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Barriers for eco-designing circular Power Electronics Converters

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Abstract

Integrating eco-design methods for circular Power Electronics Converters (PECs) based products in industry is crucial to endorse Sustainable Development Goals within planetary limits. However, eco-designing Power Electronics (PE) remains today on optimising the energy efficiency and the power density of the usage phase of the electronic designed. PE engineers design the PECs by developing electrical equations and topologies, with a weak consideration of the physical connections and kinematic relations between components. Therefore, there is a lack of engineering research focusing on PECs architectures to eco-design for sustainable life cycles, integrating well-known mechatronics methods for repair, reuse, and remanufacturing. This paper investigates two major eco-design challenges: first, the existing circularity design criteria are not yet adapted to PECs physical subsystems. Second, the conversion topology design process needs to integrate this new “potential circular” physical structure. This paper therefore suggests requirements to allow PE designers to overcome these two issues from the early design phases.

Keywords: Design for sustainability; Power Electronics; Integrated ecodesign; Circularity strategy; Life-cycle design

1. Introduction

Currently, eco-design in Power Electronics (PE) mainly focuses on improving the energy efficiency of products using optimisation algorithms [1]. Engineering research on Power Electronics Converters (PECs) architectures aiming to eco-design sustainable lifecycles is lacking. Although a number of circular eco-design methodologies are available in the literature, they are rarely applied in PECs developments.

The objective of this paper is to identify the major barriers faced in integrating circularity requirements into the PE design process. Through literature research and interviews of PE designers, this paper clarifies the PEC design process, and analyses the difficulties to integrate eco-design requirements at each stage. The specific requirements for the development of the eco-design methodology are also suggested based on the needs of designers in the context of PE industries.

Section 2 describes the current interpretation and implementation of eco-design methods in PE design research. Section 3 proposes a framework of PE design process through literature review and interview results. The difficulties regarding this integration are analysed in section 4, and the requirements to further integrated eco-design methods for circular PECs are proposed in section 5. Finally, section 6 discusses the main contributions of this paper and the future research issues opened.

2. Eco-design in Power Electronics Research: the necessity to introduce circularity into product design

2.1 Power Electronics Converters are not yet circular

PECs perform circuit control and conversion functions in electronic equipment are the key drivers towards a more renewable energy mix in our contemporary societies. For example, PECs interface with advanced renewable energy production, from wind turbines, or photovoltaic panels sources. With a wide range of applications ensuring services using energy, from electric mobility, heat pumps, air conditioning, to

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any home appliance PECs market exceeded USD 22.5 billion in 2020 and is expected to reach USD 37 billion in 2030 [2].

The continuous increase in its demand and production volume every year inevitably leads to mass extraction and consumption of natural resources, such as raw materials, water and energy. The functional obsolescence of PECs participates to increase the amount of e-waste accumulated widely, and the pressure on the environment, especially as discarded products are weakly recycled, and mainly incinerated or landfilled [3]. Despite these ultimate damages, discarded PECs have generally a high residual value, both in terms of functional potential and resource value, before being shredded or burnt. However, the value conservation processes face numerous issues.

Based on sustainability and circularity aspects presented in New Circular Economy Action Plan (CEAP) (2020), a proposal for Eco-design for Sustainable Products Regulation (ESPR) released in March 2022 aims to set eco-design requirement to promote durability, repairability, upgradability, maintenance, reuse and recycling of ErP, which included PECs [5]. As a starting point, this research focuses on helping multiple-usage lifecycle scenario, i.e. modular and circular, PECs to emerge [6]. Eco-design methods must be integrated into the PE designer's activities, to support them in aligning functional and sustainable circular optimisation [7]

A state-of-the-art literature-based research has been conducted in this research to explore the implementation of eco-design practices in the field of PECs design. By combining two sets of keywords concerning « ecodesign » and « Power electronics », 82 articles have been published from 1999 to 2022 in journals edited by IEEE, Springer, Science Direct, Web of Science. The result shows that eco-design practices in PE are usually reduced to an optimisation of the energy efficiency and energy density of the product (e.g. during the use stage) [8-9]. This reveals the shortcoming of circular design research in PECs and the relatively low degree of penetration in PE designers' practices in industrial contexts.

