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# Analysis of Passive Power Components Reuse

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## Abstract

Eco-designing static converters becomes a necessity to tackle the growing issue of e-waste, and to mitigate the environmental impacts occurring during the manufacturing, usage and the end of life stages. This research focuses on multicellular power converters as original designed systems providing the opportunity for optimizing their functional usage throughout their life cycle. This paper proposes a quantitative method for designing for reuse. The suggested models rely on the concept of keeping the components' value high during multiple lifecycle stages within a circular economy scheme.

## 1 Introduction

The massive electrification of products led to an extraordinary growth of the e-waste stream around the world. Functional components become obsolete as the technology is renewed rapidly. The e-waste is considered by the UN and by the EPA as the fastest growing waste stream in Europe with a growth rate of 1,7 million metric tons per year in the world [1]. This generates an exponential increase of raw materials and energy consumption among other negative environmental impacts in air, water and soils.

The current recycling scheme process including collection and electronics treatments only covers 20% of the e-waste stream around the world [1].

Power electronics hold an important share in the Waste of Electrical and Electronic Equipment (WEEE) through the targeted categories: small equipment, large equipment and small IT. Such equipment contain power converters, power supplies or transformers and constitutes more than 50% of the total waste stream [1].

One of the tangible actions to tackle this worldwide growing issue is the *European circular economy action plan* that rolls out the sustainable product policy and translates it into specific legislation to improve the e-waste management [2]. The slogan of this plan is "less waste, more value". It seeks to foster reuse, reparability and promote a higher quality in recycling (effective separation and collection of e-waste).

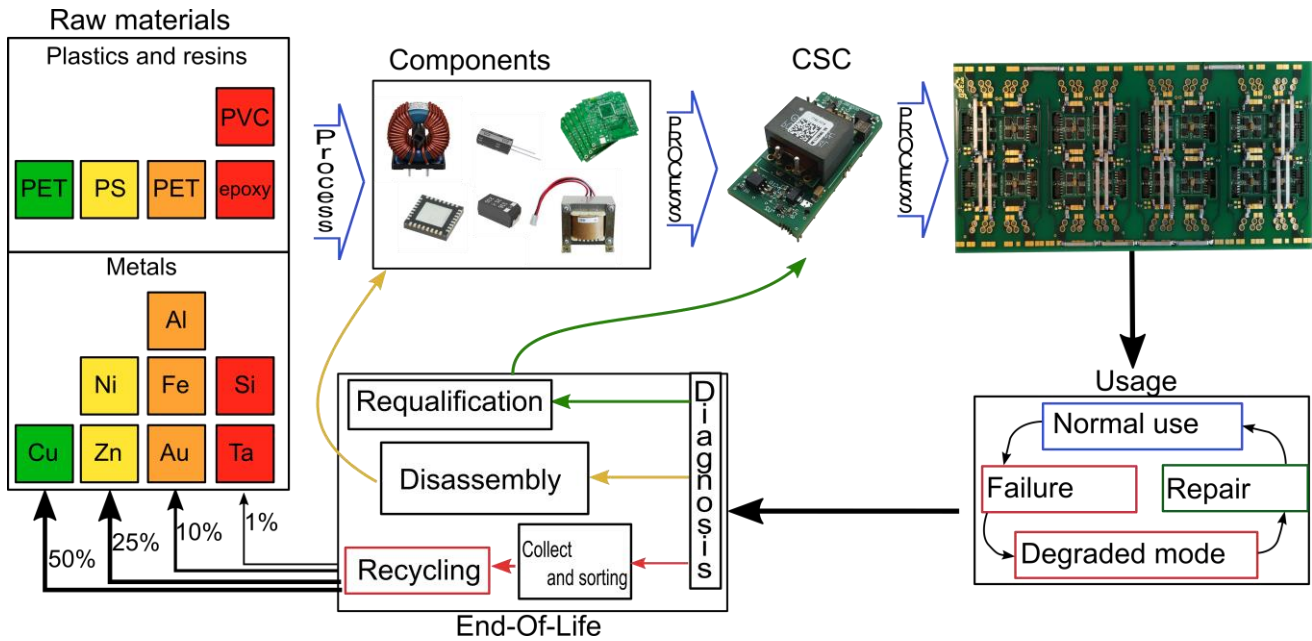
This paper's ambition is to support an alternative scenario to recycling. The approach is heading

