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PS 3. Opportunities for Sustainability and Circular Economy
with Substations and HV Equipment

Transformers and the Circular Economy

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SUMMARY

Transformers and reactors are amongst the most important components in the electric power infrastructure. They are generally reliable and durable. However, they reach the end of their useful lives and then need to be disposed of. This paper examines best practices for disposal of transformers and reactors at the end of their lives, and especially transformer and reactor recycling. This paper gives consideration to different design concepts. This paper also gives consideration to specification, design, and construction of new transformers and reactors for easier recycling at the end of their useful lives.

KEYWORDS

Transformer, reactor, specification, design, construction, end of life, recycling

1 Introduction

Transformers and reactors are amongst the most important components in the electric power infrastructure. Large amounts of valuable materials are used in the construction of new transformers and reactors. Large amounts of valuable materials are also used in the construction of substations to accommodate transformers and reactors, including foundations, sumps, sound walls/houses, and fire walls/barriers. There is great value to the industry in applying a circular economy approach to the life management of transformers and reactors to ensure the best and responsible use of materials and other resources. Special attention is required at each end of transformer and reactor operational life, i.e. during procurement and again during disposal.

This paper will set out a circular economy approach, based on the United Nations Environment Programme circularity framework. This paper will then consider how transformers, reactors, and associated substation infrastructure can be re-used, repaired, refurbished, remanufactured, or repurposed. As this is not always possible, this paper will examine how transformers and reactors which have reached the end of their useful lives can be disposed of. Careful consideration is given to different design concepts. Finally recommendations are made for the specification, design, and construction of new transformers and reactors for easier recycling at the end of their useful lives.

2 Circular Economy Approach

The concepts of material stewardship and design-for-recycling are rapidly growing in importance. In 2019, the United Nations Environmental Programme set a clear framework for all future steps for products with the UNEP circularity platform [1]. This approach is shown in Figure 1.

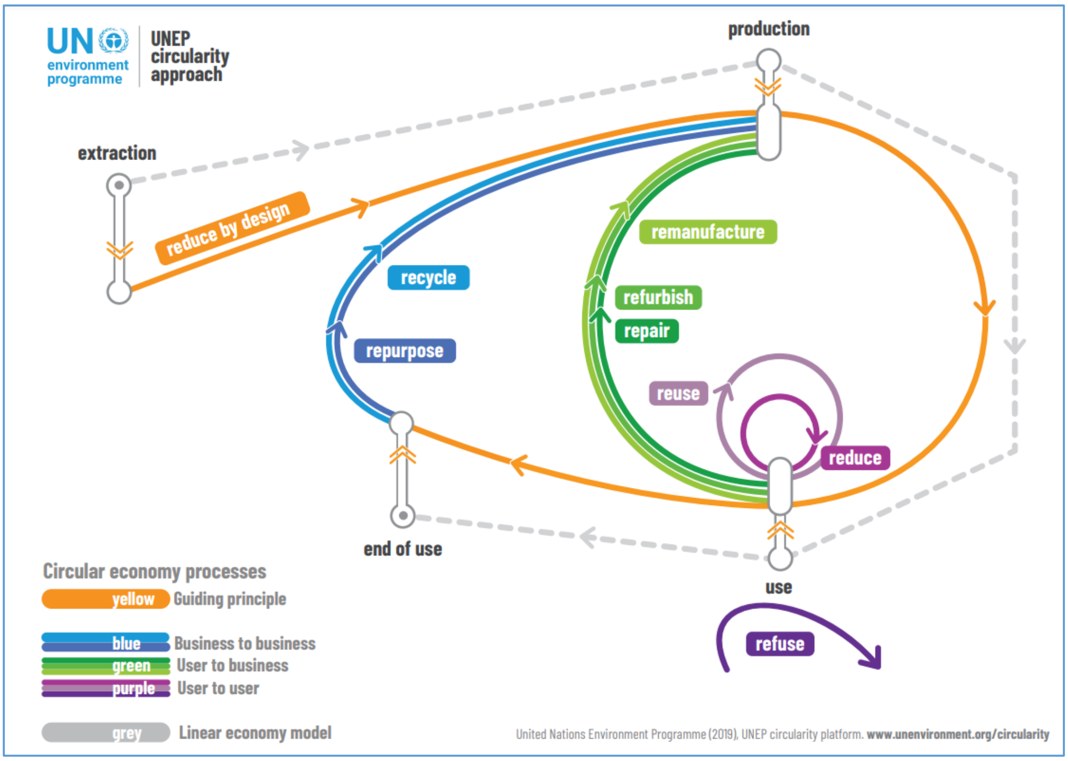

Figure 1

United Nations Environment Programme Approach to the Circular Economy, including differences between circular economy and linear economy (image licensed under the Creative Commons Attribution 3.0 IGO License)

The main elements of the United Nations Environment Programme circulatory framework as shown in Figure 1 are as follows:

Reduce by Design leads to the design of products and services that are using less materials per unit of production, and/or during their use.