2.2 Issues of implementation of eco-design methods in PECs

Considering that the transition to a PECs circular economy can be driven and guided by eco-design practices [10], Pigosso et al. reported a thorough literature review in 2011, identifying and categorising more than 106 studies on eco-design methods and tools, that has not been reached in companies worldwide [11]. Since then, they developed a number of methods and tools to address the difficulties in implementation of eco-design and circularity strategies, such as eco-design maturity model web portal [12] and measurable environmental performance indicators [13]. Current eco-design research is focusing on how to integrate eco-design methods into conceptual design, enabling a circular economy. Circuit workbooks published in 2020 help to tackle these issues [14]. These integrated methods and tools are therefore an essential basis to achieve eco-design for circularity in the PEC product development and associated processes. However, due to the lack of concrete contextual information regarding the PE-industrial field specificities, it appears crucial to firstly clarify the PECs product development process to envisage a successful and contextualised eco-design practice implementation.

Raising the research question: how to integrate "circularity criteria" into PECs design process development and support designers' capacity to monitor the product sustainable circularity performances? This paper investigates the context of PEC process development, as an opportunity for circularity.

3. A framework of PEC design process to integrate circularity issues

Power converter's topology design is based on PE designer's own past experience [1]. But an experience-based approach is not sufficient in eco-design for circularity addressing the designer the ability of the converter to be repaired, reused, upgraded, remanufactured, and recycled, while assessing the environmental impact generated. There is firstly a lack of universal PEC design methodology and process framework in the literature, partially covered by the good practices for analysing and designing PE systems published in [15] Secondly, there is a lack of guidance coming from eco-design experts to address circularity issues specifically and contextually in PE designer's activities.

Combining such literature-based findings with ground investigation, this paper therefore presents the interview-based study conducted from June 2022 to October 2022 to explore the contextual factors enabling eco-design choices in PEC designer's activities. The research method adopted is based on the Design Research Methodology [16]. The eight semi-structured interviews of PEC designers covered small, medium and large enterprises, as well as academia profiles, as illustrated in Table 1 and situated in Grenoble region (France).

Table 1. Profiles of interviewed PEC designers

Code	Application	Power range	Number of PEC designers/total employees
INT1	• Aerospace, • automotive, • renewable energy sector	100W-100kW	2/2
INT2	• Consumer products	100W	2/~30
INT3	• New technology integration	Diverse	~30/~5000
INT4	• Conversion structure for Grid application	100W-100MW	Academia
INT5	• Renewable energy sector	100W	~20/~2000
INT6	• Heavy electric mobility • Renewable energy sector	100kW-100MW	2/~50
INT7	• Aerospace	100 kW	~30/~5000
INT8	• Heavy electric mobility	100MW	~30/~5000

During the industrial development of PEC, the functional specifications systems are drafted and reviewed by clients or by the marketing department of the company. They discuss technical requirements with PEC designers who initiate the design activities. The design activities are structured in two stages: (1) Conceptual design consisting of the conversion architecture design, and of the hardware technology determination. Between these two conceptual design substages, PE designers reiterate their technology and architecture design choices. Design reviews allow stakeholders and experts from different technical fields address the design assessments conducted, and suggest multiple view-based improvements.

The deliverable is an optimised analytical model developed with a higher validity degree crossing different expertise. (2) Detailed design leading to the definition of 3D numerical models. Finite element simulations can be conducted to model the behaviour of components placements under thermal and EMC constraints, and optimise their placement. The validated numerical model will reduce the risks furtherly generated during the component 3D integration. The prototype will be created to validate the hardware performance by using experimental bench tests. The design process ends with a prototype and the manufacturing files for the product industrialisation.

Table 2: Overview of PEC design activities occurring in conceptual design and detailed design, based on literature study material and information collected through interviews.

