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Towards circular power electronics in the perspective of modularity

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Abstract

Designing more circular products is essential to reaching Sustainable Development Goal 12, Responsible Consumption and Production, which is anticipated to be achieved by 2030. To achieve progress toward a circular economy in power electronics, discarded products, modules, or components must be recovered. This requires the implementation of End-of-Life (EoL) strategies. In order to maximize the high-value circularity efficiency of a power electronic product, EoL choices and constraints should be taken into account early on in the design phase. Since disassembly is a known bottleneck in EoL practices, design to enable disassembly is essential. Modularity enhances the product's reconfigurability and disassemblability, its reuse in other product families, as well as the product's maintenance, and serviceability. So, it is anticipated that this multiple life cycle thinking enabled by modularity would contribute to the transition towards more circular power electronic designs. Therefore, in this paper, we aim to consider modular designs of power electronic converters (PECs) and categorize them. As a result of a corresponding discussion about the existing PECs, we point out the general potentials to enhance circularity by modularity applied to PECs.

Keywords: Circular Economy; Design for Disassembly; Modularity; Power Electronics

1. Introduction

The EU action plan considers product design as one of the main pillars of the circular economy and it states the need to develop standards to set eco-design requirements for the durability, repairability, and recyclability of products [1]. There are three main design approaches aligned with the circular economy vision: (i) increasing material efficiency, (ii) extending product lifespan, and (iii) increasing recycling efficiency [2]. Strategies for extending product lifespan require facilitating access to components for repair, reuse, and remanufacturing. To improve access to components during disassembly for inspection, maintenance, and repair, some requirements should be defined such as increasing the disassemblability of frequently failing, reliable, and high-material-value components for end-of-life (EoL) scenarios [3]. Product architecture has a crucial impact on the entire product life cycle and it affects the EoL characteristics of the products. Applying the concept of modularity implies that the product architecture is broken down into physically independent units. Modularity allows the combination of independent units (different modules) through well-defined interfaces to form products [4]. Considering this attribute of modularity, modular design can be considered as an enabler key for developing circular products in the concept of extending product lifespan. Therefore, remanufacturing and reusing with their higher environmental advantages can overtake recycling and disposal by improving the disassemblability [4].

The present article aims to explore the circularity of power electronic converters (PECs) by considering modularity in their design. We will investigate how modularity can be useful to meet the demands of circularity by considering disassembly, repair/maintenance, reuse, upgrade and recycling and discuss the advantages of enhancing of modularity which, at present, is

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only employed in a limited number of applications in PECs. The novelty of this study lies in its investigation of the current situation of modularity in the power electronic domain and its examination of the potential relationship between modularity and circularity. The authors aim to explore how modularity can be used to meet the demands of circularity in the design of power electronic converters (PECs) by considering various factors such as disassembly, repair and maintenance, reuse, upgrade, and recycling.

Studies conducted within the scope of this review are grouped under five following sections:

- Sec. 1: An overview of the concepts of circularity and modularity, as well as their potential impact on each other, is provided.
- Sec. 2: The current state of modularity in the power electronic domain is examined, and suggestions are made for how modularity can be modified to enhance circularity.
- Sec. 3: The application of modularity in the power electronic domain is discussed.
- Sec. 4: Concluding remarks are presented, summarizing the main findings and implications of the study.

Nomenclature

CSC	Conversion standardized cell
EoL	End-of-life
PCB	Printed circuit board
PCA	Power converter array
PEBB	Power electronics building block
PEC	Power electronic converter
MIC	Multicell interleaved converter
MMC	Modular multilevel converter

1.1. Modularity

A module is defined as “an independent building block of a larger system with a specific function and well-defined interfaces. It has fairly loose connections to the rest of the system allowing for independent development, outsourcing, manufacturing, recycling, etc.” [7]. Another definition is “an essential and self-contained functional unit relative to the product of which it is part. The module has standardized interfaces and interactions that allow composition of products by combination” [8]. A module is an independent element with loose inter-element connections, where most functional interactions occur within the module [9]. Following these definitions, modules must feature a standardized interface and exchangeability to enable components to be quickly and systematically (dis)assembled from/into a system with various modular architectures.