Refuse is a user choice to buy or use less.

Reduce is a user choice to use items and services for a longer time and buy less frequently. Reduce can be implemented at no cost and has strong potential in retaining value of a product or service for a longer time period.

Re-use refers to the using again of a product, object or substance that is not waste, for the same purpose for which it was conceived, without the necessity of repair or refurbishment (as defined in the Basel Convention [2]). Re-use and re-sell can be implemented at little costs and has strong potential in retaining value of a product or service for a longer time period.

Repair refers to the fixing of a specified fault in an object that is a waste or a product and/or replacing defective components, in order to make the waste or product a fully functional product to be used for its originally intended purpose. Repair extends the product lifetime.

Refurbish refers to the modification of an object that is a waste or a product to increase or restore performance and/or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended (as defined in the Basel Convention [2]).

Remanufacture refers to an industrial process that takes place within industrial or factory settings, in which products are restored to same-as-new, or better condition and performance. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products.

In **repurpose**, by reusing discarded goods or components adapted for another function, the material gets a distinct new life cycle (i.e., plastics used in handbags). Converting old or discarded materials into something useful allows to return them into the economy retaining some of its value, if not all its value.

Recycle refers to the relevant operations which prevent waste disposal and allows material to re-enter the loop. These are defined in the Basel Convention [2].

3 Applying the Circular Economy Approach to Transformers

Not all of the elements of the United Nations Environment Programme circularity framework are applicable to transformers and reactors. In the opinion of the authors of this paper, the following elements can be applied:

Re-use is possible when a transformer or reactor becomes redundant and sometimes also when it becomes obsolete (e.g. when it needs to be replaced by another transformer or reactor with different rated voltage or rated power). The transformer or reactor can be re-used at a different substation or installation. This may involve either redeployment by the user or sale to a different user, often via a third-party. It is facilitated by standardisation, esp. of rated characteristics and of interfaces, to enable interchange of transformer or reactors of different ages from different suppliers. Large users are in good position to implement standardisation, especially for distribution and medium power transformers. In some countries, standardisation has been implemented across multiple users or even the whole industry either by the National Standards organisation or by Industry Associations.

Re-use of foundations, sumps, and usually also fire walls/barriers is possible when a transformer or reactor is replaced. It requires that the replacement transformer or reactor is compatible with the replaced transformer or reactor in terms of mass, dimensions, terminal arrangements, etc. Again, it is facilitated by standardisation, esp. limitations on installed mass and dimensions. Certain terminal arrangements facilitate re-use, esp. use of oil/air bushings or cable plug-ins of a standardised type. Conversely certain terminal arrangements complicate re-use, esp. direct connection to GIS.

Re-use of sound walls/houses and sometimes also fire/walls barriers is more challenging, as removal of the transformer or reactor usually requires the partial or total demolition of the walls/barrier/house. In case of a sound house, it may be possible to retain and **re-purpose** one or two of the walls as sound walls.

In the context of the United Nations Environment Programme circularity framework, **Repair** refers mainly to corrective maintenance performed at the transformer or reactor installation site. Given that transformers and reactors are generally reliable and durable, most transformers or reactors receive some corrective maintenance during their operational lives. Typical tasks include correction of corrosion, correction of liquid leaks, or replacement of worn out parts (e.g. fans or tap changer contacts). In certain cases more complicated tasks may be necessary, e.g. reclamation of the liquid, replacement of bushings.

In the context of the United Nations Environment Programme circularity framework, **Refurbishment** would typically refer to **Repair** at the end of the operational life of a transformer or reactor before **Re-use** at a different substation or installation.

In the context of the United Nations Environment Programme circularity framework, **Remanufacture** refers mainly to rebuilding transformers or reactors in a workshop. There is some overlap between **Repair** and **Remanufacture**, e.g. some smaller transformers may be taken to a workshop for repairs described in the previous paragraph and some larger transformers maybe rebuilt at site where transport to a workshop is impractical (there are a number of case studies of large transformers being rebuilt at site in CIGRE brochure 857 [3]).

In **Remanufacture** the core/magnetic circuit, frame, tank, and fittings are typically retained and reused, while the windings, leads, and insulation are replaced and often also re-engineered. The reused components and fittings should preferable be of modern design and in good condition. In case of older designs of core/magnetic circuit, remanufacturing may also require the core/magnetic circuit to be replaced or restacked new laminations to comply with contemporary loss and sound level requirements. Re-using the existing tank and fittings has the advantage not only of reducing costs but ensuring that the remanufactured transformer or reactor is fully dimensionally compatible with the original transformer or reactor.