Contextual factors	Conversion architecture design	Hardware Allocation	3D layout
Collaborative Actor	• PE designer	• PE designers, software engineers. Clients. purchasing engineer	• PE designers, layout designers, mechanical engineers, clients. purchasing engineer
Representation	• Analytical equation (0D)	• Analytical equation (0D)	• PCB routing (2D)
D: model Dimension	• Electrical schematic (1D)	• Electrical schematic (1D)	• Product layout (3D)
Considered criteria	• **Design Criteria:** volume, mass, cost • **Functional criteria (application performance requirement):** • Characteristics of input/output voltage and current, control	• **Design Criteria:** volume, mass, cost, reliability (MTBF), energy efficiency, power density, availability of components, developing time • **Additional multi-physical criteria:** power loss, electrical, thermal, electromagnetic	• **Design Criteria**: 3D constraints and contextual dimensions, repairability (MTTR) • **Critical multi-physical criteria for 3D placement:** thermal, electromagnetic.
Activities	• Develop solutions and establish functional structures. • Define power converter's architecture and power topologies. • Choose the technologies of power components. • Develop analytical models to estimate performances. • Identify the physical variables related to the way the architecture is functioning. • Evaluate variants against main design criteria and functional criteria	• Optimise the architecture and the size of chosen technologies by imposing additional multi-physics constraints. • Refine and improve analytical models representing additional multi-physics constraints. • Identify the physical variables related to the way the architecture is functioning. • Evaluate variants against design criteria, and against additional multi-physics functional criteria.	• Develop 3D construction structure from electrical schematic. • Place components on the PCB. • Route the PCB. • Check the logical rules and physical integrity of design. • Develop numerical (finite elements) model representing the 3D integration of PCB. • Re-evaluate variants against the critical design criteria and multifunctional physical criteria. • Optimise the 3D placement of components. • Check the risk on their 3D integration by considering critical aspects.
Deliverables	• Conversion architectures candidate with software configuration	• Best conversion architecture (s) with hardware allocated • Quotation for hardware components	• 3D layout and detailed plan • Nomenclature of components
Design tool	• Analytical equation. • Temporal simulation tool: e.g. MATLAB-SIMULink©	• Temporal simulation tool: e.g. SPICE©	• PCB design tool: e.g. Altium©, EAGLE©, KiCAD© • Finite element simulation: e.g. COMSOL©, Ansys©
Created / useful information	• Power converter's 1D architecture. • Component's technologies. • Evaluation of the main criteria (volume, cost, application performance, ...)	• Optimised 1D architecture. • Evaluation of multi-physics criteria.	• 3D placement of the components. • 3D layout of the power converter product • Re-evaluation of the critical multi-physics criteria

PEC design activities are basically about seeking solutions satisfying design criteria and optimising them under multi-physical constraints (thermal, electromagnetic, control, etc.) [1]. The product specification usually addresses such common design criteria: efficiency, volume, mass, cost and development time [15]. Circularity criteria such as maintainability, disassembility, repairability are rarely specified, but may be implicitly integrated in practice for reasons linked with specific development.

3.2. Key moments to integrate circularity requirement

The interviewees generally believed that the circularity requirement should be considered as design criteria from the conceptual design stage. This integration would allow them (as designers) to orient product designs towards circularity principles. Several interviewees mentioned that it would be necessary to start projecting modular assembly allowing reuse and repair, of the conversion structure, when choosing topologies and controls (INT1). This involves engaging discussions about PCB cutting considerations, about interconnections issues between different boards, about the number of steps to disassemble and assemble a board, as well as defining the best distribution of components to ensure their individual reliability.

Interviewees also mentioned the necessity to address the circularity constraints during the choice of hardware technologies for each component. For example "in an environment facing a lack of professional technical support, it would be better to choose through-hole components than surface-mount components that are requiring more complex tools and a higher skill level of technicians to deal with" (INT4).