toward a "Design for reuse/repair method" of power electronics converters that relies on the functional value of its components. This method is meant to be integrated in the usual design methodologies of converters.

Several methods supporting design for circularity target modularity and standardization in electronics [3]. This focus allows a straightforward failure or default identification, safe and easy dismantling and therefore simplified repair. The lack of post repair 'health' status predictive models of components and subparts however constitutes an important issue for the creation of a well-functioning market for second hand components. This remains a stumbling block for a successful repair industry [4].

Repairing components, reuse sub-systems or remanufacturing are among the most desirable options to maximize the environmental benefits. Nonetheless, it is important to be able to identify which component or subsystem are worthy to be repaired, reused or remanufactured. The value of the components is directly related to its ability to be reused. Several indicators can help the manufacturer choose the right components design its converter.

The next section presents the multicellular converters approach on which the design method proposed in section three is based. Section four investigates the degradation and failure of components that may occur during the repair stage. Section five presents the experiments conducted to characterize the degradation on the



**Fig.1**- A life cycle of a power converter

transformers and on the capacitors, in the case of a potential reuse and repair scenario to extend the electronic system lifespan.

## 2 Introduction to the multicellular converters approach

The smartphone or the automotive industries are common examples of products, designed for modularity and standardization. Cf. emerging companies like such as Fair-phone© or the modular batteries designed by Volkswagen [5] [6]. A standard design has many benefits starting from the acceleration of prototyping and manufacturing to the optimization of the e-waste collection, remanufacturing and recycling.

For instance, in microelectronics, the standardization of the main modules helped the manufacturers optimizing the industrial chains to improve products reliability [7].

It is also important to note that high power converters are already mostly modular and repairable and every sub-module is assembled with some mechanical tools in order to ensure proper mechanical strength but also to ensure maintenance steps in case of a failure [8][9]. Nevertheless in medium and low power applications, reparability and reuse are still not part of the specifications during the design period.

In the specific case of medium and low power electronics (<1kW) that is a big part of the e-wastes found in small and big appliances, power converters are usually fully customized from one

application to another and they are mostly based on printed circuit boards. A rising interest is currently heading toward a disruptive approach of converters' design built from modular and standardized sub-modules [10] [11] [12].

Among them, the-so-called Power Converter Array (PCA) are of interest regarding the main topic of this paper as it contains a set of standard cells, which can be combined under constraints to answer numerous different applications with the same parts. Among the standard cells needed to implement a full power converter [13], the standard conversion cell (CSC) is the most important, in values and numbers of repetitions. In past and more recent works, this conversion sub-module consists of a generic DC/AC converter made of an isolated conversion stage (a Dual Active Bridge (DAB) in the case of this paper) cascaded with a full bridge inverter stage. In medium and low power range, the elementary conversion cell is rated low voltage and current in order to maximize its granularity. In order to fulfill a certain specification, it is therefore necessary to associate several CSC in different series and parallel configurations with the best possible performances [14].

The main advantages of achieving this granularity in the design of the converter are to distribute voltage and current constraints over the entire PCB surface, to distribute losses, and to interleave control signals in order to increase dynamics and to reduce at best storage and filter needs. Furthermore, this granularity is also interesting with respect to fault tolerance and global

robustness, since in case of a single unit failure, the other units can take over and insure service operation continuity. Finally, the standardized approach can also be beneficial in terms of life cycle point of view if the end of life can be simplified by the standardization, as well as the opportunity to reuse sub-systems such as CSC or at least valuable components from it. The standard aspect of the cells allows us to create predictive models of reliability and end-of-life as a cell is always constituted from the same components and in the same spatial layout.