Remanufacture is most often applied to transformers and reactors at the start of their operational lives, which are still the subject of a supplier warranty, and to transformers or reactors where dimensional compatibility for the rebuilt transformer is absolutely essential, e.g. traction transformer mounted on railway rolling stock, large furnace or rectifier transformers, etc.

Repurpose may be an alternative to **recycle** for certain transformer and reactor materials, components, and fittings at the end of the useful life of the transformer or reactor. Certain components and fittings may be suitable for salvage and **re-use**, e.g. bushings are often salvaged for use as spares esp. if they are of an obsolete type for which direct replacements are no longer available. Core laminations can be salvaged and restamped to make cores for new transformers, if they are in good condition and of a sufficiently high grade. Conducting or insulating materials are not suitable for reuse, mainly owing to ageing and contamination in service and during the scrapping process.

4 Recycling and Disposal of Transformers

The main steps of transformer and reactor recycling are shown in Figure 2.

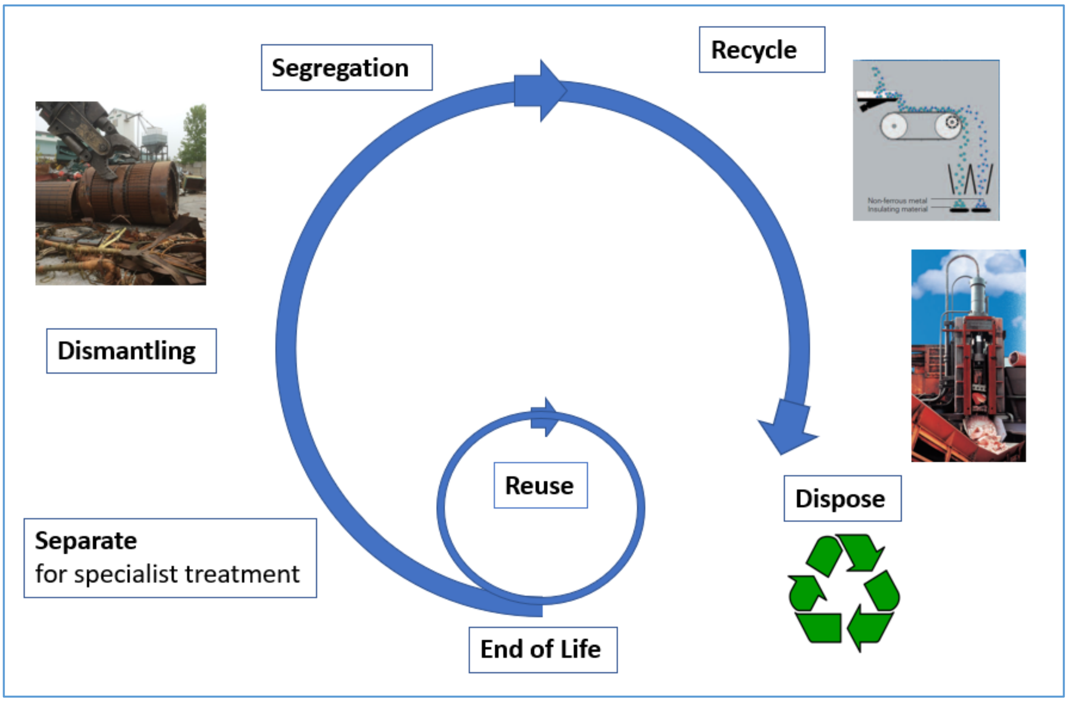

Figure 2

Main Steps in Transformer Recycling

Dismantling is typically performed by specialist teams with experience of transformer and reactor design and construction. The process begins with removal of the external parts of the transformer or reactor – tank, coolers, fittings, etc. The transformer or reactor is carefully opened to access the core and winding assembly.

Once the transformer or reactor is opened, the various materials are **separated** into different categories. This includes different metals (iron and steel; copper; aluminium) as well as insulation materials (liquids and solids). Care is taken to separate potentially hazardous materials, e.g. asbestos gaskets or liquids contaminated with PCBs.

The next step in the recycling process is to **process** the segregated materials. This may involve shredding, melting, or otherwise breaking down the materials into smaller, more manageable pieces. For example, the copper windings may be melted down and made into new wire or other products, while the insulation materials may be ground into small particles for use in other products or as fuel.

After the materials have been processed, they may need to be further **refined** or **purified** to remove impurities. For example, the copper from the transformer windings may need to be refined to remove any remaining impurities or alloys. Similarly, the oil from the transformer may need to be reconditioned and reclaimed or even re-refined to remove any contaminants or impurities.

