA, M0H, mineral oil, aluminium in HV winding (kg)	400 kVA, M0H, mineral oil, aluminium in HV winding (%)	400 kVA, M0H, mineral oil, copper in HV winding (kg)	400 kVA, M0H, mineral oil, copper in HV winding (%)
Re-use and 1st grade recycling (circular)	**76%**		**82%**	
Magnetic steel	1056	40%	1018	34%
Mineral oil 1st grade (70%)	363	14%	405	14%
Copper 1st grade (95%)	0	0%	458	15%
Structural steel	569	22%	575	19%
2nd grade recycling (non-circular)	**17%**		**11%**	
Aluminium	273	10%	93	3%
Mineral oil 2nd grade (30%)	156	6%	174	6%
Copper 2nd grade (5%)	0	0%	24	1%
Porcelain	26	1%	30	1%
Incineration with energy recuperation	**5%**		**5%**	
Wood, paper, cardboard	131	5%	149	5%
Land-fill disposal	**2%**		**2%**	
Other parts (kg)	53	2%	60	2%
Total weight (kg)	**2627**	**100%**	**2986**	**100%**

It is assumed that most windings from cast-resin dry-type transformers end up in India, where a low-paid workforce separates the resin from the metal coils in semi-automated processes

subject to first-grade recycling. Its degree of circularity can be enhanced further when copper is used for the high voltage winding because the metal can be recuperated and recycled at high purity. Copper windings also increase the end-of-life value of the unit, enhancing the business case for recycling and reuse.

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