The modules can be easily updated or upgraded on regular time cycles, some can be made in multiple levels to cover a wide market variety, some can be easily removed when worn out, and some can be easily swapped for additional functionality [10]. Modules help the design process to move forward smoothly from the conceptual phase to the embodiment phase. The energy, material, and signal flows of the product serve to define them. Realizing modularity in products involves identifying similarities and reducing component interactions [11].

Two different approaches can be considered to define the modules: (i) The functional approach identifies the module as a component of a system that is functionally separated from the other components that are placed in the same system. (ii) The structural approach refers to a module that is built up of components that are strongly connected within themselves and weakly connected with other components from other modules [12]. In addition, a third consideration can be added for circularity: (iii) the components can be grouped considering their similar reliability levels, material values, failure rates, and lifetime value to consider increasing their circularity. In order to define circular modules, these three approaches should be considered together. This connection can take the form of technology or material similarities, current, voltage or power ratings, and safety, but it could also be in terms of initial of EoL expected values from the economical and/or environmental points of view.

A modular product consists of different groups of physically independent parts that fulfill a single function or group of functions [11]. Complex systems can be broken down into several modules, and assembled in a customized way by increasing the flexibility of the design. Modular design is the process of assembling block modules or functional units, each of which satisfies one product function related to the consumer’s needs. [13]. Product flexibility is an important factor in enabling product customization and rapid changes in the product [9]. The designer can easily replace or modify each module instead of changing the whole product. The product can be enhanced within a certain range by upgrading the product, by adding new functionalities, or simply by designing a new module [13]. Compared to non-modular products, modular ones can offer several advantages such as a potentially more efficient design process, shorter assembly time, and minimized number of parts. Moreover, modularity allows for product customization by adding, removing, and replacing modules and potentially facilitates disassembly, maintenance, repair, and recycling [11], [14].

Product modularity can be divided into two categories: technical and strategic modularity (see fig. 1). Technical modularity enables the replacement of components at interfaces. Within this framework, technical modular interactions are usually grouped into functional and physical interactions. Strategic modularity fulfills functionality with one or more components. Strategic modularity groups functions into modules with one or more similarities often referred to as module drivers [9].

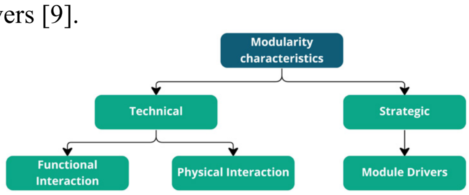

Fig. 1. Modularity characteristics.

Modularization is realized in the early design phases of product development, using information from the requirements of the engineering phase to propose modules in the design concept and architecture phases. During the preliminary design phase of the product lifecycle, functional decomposition is performed for modularization. Functional decomposition is a major tool in concept generation aiming to divide complex problems into simpler sub-problems. This leads to solution fragments which are evaluated, selected, and then combined both functionally and physically in the architecting phase as modules [9]. The initial step in all strategies for modularization is to define the overall product function and divide it into manageable sub-functions. The sub-functions are addressed, and after finding solutions for each of them, the device's overall form is determined [11].

1.2. The role of modularity in circularity

All stages of the product's life cycle, including disassemblability, recyclability, maintainability, repairability, reusability, and upgradability, might benefit from the modular design [15]. Modularity promotes easier upgrading, adaptation, modification, and product assembly and disassembly, as well as increased product variety, economies of scale, and reduced production time [4].

Preventive maintenance and repairs are required for various products. Varying components of a product require different maintenance and repair frequencies. Failure analysis and maintenance are enhanced when product components are organized into readily detachable modules. When a module fails, it is possible to substitute temporarily while the damaged components are repaired and the module is returned to service. Furthermore, material compatibility must be considered for recycling, as the different materials may require different methods for recycling. The separation and classification of the various materials for the favorable recycling procedure can be facilitated by a modular solution [16]. In addition, modularity can be a solution for obsolescence. The retirement of a product is influenced by a variety of factors, including customer demand for new models, product wear, a highly competitive market, and high consumer expectations. Also, the rapid evolution of technology renders things swiftly obsolete, despite their continued usability. In a conclusion, the rapid introduction of new models by manufacturers is needed [16]. In this case, instead of the introduction of new model products, new modules with better functions can be introduced such the functions of the current product can be upgraded.