The final step in the recycling process is to **reuse** or **repurpose** the recovered materials in new products. The copper and aluminium may be used to manufacture new wire or other products, while the oil may be reused in new transformers or other machinery.

5 Recycling and Disposal of Transformers

A number of different transformer design concepts have been developed to meet customer expectations and requirements. The conventional oil-immersed power transformer was developed shortly following the introduction of the first power transformers and remains the most widespread type today. Alternative insulating liquids have been developed to replace oil, and are now used across the full size range.

5.1 Liquid-Immersed Transformers and Reactors

Liquid-immersed transformers are normally constructed in a modular way. Core; windings; clamping frame; and tank, cooler, and other steelwork will produced in different production steps and assembled. Typically they are connected together in a way which allows easy assembly and disassembly.

Depending on the core design, unstacking or unwinding of the laminations should be possible with more or less difficulty. Edges of laminations may be glued in some cases, which may complicate disassembly and especially reuse of either the complete core or the laminations. The top yoke is rarely glued, and so removal of the winding assemblies is rarely affected.

Winding assemblies are normally blocked or wedged to the core limbs, and should be possible to lift from the core with little difficulty. In case of radial collapse of the inner winding during failure of the transformer, removing the winding assembly is more challenging and it may be necessary to cut the winding.

In theory, some 90 - 95% of every liquid-immersed transformer could follow an entirely circular recycling route. The materials can be recovered and re-used in new transformers or recycled into the same material needed for the manufacture of new transformers. In practice, some of the material will be downgraded for use in second-life products with lower purity requirements, where the circular route is technically complicated and economically unfeasible. This includes all of the aluminium and about 30% of the oil content. Replacing aluminium conductors with copper increases the degree of circularity, since most of the copper is recovered with very high purity for re-use as electrical conductor material. Only a small proportion of end-of-life transformer material is incinerated with heat recovery (3 - 5%) or ends-up in landfill (1 - 2%).

5.2 Dry-Type Transformers and Reactors

As the cores of dry-type transformers are exposed to the atmosphere, the laminations must be protected from corrosion by paint, resin, or glue. This includes the laminations in the top yoke, so opening the core to remove the winding assemblies is challenging. It is difficult to reuse either the complete core or the laminations.

The windings are also exposed to the atmosphere, and so must be protected against ingress of moisture and contamination. There are a number of different technologies used for the winding insulation, with different characteristics. Vacuum pressure impregnated (VPI) and similar transformers are covered and protected with varnish, typically polyester-imide. Windings can be recycled by shredding. Cast-resin designs, where the windings are encapsulated in resin, are more challenging to recycle.

Partly to improve dry-type transformer recyclability, a new design concept for dry-type transformers has been developed. The epoxy resin is replaced with silicone rubber, which can more easily be separated from the winding conductors to allow recycling. This is an emerging technology and experience remains limited. For more information, please refer to Han et al [4].

6 Conclusions and Recommendations

Transformers and reactors are amongst the most important components in the electric power infrastructure. Large amounts of valuable materials are used in the construction of new transformers and reactors. Large amounts of valuable materials are also used in the construction of substations to accommodate transformers and reactors, including foundations, sumps, sound walls/houses, and fire walls/barriers. There is great value to the industry in applying a circular economy approach to the life management of transformers and reactors to ensure the best and responsible use of materials and other resources.

In the specification of new transformers, standardisation of rated characteristics and terminal arrangements is desirable as it increases the possibility of re-use of the transformer or reactor and of associated foundations, sumps, and usually also fire walls/barriers. However, re-use of sound walls/houses and sometimes also fire/walls barriers is more challenging, as removal of the transformer or reactor usually requires the partial or total demolition of the walls/barrier/house.. Use of sound houses should be avoided where possible.

Liquid-immersed transformer and reactor design concepts are more inherently recyclable than dry-type transformer and reactor design concepts, especially cast resin design concepts. A new dry-type design concept with improved recyclability has been developed, but experience is limited.

Both copper and aluminium conductors used in transformers and reactors can be recycled. However, recycling of aluminium conductors is more challenging owing to loss of purity, and aluminium conductors are often down-cycled.

7 References

[1] UNEP Circularity Platform (https://buildingcircularity.org)

[2] Basel Convention of the Control of Transboundary Movement of Hazardous Wastes and their Disposal, signed 22 March 1989, effective from 5 May 1992

[3] CIGRE brochure 857, “On-Site Assembly, On-Site Rebuild, and On-Site Testing of Power Transformers”, final report of working group A2.59, December 2021

[4] S Han, J Wu, Y Jin, L Zhang, Y Yang, and J Han, "A New Solution of High Energy-Efficient Dry-Type Transformers with Silicone Rubber Casting Technology”, paper A2-10277, CIGRE Paris session, 2022