In the converter life cycle description given Figure 1 above, the benefit of sub-system or component reuse and remanufacturing before total end of life is well underlined by the diversification of end-of-life streams.

To make the alternative end-of-life scenarios possible in figure 1, diagnosis models should be made available to designers/engineers/operators to evaluate the remaining interest of the sub-system or component before its reintroduction in the value chain as a second hand component or subsystem. The following parts of this paper are focused on what needs to be done in order to close that loop, preventing full end of life recycling, and offering additional path for the elements with remaining value from both economic and environmental point of view.

### 3 Design method by value analysis

When designing a power converter, the manufacturer goes through sizing passive (capacitor, transformer, inductors...) and active (transistors, diodes, drivers...) components as well as interconnects, cooling and mechanical devices to achieve the best performances and efficiencies for a certain application.

Some of these components have a high value, stable over time, meaning they are reliable, long lasting, expensive and rich with metals. It is then logical to think about reusing them and to reintroduce them in the value chain, possibly after remanufacturing, in similar applications or in another less constraining application.

Therefore, as it is a common practice to separate and to isolate the power parts from the digital ones to preserve each one from the other, it is interesting to explore how isolating sub systems can be worthwhile with respect to not only functionality but also characteristics such as less reliable, repairable or expensive components from

the others to ensure a safe and lucrative disassembly.

For that, we propose a design method for reuse built on an index that results in a set of guidelines that will help the manufacturer achieve a good disassembly efficiency. The index could be constituted of four indicators:

- The price of the component: reflects approximately the energy costs necessary to make a component from raw materials, logistics to transformation processes
- MTBF (Mean Time Between Failure): Reflects the reliability of a component and it is calculated with MIL-HDBK reliability models
- The reuse rate: It is an empirical value obtained from repairing experiments; this indicator will be developed further in section four and five with two examples of calculation.
- Ease of disassembly: It is a theoretical indicator made of a scoring system that groups three others criteria: Number of tools used, time consumed, cost/energy consumed.

## 4 Degradation and failure mechanisms of components

### 4.1 Current repair procedures

The extraction of components from a printed circuit board can be either manual or semi-automated. These disassembly procedures do not guaranty the integrity of the components and many of them are still in the research phase.

The disassembly method can be categorized into two main families [16]:

- Mechanical/Thermal damage to the solder joints between the component and the PCB (reflow oven, induction furnace, infrared heaters, soldering iron...).
- Dissolving the welds using chemical reagents (Silicon oil, methylphenyl [17]...).

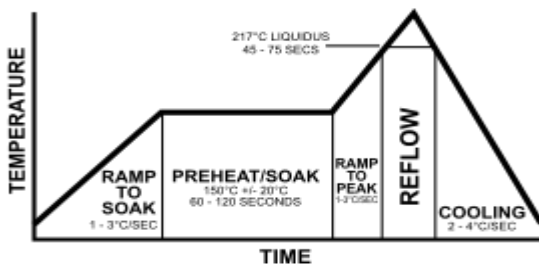
For the identified components (see later their selection), the reflow oven is selected at first for its ease of implementation [17].

The reflow oven was initially made to assemble and to solder mainly SMD components on PCB with heat, but it can also be used to soften the solder joint and free the components from the board. In complement, the through hole-component mounting requires wave soldering techniques or manual soldering. All these techniques can be used and optimized to

disassemble the PCB board and to collect the components. Some techniques are less stressing for the components since they do not rise the component internal temperature. Some other are more stressful.

In the oven, the PCB board and all components go through three thermal steps (figure 2):

- The preheating phase to start the reaction in the soldering paste (1min-3min)
- The reflow phase to melt the solder (1min-3min)
- The cooling down phase to harden the solder (5min)



**Fig. 2:** An example of an oven soldering profile (the peak temperature is up to 270°C and the preheat temperature is about 180°C) [18].