2. Modularity in PECs

PEC is a technology to convert and control electrical energy from one form to another form. They are used increasingly in a wide range of application fields, such as variable-speed drives, electric vehicles, and renewable energy systems by being the interface between the energy production side and the consumption side [17]. In the power electronic domain, modularity exists in some specific applications. There are two main different modularity approaches applied to PECs: (i) creating the modules based on the functions of PEC “Power electronics building block (PEBB)” and (ii) creating the modules which can perform one specific function, i.e. power conversion function and use the modules for scaling the voltage/current. This second modular approach is defined based on breaking down the conversion function into smaller ones which will be assembled then to make the same function at the end “interleaved multicell converter, modular multilevel converter, and power converter arrays”.

2.1. Power electronics building block (PEBB)

The PEBB has the largest influence on modularity in PECs. It was introduced as a new paradigm in PECs and was expected to be the building block of a universal power processing unit [18]. The complexity of the product was reduced during the design process and allowed for efficient collaborations at the subsystem levels with building blocks defined by their functionality and interfaces [19]. Some of these common sets of functionalities defining the PEBB are given in fig. 2 [20]. The building block functions are fulfilled by different hardware components in the block such as power module, energy storage, and auxiliary power supply [20]. These building blocks are aggregated to form PECs including the interconnections such as auxiliary power, control, cooling, and power [21]. The advantages of PEBB are [21], [22]:

- Fault tolerance feature,
- Rapid replacement of building blocks,
- Standardization,
- Upgrade the product through standard interfaces,
- Reduce design expenses by utilizing the same PEBB for several applications,
- Modules with plug-and-play flexibility,
- Less expensive, easier, and more convenient maintenance.

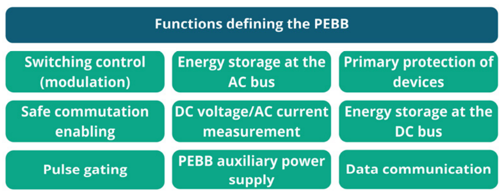

Fig. 2. The common set of functions of PEBB [20].

2.2. Multicell interleaved converter (MIC)

High power converters that are modular and scalable necessitate the parallel functioning of power electronic components. The MIC is composed of numerous converters that are connected in parallel. [23]. Owing to the layout of MIC, the level of current passing through each conversion cell is limited. The conventional switching cell is seen on the left of fig. 3, and its components withstand the entire source current. On the other hand, an example of a buck MIC circuit topology is shown on the right side of fig. 3, and components are subjected to the current in a quarter of the source, as there are four parallel cells in this illustration. Consequently, high-current applications are made achievable by this technology.

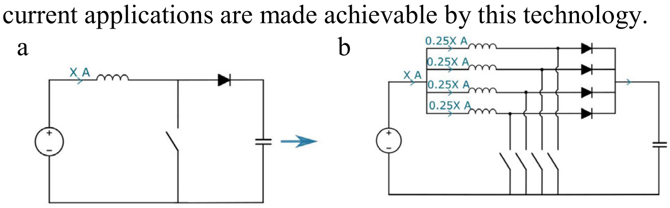

Fig. 3. Simple converter topology (a) and MIC topology (b).

Moreover, this modular architecture can provide the fault-tolerant capability. In fact, if one cell fails, the PEC can continue to work with the other cells by bypassing or commissioning redundant cells [24]. Furthermore, in this design, a mutual inductor can be used by different converter cells, therefore, it brings a reduction of the size of the inductor used in the whole converter [25]. Thanks to interleaving, the filter inductor was spread into numerous much smaller parts, leading to a significant mass and volume reduction.