The architecture determined in the conceptual design usually stands on the final PECs. PE designers try to avoid design iterations between conceptual design and detailed design due to development and time cost (INT2, INT3, INT5). Before converting the electrical schematic to 3D layout, there is more flexibility to rethink the PECs design of the system and subsystem levels, or even initiate an innovative design approach. Nevertheless, at detailed design phase, PE designers have more information to make improvements on the 3D component placement against circularity requirements (INT4, INT6). Meanwhile, this stage seems to be relevant to analyse the potential mechanical connection required between the PECs and the external environment (casing design). This system integration opens to eco-design considerations allowing PEC's up-system-level circularity.

4. Main barriers to integrate circularity requirement

The emerging demand for circularity in the functional specification of PECs is challenging for designers, because there is a lack of simple and reliable support to integrate the circularity criteria into power converter's functional analysis, and to measure the potential improvement generated during the product lifecycle (i.e. PECs' circularity performance).

According to the interviewees, this integration is currently undertaken through the designer's own experiences, or the "informal discussion between the PE designer and the disassembly/assembly workshop manager" (INT1). Most interviewees mentioned that they "do not have the ability or design support to measure the circularity aspect of conversion architecture", and "there is a lack of knowledge in mechanics and materials to assess the physical aspects of PECs: reliability of the chosen materials, projections into disassembly, assembly, repairability, etc." (INT2, INT3, INT5).

Three of the main difficulties in integrating circularity indicators into the PECs design process are identified (Figure1), and studied in the next subsection:

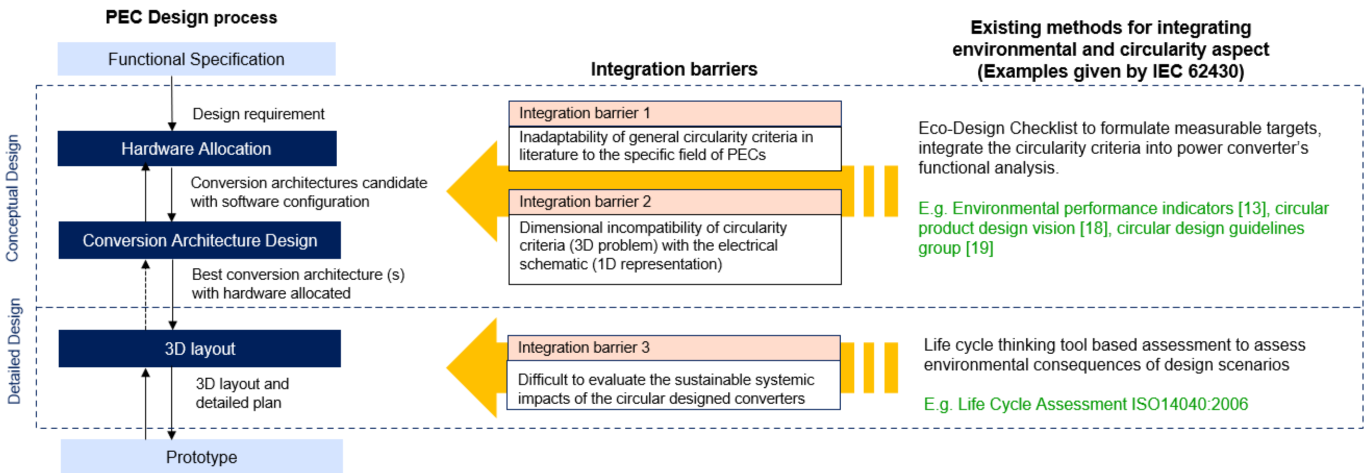
1- Inadaptability of general circularity criteria in literature to the specific field of PECs.
2- Dimensional incompatibility of circularity criteria (3D problem) with the electrical schematic (1D representation).
3- Difficult to evaluate the sustainable systemic impacts of the circular designed converters.