Intrinsically these disassembly means may be destructive and may degrade the material properties of the components. Consecutive the disassembly, a remanufacturing step is required to clean up the component pads. Although this step may add an additional stress to the device, it will be neglected initially and its impact will be studied later. Also, in order to soften the solder joint to collect the device, the temperature profile might be different from the one to solder it. For example, the help of the mechanical strength may help collecting the device under lower temperature. This is also left to another study. The following sections investigate the effects of soldering profile temperature cycling in the oven on some components in order to evaluate if the disassembly thermal profile, identical to the one of an assembly thermal profile, could be considered as an option to collect second hand components. This will be illustrated with two very different examples an electrolytic capacitor and an HF planar transformer, both coming from the same CSC.

## 4.2 Transformer degradation and failure mechanisms

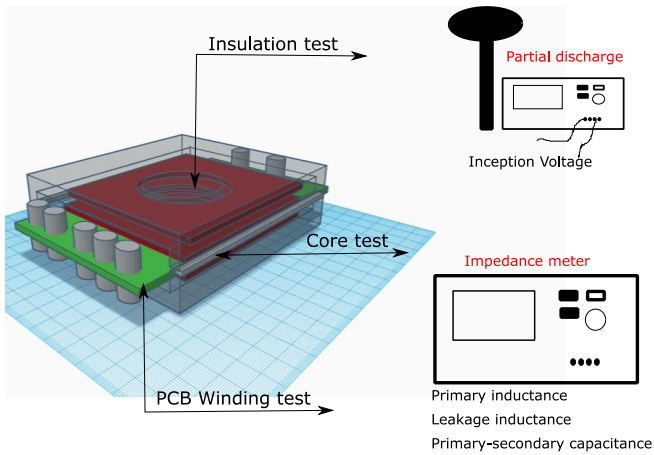
To account for the DC/AC CSC, the hardware considered in the work is a Dual Active Bridge (DAB) converter including an HF magnetic transformer cascaded with an H bridge inverter stage. The transformer performs the required galvanic insulation, necessary to implement CSC series and/or parallel associations. In this specific hardware implementation onto a PCB board, we are using a commercial planar transformer, optimized for low power, low voltage applications. The component exhibits good characteristics in terms of power densities, losses, collective and standardized mounting conditions as well as an excellent reliability level [19].

Concerning this specific type of component, based on a ferrite magnetic core, plus PCB windings + copper flat wires, the literature reports on three main types of degradation and the indicators to explain them:

-The insulation degradation: there are two kinds of insulation in the planar transformer. The first is the solder mask and FR4 in the PCB and second one between boards made mainly with Polyvinyl Chloride, Vinyl, Mica etc. These materials once aged turn black and crack resulting in exposing the copper layer to the air and losing the insulation function.

To measure this degradation, it is possible to do partial discharge or measure the primary-secondary capacitance and parallel resistance, which is known as an insulation failure precursor [20].

-The magnetic core degradation: the magnetic core we are using (Ferrite) is rather stable with respect to temperature [21] compared to iron powder. Although, this analysis is carried out with temperature up to 165°C, we will at first consider that it remains the case for higher temperatures. The aging of the magnetic core, made from the assembly of two or more parts is mainly attributed to the core glue that tends to dissipate with time [22] (Fig.3). The Magnetizing inductance can be a good indicator to measure this degradation as it indicates the reluctance evolution of the core.



**Fig. 3:** A summary of the transformers parts and the mean of measurements of every parameter.

-The flat wire and PCB winding degradation: the copper trace turn-to-turn varnish insulation mitigates and the PCB bends with the heat, producing deformations leading to cracks. It results in exposing the copper material to oxidation and changing the shape of the physical structure of the transformer. The leakage inductance can describe well the degradation of the structure of the transformer and the short-circuit resistance increase with the increase of the copper oxidation.