2.3. Modular multilevel converter (MMC)

A modular multilevel converter consists of a topology with many serially connected, homogenous converter cells, each having its own DC link capacitor. MMC has been initially used in high voltage, high power applications in order to overcome the voltage limitation of components. Since the circuitry inside the cells is not subjected to the entire converter voltage, existing components can be used in high-voltage applications [25][26].

As illustrated in fig. 4, the modules are exposed to a fraction of the total voltage. With this topology, high-voltage converters can be achieved with lower-voltage components. The multiple levels allow many degrees of freedom, offering many options for control methods and trade-offs between losses (number of switching actions), waveform quality, energy storage requirements, and component stress. [25]. The MMC can guarantee continuous operation notwithstanding if the sub-modules stop functioning [27].

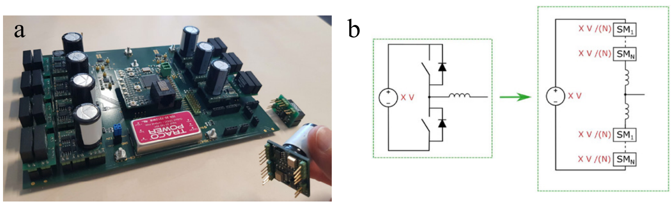

Fig. 4. Product architecture of the MMC (a), MMC topology (b).

2.4. Power converter arrays (PCA)

In this architecture, conversion standardized cells (CSCs) are serially and parallelly interconnected to frame a PCA, see fig. 5. The PCA technology takes the advantage of MIC and MMC. The fault tolerance feature increases with power converter arrays. PCAs rely on CSCs that can be considered independent. They are assembled and interconnected in vector or matrix formats in order to meet the overall specifications [28]. Provision for failure with additional CSCs can be implemented. In this approach, the functional connection among CSC is further loose compared to the other modular approaches. Indeed, power interactions are minimized, reducing the coupling among the CSC. On the other hand, this approach is facing the main issue which is the number of implemented components.

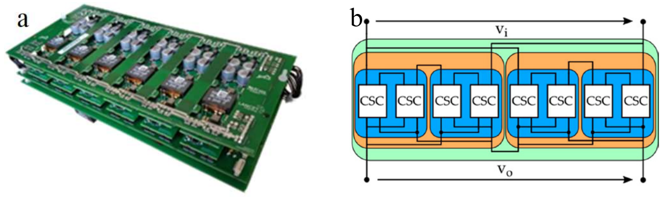

Fig. 5. Product architecture of the PCA (a) and its topology (b) [28].

2.5. Link Between Modular Design and Modularity in PEC

Four different modularity approaches were introduced in the PEC field; PEBB, MIC, MMC, and PCA. According to Stewart and Yan (2008), structural independence and functional independence are essential characteristics of a module. [29]. In accordance with this definition. Table. 1 was developed to elaborate on the link between modular design and modularity in PEC. Structural independence refers to different bricks in the architecture; functional independence indicates grouping the functions in the module. In order to better interpret the designs, the PEC products are considered in four main categories: (i) PCB-based traditional PEC, (ii) PEBB, (iii) MIC & MMC, and (iv) PCA. In traditional PEC, the modularity concept is not applied. In PEBB, the functional decomposing is realized and the functions have their structural independence. However, it is not always the case that they can be easily separable. MIC and MMC are categorized together since their designs are identical. Although their conversion cells are functionally modular, their structural modularity can be ignored in the product architecture. In the case of PCA, functional and structural independence is applied.

Table 1. PEC products versus basic module features (considered: +, partly considered or not considered in detail: +/−, not considered: −).

	Traditional	PEBB	MIC & MMC	PCA
Structural independence	−	+	+/−	+
Functional independence	−	+	+/−	+

2.6. Suggestions for modular PEC design for circularity

The modules of the PECs should be designed in order to facilitate reuse, upgrade, maintenance/repair, and recycling to enhance the circularity, see fig. 6. If modules will be used in many different product variants, it is essential to design a standardized interface system. Moreover, similar reliability levels must be considered when the modules are grouped.