4.1. Inadequate circularity criteria

Electronic product circularity aspects have been analysed and researched intensively during the past decades (including the whole supply chain [17], and currently are boosted in design by the release of a broader set of material efficiency and circularity standards published in 2019 and 2020 (EN4555x standard family). Bakker et al. (2015) presented a guideline list overview to support a designer to address circular product design [18]. 46 circular product design guidelines for electrical and electronic equipment (EEE) are identified and classified by an extensive literature review described in Bovea and Perez-Belis (2018) [19]. The guidelines are established in areas such as durability (e.g. remaining lifetime prognostics of products or critical components), disassembly (e.g. simple structure, easy removal of certain components), product reuse (e.g. easy maintenance or cleaning tasks), component reuse (e.g. modular design, reliability assessment and standardisation of components) and material recycling (e.g. limit the number of different materials assembly; fast detection, separation and recycling of materials). These aspects are covered by the EN4555x standards family, which provides generic methods and criteria for the assessment of durability of energy-related products; ErP's ability to be repaired, reused, upgraded, remanufactured, recycled and recovered.

Patra (2021) however pointed the lack of application of these generic horizontal standards EN4555x to unique energy-related products such as power electronics drives [20]. The current literature-based design guidelines are excessively

Figure 1: Synthesis of PEC design process and related barriers for integrating environmental and circularity aspects.



general. The specific application of EN4555x standards circularity criteria to PECs requires a further specification and adaptation to be incorporated in the conceptual stage design requirements.

Indeed, PEC's challenges to circularity are different at its supersystem (application product), system (power converters) and subsystem level (components as capacitors, transformers, diodes, etc.). The product-related and support-related criteria and their qualification criteria need to be adapted regarding different system levels of PECs.

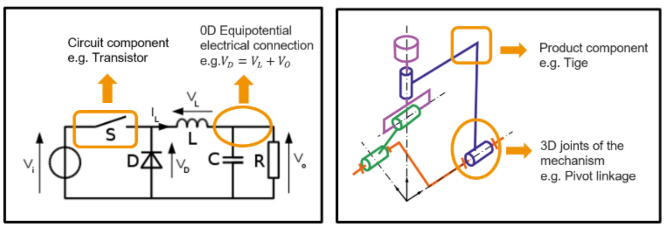
4.2. Dimensional incompatibility

Product-related circularity criteria mainly focus on the 3D physical (and rather mechatronical) relationship between the target functional module and its surrounding components: e.g. the number of steps required to disassemble a functional module; the type of connector used to connect the functional module to its surrounding components, and the tools required to disassemble them. PE designers are not equipped to consider and evaluate these criteria in the conceptual design because of dimensional incompatibility of circularity criteria (3D problem) with the electrical schematic (1D representation).

As mentioned in section 3.1, PE designers use electronic schematics to design conversion architectures and develop analytical models displayed in 1D.The electrical connections within electronic components are modelled using standardised symbolic items and lines, as presented in Figure 2. Unlike kinematic schematic in mechanical design, the spatial relationship (3D) of wires, electronic components and their physical connections are actually not considered and depicted in electronic schematics. The physical arrangement issues are usually addressed at the detailed design stage within the layout diagram when the conversion structure and the choice of technologies are mostly determined. The flexibility to improve the design toward circularity will therefore be limited without requestioning the conceptual design choices made.

This disconnection between the conversion architecture design and the physical structure design therefore prevents the product circular functionality to be integrated in the early phase. Existing guidelines are constrained to marginal effects.

Figure 2. Dimension comparison of electrical schematic (1D) and kinematic diagram (3D).



a. Electrical schematic (1D) b. Kinematic Diagram (3D)

4.3. Difficulties of systemic evaluation

Circular PECs development should be an opportunity to achieve radical eco-innovation in companies. A systemic vision of the whole value chain(s) should be promoted, supported by multidimensional assessment indicators, covering multiple environmental and socio-technical impact indicators. However, the common decision-making tool used by PE designers is the optimal Pareto fronts, which is only efficient for searching an optimal configuration regarding pairwise objective criteria. A multicriteria decision-making analysis is therefore needed to enable trade-offs management toward sustainable circularity radical innovation.