## 5 The disassembly indicator

### 5.1 Method outline and experimental setup

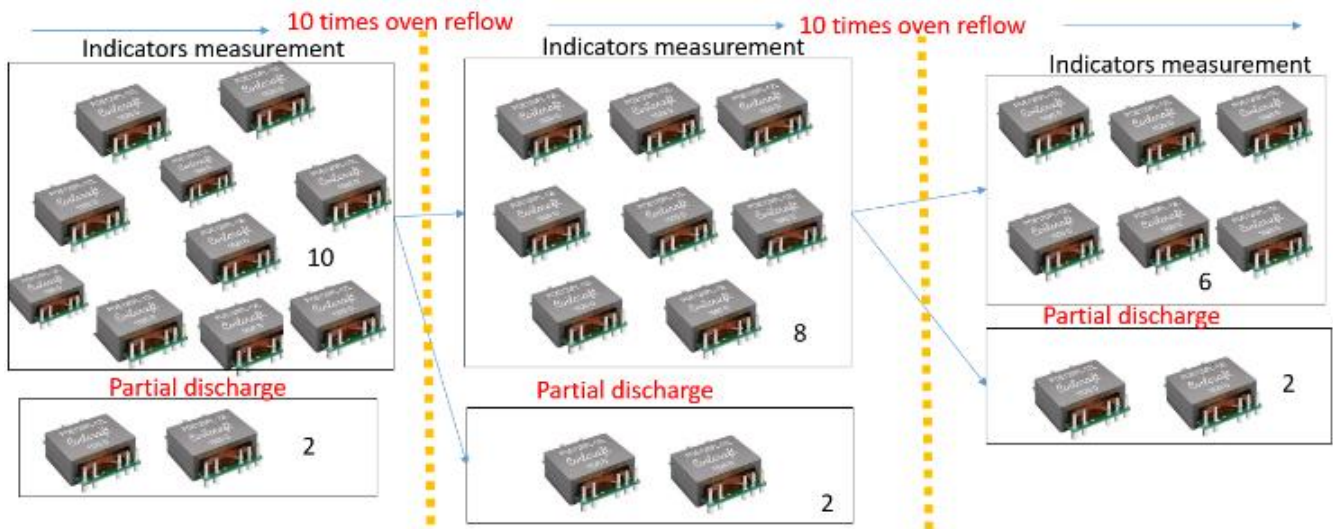
To measure the impact of the collect protocol on the remaining value and the resulting characteristics of the components wished to be reused, a specific study is carried out on the transformers. They will experience multiple reflow

oven thermal cycling and after a set of passages as illustrated in Figure 4, we will proceed into measuring the indicators identified for every component in section 4. Even if it is not expected to reuse many times the same device, the aging protocol intends to derive tendencies, which can afterwards serve as component remaining value indicator settings.

This experimental method does not include the aging during the usage or storage of the components, which is usually studied and described by other works or even the component manufacturer itself. However, if the components remain in their lifetime in a safe operating area, damaging combination of both aging can be derived, offering a global indicator on the component "Argus" over time and usage.