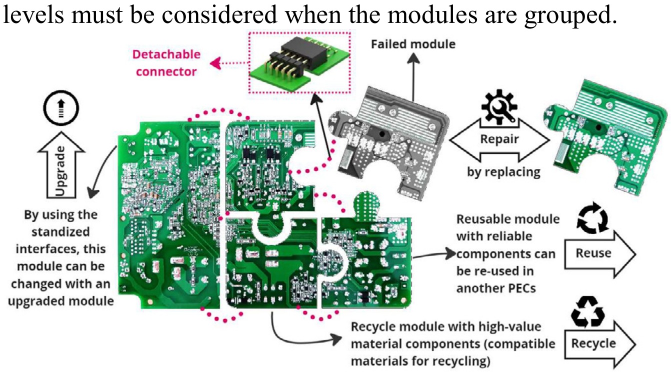

Fig. 6. Modules purposed for reuse, repair, upgrade, and recycling.

For repairability and maintenance, it can be considered to redesign the PEC by arranging the weak, unreliable, and/or frequently failed components on specific modules with mechanical loose connections in order to increase disassemblability. If mechanical loose connections are provided i.e., using the connectors between the modules, the detachability of the modules increases, and therefore, disassembly will be facilitated. On the other hand, the electrical losses caused by the mechanical loose connections are another issue and a trade-off should be defined between increased detachability and reduced efficiency. Furthermore, using data management for predictive lifespan calculation for each module or intelligent module with detection of the early signs of failure can be considered for repair/maintenance. In this way, maintenance can be realized before the module fails, or in the event of a failure, it will be simpler to swap the malfunctioning module with a functional one. Therefore, it will aid in extending the PEC's lifespan and keep its functional value in the circular economy for longer. In the literature, it is reported that the less reliable components are capacitors, power switches, gate drivers, and semiconductors [31], [32]. It is therefore conceivable to group these components in an easily detachable module. Furthermore, a switching cell is basically composed of a power switch, gate driver, fast diode, and decoupling capacitors. Since these components are less reliable, switching cells can be designed as a module in product architecture.

For reuse, the components with high reliability, lifespan, and value should be grouped such to reuse these modules in other PEC applications in the same product family. The most reliable components in PEC are transformers, inductors, and controllers [32]. In some PEC products, the controllers are already modular and when the PEC reaches its EoL, the controller has used another product in the same product family.

For upgrade, the components can be grouped considering their low lifetime value. For example, the functions of the PEC can be upgraded at the limit of its components with a new controller with updated functions.

For recycling, it is important to define the components containing non-recyclable, non-compatible, hazardous, precious, rare, and critical materials. In order to increase the material recovery, the modules should be created by grouping the components with precious, rare, and critical materials, and compatible to be recycled together without separation. For instance, the heat sinks cooling the PEC, consist of aluminum and it is remarkable to recycle these components. In Table 2, the summary of different EoL scenarios and suggestions to define the modules are given.

Table 2. Suggestions for modular PEC design for circularity.

Eol Practice	Module defining recommendations
Repair & Maintenance	A group of frequently failed electronic components that have a low lifespan
Reuse	A group of electronic components being reliable, having a high lifespan and high lifetime value
Upgrade	A group of electronic components that have a low lifetime value
Recycling	A group of electronic components that are compatible with recycling

After defining the modules, the interconnection technics between the modules must be chosen correctly. In mechanical products, mechanical, material, and thermal characteristics are necessary to consider the connections. In the electrical domain, in addition to these characteristics, the electrical characteristics of the connections are also absolutely critical because of the energy flow inside of the connection. Modules require to have mechanical loose connections to ease their separation from each other. However, mechanical loose connections can cause other issues such as extra cost for connectors, extra failure risks, and electrical loss in performance because of increasing the internal resistance of the connections.

3. Discussion

As described in section 2, the concept of modularity currently exists in PEC products. In the beginning, modular design was intended to overcome the current and/or voltage limitations of components in high-power applications. It was also introduced to minimize energy storage requirements, resulting in converters with higher power densities and faster dynamic responses. Because of the enhanced efficiency optimization options granted by the increased number of cells, it also starts to be considered for medium and low-power applications [33].