5. Requirement for circular eco-design methods for PECs

Considering these issues, a requirement for circular eco-design methods specific for PECs is proposed.

Table 3 presented the methods' functional specification for the conceptual design stage. While eco-designing conversion structure of PECs, PE designers should be supported to consider its physical aspect, such as mechanical cutting of architecture, interconnections between the assembly modules of PEC and the other functional modules in its super system (e.g. batteries, casing). Circularity of each assembly modules should be evaluated. For the choice of hardware for the components (e.g. transistor, capacitor, inductance) in the assembly modules, the potential circularity scenario and multiple environmental impacts caused should be considered according to results of simplified LCA. The method should be able to generate a circularity report. This will support PE designer to identify hotspots in design, which may increase the risk of failures to follow the chosen circularity strategies. Moreover, life cycle inventories are expected to be generated by the method. This will enable assessing environmental consequences of design scenario. During the product reviews, the methods have to support PE designer to justify their ecodesign choices with multi-criterion indicators.

Table 3. Functional specification for circular eco-design methods PECs at conceptual design stage

#	Specification for each function
F1	Eco-design conversion structure taking into account its physical aspects;
F2	Evaluate the circularity of the interconnections between the assembly modules of PECs and the other functional modules in its supersystem;
F3	Choose the technology for the components in the assembly modules of PECs, taking into account the multiple potential environmental impacts, within the potential circularity scenario (reuse, repair, remanufacture, recycle);
F4	Generate a circularity report, identifying locking points, and estimating the design scenario's potential failure to follow this lifecycle strategies;
F5	Generate lifecycle inventories (LCA ISO 14040) calculations to assess environmental consequences of design scenarios;
F6	Argue multi-criterion eco-design choices with specific indicators for circularity during product reviews.

At the detailed design stage, the necessary functions of methods are specified in table 4. Firstly, the 3D layout of the converter in its super system is necessary to visualize and organize its physical connections with other functional modules, such as batteries, casing. The methods should indicate the potential improvement for 3D placement of the assembly modules and associated components. Evaluation and validation of the circularity performance of the final design solution referring to multiple indicators is necessary. Radical eco-innovation PEC should also emerge in the value chain.

Table 4. Functional specification for circular eco-design methods PECs at detailed design stage

#	Specification for each function
F1	Model, visualise, and organise the 3D layout in the supersystem and its physical connections with other functional modules.
F2	Improve the 3D placement of components in each assembly module of PECs for its circularity
F3	Evaluate and validate the multi-indicator based circularity performances of the final design solution;
F4	Allow radical eco-innovation PEC to emerge in the value chain (argue for functional value conservation).

6. Conclusion

Through literature review and ground investigation, this paper questioned the integration of "circularity criteria" into Power Electronic Converters conceptual and detail design stages, allowing designers to monitor the sustainable circularity performances of PECs. The current implementations are centred on energy efficiency and power density optimisation only, and usually mono environmental impact indicators based (carbon emission related). They are based upon technological choices, limited to the design choices of designed-manufactured-sold-discarded products, rather than extending the analysis of additional environmental impact criteria, and to more complex and sustainable circular scenarios.

The major contribution of this study is the identification of the main barriers to overcome to integrate circularity criteria into the PECs design process. First, product-related and support-related criteria proposed in EN4555x standards family need to be urgently adapted in order to enable circularity ability evaluation of PECs. Second, the dimensional incompatibility of circularity criteria (3D problem) with electrical schematic design (1D representation) should be addressed. This is indispensable to enable designers to consider circularity of assembly modules of PECs at its supersystem, system and subsystem level, while designing conversion architecture and choosing technologies for each component.

This study concludes on further requirements for circular PECs eco-design integrated methods. By aligning circular objectives with functional optimisation of the PE system lifecycle, the method underdevelopment aims to facilitate the circularity of PE systems through 'closed' loops based on circular economy concepts and evaluated on several environmental impact indicators to allow the PEC fraction of electronic-based industrial world stay under planetary boundaries in the future decades [21].

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