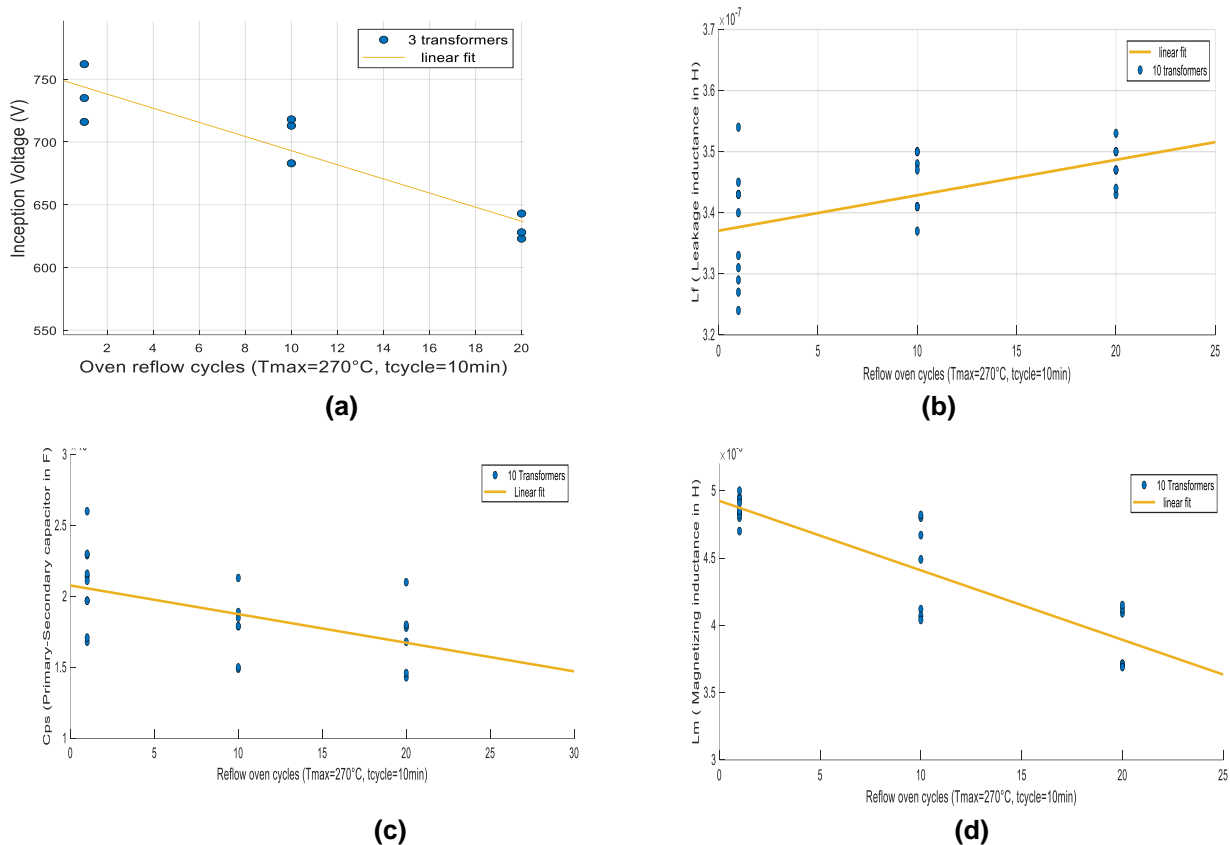
Preliminary tests were carried out on a single transformer and capacitor to calibrate the limit of oven reflow cycle the transformer has to go through in order to soften the solder joints. In addition, thanks to this initial testing, the number of thermal cycles required for the clear identification of tendencies was observed. As far as the transformer is concerned, 20 cycles were enough to identify several critical characteristics' variations. Considering the electrolytic capacitors, 5 cycles were required to clearly observe tendencies.

The second phase of the experiments to model and to represent the aging trend with respect to solder thermal reflow is to take a representative initial amount of components that will undergo the same thermal cycling process. Ten transformers were initially involved in the experiment, 2 of them being extracted at each step to follow destructive characterizations (Partial discharges). In figure 4



**Fig.4** The progress of the experiment for the transformer, the capacitor goes through the same phases without dielectric tests





**Fig.5** The transformer's parameters variation. (c), the primary-secondary capacitance, (d) the magnetizing inductance. (b), the leakage inductance and (a) is the partial discharge inception voltage (The 3 first parameters were measured at 200 kHz).

below illustrates the chronological steps of the experiment.