A modular product composes of physically separate modules that work together to perform their intended functions. Nonetheless, this definition does not always correspond to the concept of modularity in PECs. Although they are defined as modular, the modular cells can be physically installed within the same PCB without allowing module interchange. In the domain of power electronics, the term modularity can refer to the circuit topology rather than to structural modularity. These modules should be designed modularly, considering not only circuit topology functions but also structural features. On the other hand, the PEBB modularity approach corresponds to the modularity definition in respect of detachable modules.

There is a high level of variation in PEC products in terms of ratings, application constraints, technologies, materials, component characteristics (i.e., size, volume, weight, etc.), physics involved, and levels of reliability. Therefore, it can be challenging to define the modules just considering the circularity criteria. For instance, after grouping the components into modules, it is necessary to verify whether the modules are compatible in terms of manufacturing technology. The control unit requires a high number of thin traces for its functions. On the other hand, the PCB of PEC needs thicker and wider traces, since they are exposed to high current flow. Therefore, these two PCBs can use different manufacturing techniques and they can be connected via connectors. Moreover, thin traces are used for low-power connections on the PCB of the converter. On the other hand, their widths increase as the power level increases. This phenomenon must be considered for detachable connections when the separation of PCB is considered for modularity. The technical characteristics of a mechanical loose connector must be capable of withstanding the high power of width traces.

4. Conclusion

Considering the advantages of modular PEC, the traditional products can be redesigned by increasing modularity not only in the topology but in the product architecture to move towards circularity to ease EoL implementations and increase reliability. The modularity concept could be applied to most of PEC applications, not only in medium and high-power applications.

There are significant benefits modular products can deliver. It is preferable if a modular PEC design can accomplish all the EoL goals. However, it is anticipated that confrontations will take place. It is quite unlikely that all of the benefits may be obtained concurrently. The development methodology should be adopted by product designers and developers to pinpoint the most important characteristics of the product and realize them. It is the role of designers to make trade-off decisions. Further plans of our research involve an extension of this study by proposing a re-design modularization methodology for classical designed PECs with the aim of increasing circularity.