As mentioned in section 4, concerning the transformer, the magnetizing inductance will be measured from the primary side maintaining the secondary side open with an impedance meter. The leakage inductance by short-circuiting the secondary side and finally the primary-secondary capacitance by both short-circuiting the primary and the secondary sides.

The partial discharge is a localized electric discharge which partially short-circuits the insulating gap between conductors under the effect of a high voltage), the non-destructive test consists in seeing at what voltage "inception voltage" the amplitude of the discharges and their numbers start to get high. This test is conducted on the transformers extracted from every reflow cycle.

## 5.2 Experimental results

After the 10 then 20 reflow cycles, the planar transformer's representative parameters evolve as

shown above in figure 5. The leakage inductance does not increase significantly during the first 20 cycles (less than 2 %). It means that the reflow temperature and duration are not enough to change the physical structure and material properties of the transformer.

However, the primary/secondary capacitance and the magnetizing inductance changed drastically.

All these parameters were measured at 200 kHz but the tendency is the same for [20Hz, 10<sup>6</sup>Hz] frequency range.

Concerning the magnetizing inductance, after only 10 reflow cycles, the inductance dropped off 10% from its initial value and 20% later after 20 passages.

It is also important to note that comparing to Lf and Cps, the magnetizing inductance is the fastest growing indicator and therefore it is an excellent one to indicate the transformer's age.

A decrease in Lm can be explained by the insertion of a gap between certain legs of the core or a chemical change of the core's microscopically structure.

We can assume that these parameters indicate the end-of-life of the planar transformer for the CSC application for example; once  $L_m$  drops below 10%-20% of its initial value, the CSC will operate abnormally and the current ripple exceeds the limitation.

It is thus starting from 10 cycles (5 repairs) that we can consider that the transformers can no longer be reintroduced in a functional CSC, nevertheless it can still be reintroduced in other applications where the robustness tolerance is lower.

The Eq. (1).(2).(3) , where  $N$  is the number of oven reflows, can be added in a more general study that includes the usage aging of the transformer to have its state of health at every period of its life.

$$L_{leakage} = 6 \times 10^{-10} \times N + L_{leakage0} \quad (1)$$

$$L_m = -5 \times 10^{-7} \times N + L_{m0} \quad (2)$$

$$C_{ps} = -2 \times 10^{-13} \times N + C_{ps0} \quad (3)$$

The Inception voltage that describes the health of the insulation decreases. This reduction of the inception voltage threshold translates to a weaker insulation and a change of the material properties within either the resin layer over the flat copper wires or the kapton layers. The decrease follows this linear law Eq. (4)

$$v_{th} = -5,6 \times N + 750 \quad (4)$$

The increase or decrease threshold of the transformer's degradation indicators is not settled yet as it depends on the needs and specifications of the converter. It is the designer's choice to take into consideration now such models if component reuse indicators become part of the design protocol's constraint.

## 6 Conclusion

This paper presents first the possible life extension of power converters, sub parts of it and its components.

As explained above, the EU circular economy action plan fosters reuse and reparability as it is the best way to salvage the value of the different parts of the converters.

Secondly, we focus on the reflow oven as a mean for component's disassembly for reuse.

Then, from the different subpart/components of the converter, two important components of the CSC were selected (transformer and capacitor) both have an important residual value when it comes to price, size and mean of disassembly. They both were tested in reflow oven and their characteristics measured. The transformers have a reuse rate of 5 to 10 repairs and the capacitors can only be reused in average two or less times for the case of the CSC technical specifications.

Once these reuse rates are calculated they can be plugged in the design process to identify every component's value and come up with design guidelines. Some sets of guidelines are possible to optimize the reuse of the transformer that has the highest reuse index and the capacitor that has a lower one:

- Separate the transformer from other components for easy access during disassembly
- Disassemble the capacitor with another mean than a reflow oven
- Lower the reflow peak temperature to 250°C to increase the reuse rate.

Additional guidelines will be formulated to support designers reuse the components in PE.

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