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References

[1] "Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Closing the Loop-An EU Action Plan for the Circular Economy."
[2] Allwood J M, Cullen JM. Sustainable Materials: with both eyes open. Cambridge Limited Cambridge, UK, 2012.
[3] Vanegas P, Peeters J R, Cattrysse D, Tecchio P, Ardente F, Mathieux, F & Duflou J R. Ease of disassembly of products to support circular economy strategies.Resour. Conserv. Recycl. 2018; 135, 323-334.
[4] Sonego M, Echeveste M E S, Debarba H G. The role of modularity in sustainable design: A systematic review. Journal of Cleaner Production 2018; 176, 196-209.
[5] Vanegas P, Peeters J R, Cattrysse D, Tecchio P, Ardente F, Mathieux F, Duflou J R. Ease of disassembly of products to support circular economy strategies. Resour. Conserv. Recycl. 2018; 135, 323-334.
[6] Diener D L, Tillman A M. Component end-of-life management: exploring opportunities and related benefits of remanufacturing and functional recycling. Resour. Conserv. Recycl. 2015; 102, 80-93.
[7] Hölttä-Otto K. Modular product platform design. Helsinki University of Technology 2005.
[8] Miller T D, Elgard P. Defining modules, modularity and modularization. In Proceedings of the 13th IPS research seminar, Fuglsoe. Aalborg Universiy Fuglsoe, 1998.
[9] Rossi F, Arfelli S, Hu S J, Tolio T A M, Freiheit T. A systematic methodology for the modularization of manufacturing systems during early design. Flex. Serv. Manuf. J. 2019; 31(4), 945-988.
[10] Dahmus J B, Gonzalez-Zugasti J P, Otto K N. Modular product architecture. In International design engineering technical conferences and computers and information in engineering conference 2000.
[11] Bryant C R, Sivaramakrishnan K L, Van Wie M, Stone R B, McAdams D A. A modular design approach to support sustainable design. In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2004.
[12] Ezzat, O. A. M. Product and service modularization for variety management in the context of mass customization. Doctoral dissertation, Université de Lyon, 2021.
[13] Tseng M M, Wang Y, Jiao R. Modular design. CIRP encyclopaedia of production engineering, vol. 1, pp. 895–897, 2018.
[14] Gu P, Slevinsky M. Mechanical bus for modular product design. CIRP Annals 2003; 52(1), 113-116.
[15] Umeda Y, Fukushige S, Tonoike K, Kondoh S. Product modularity for life cycle design. CIRP annals 2008; 57(1), 13-16.
[16] Gu P, Sosale S. Product modularization for life cycle engineering. Robotics and Computer-Integrated Manufacturing 1999;15(5), 387-401.
[17] Falck J, Felgemacher C, Rojko A, Liserre M, Zacharias P. Reliability of power electronic systems: An industry perspective. IEEE Industrial Electronics Magazine 2018; 12(2), 24-35.
[18] Purgat P, Gerber-Popovic J, Bauer P. Modularity in power electronics: Conceptualization, classification and outlook. 43rd Annual Conference of the IEEE Industrial Electronics Society 2017.
[19] Steimer P K. Power electronics building blocks-a platform-based approach to power electronics. IEEE Power Engineering Society General Meeting 2003; Vol. 3, pp. 1360-1365.
[20] Rosado S, Wang F, Boroyevich D. Design of PEBB based power electronics systems. IEEE Power Engineering Society General Meeting 2006; pp. 5-pp.
[21] Baran M, Mahajan N R. PEBB based DC system protection: opportunities and challenges. In 2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition.
[22] Liserre M, Buticchi G, Leon J I, Alcaide A M, Raveendran V, Ko Y, Franquelo L. Power routing: A new paradigm for maintenance scheduling. IEEE Industrial Electronics Magazine, 2020; 14(3), 33-45.
[23] Rashid M H, Power electronics handbook, Fourth edition. Kidlington, Oxford Cambridge, 2018.
[24] Guépratte K, Jeannin P O, Frey D, Stephan H. High efficiency interleaved power electronics converter for wide operating power range. In 2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition, 2009; pp. 413-419.
[25] Busquets-Monge S, Caballero L. Switching-cell arrays-An alternative design approach in power conversion. IEEE Transactions on Industrial Electronics, 2018; 66(1), 25-36.
[26] R. Rafiezadeh, S. Busquets-Monge, S. Alepuz, "Benefits of Finer Semiconductor Device Granularity on Power Converter Thermal Stress and MTTF," IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, 2021, pp. 1-6.
[27] Afonso J L, Cardoso L A L, Pedrosa D, Sousa T J, Machado L, Tanta M, Monteiro V. A review on power electronics technologies for electric mobility. Energies, 2020; 13(23), 6343.
[28] Andreta A, Lavado Villa L F, Lembeye Y, Crebier J C. A novel automated design methodology for power electronics converters. Electronics, 2021; 10(3), 271.
[29] Stewart B, Yan X T. Modular product family development within a SME. In Global Design to Gain a Competitive Edge, 2008; pp. 21-30.
[30] Kaya M., Electronic waste and printed circuit board recycling technologies. Springer, 2019.
[31] Yang S, Bryant, A, Mawby P, Xiang D, Ran L, Tavner P. An industry-based survey of reliability in power electronic converters. IEEE transactions on Industry Applications, 2011; 47(3), 1441-1451.
[32] Wang H, Ma K, Blaabjerg F, Design for reliability of power electronic systems, IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, 2012; pp. 33-44.
[33] Mendes V F, de Rezende G M, de Sá Ferreira T, da Silva J L, Régnier J, Meynard T A. Design Aspects for Achieving High Bandwidth Series and Parallel Multicell Converters. *IEEE Transactions on Power Electronics*, 2021; *37*(6), 6437-6449