

Article

Smart Energy Systems Based on Next-Generation Power Electronic Devices

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Abstract: Power electronics plays a key role in the management and conversion of electrical energy in a variety of applications, including the use of renewable energy sources such as solar, wind and hydrogen energy, as well as in electric vehicles, industrial technologies, homes and smart grids. These technologies are essential for the successful implementation of the green transition, as they help reduce carbon emissions and promote the production and consumption of cleaner and more sustainable energy. The present work presents a new generation of power electronic devices and systems, which includes the following main aspects: advances in semiconductor technologies, such as the use of silicon carbide (SiC) and gallium nitride (GaN); nanomaterials for the realization of magnetic components; using a modular principle to construct power electronic devices; applying artificial intelligence techniques to device lifecycle design; and the environmental aspects of design. The new materials allow the devices to operate at higher voltages, temperatures and frequencies, making them ideal for high-power applications and high-frequency operation. In addition, the development of integrated and modular power electronic systems that combine energy management, diagnostics and communication capabilities contributes to the more intelligent and efficient management of energy resources. This includes integration with the Internet of Things (IoT) and artificial intelligence (AI) for automated task solving and work optimization.

Keywords: artificial intelligence; eco-design; modular electronic devices; next-generation power devices; smart and flexible power electronics



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1. Introduction

Power electronics is a key area of engineering focused on the efficient production, conversion, distribution and storage of electrical energy for various needs. The most notable and high-impact achievements are related to the use of renewable energy sources (solar, wind and hydrogen), in electric vehicles, industrial technologies, homes and smart grids. These technologies are essential for the successful implementation of the green transition and sustainable development, as they contribute to the reduction in carbon emissions and promote the production and consumption of cleaner energy produced with minimal impact on the environment [1,2].

In this regard, power electronic devices and systems are the tools for the wide application of power electronics, as an innovative and rapidly developing technology for the creation and rational management of energy flows. In accordance with this role, the following clearly expressed trends are observed in the evolution of power electronic devices and systems [3–5], and one of the main goals in the development of power electronic devices is to increase their efficiency. This means the better management of energy consumption and reduction in losses in the conversion of electricity. On the other hand, the integration of more functionalities into one power supply unit is increasingly common. This involves integrating control, communication and security functions into a single chip. As power electronics continues to evolve, the drive is to achieve smaller and lighter products, which is especially important in applications such as mobile devices, the automotive industry and

portable electronics. Another important aspect is the increase in the operating frequencies of electronic converters, which allows for faster and more efficient conversion of electricity, and the use of advanced control algorithms contributes to increasing the efficiency and reliability of energy systems. The evolution of technology provides better methods for protecting energy systems from various overloads, short circuits and other failures, and the development of “smart” energy systems that can adapt and optimize their work in real time, according to the specific conditions of work, plays an increasingly important role in their development. Information security, which is a relatively new aspect of the power electronics ecosystem, is of particular importance as these devices are often part of critical infrastructure, for example in power systems, industrial processes or transport systems. When working with power electronic devices, especially in critical infrastructure, it is important to apply a holistic approach to security, which includes technical, organizational and physical protection measures [6–8].

These trends have the main objective of improving the efficiency, reliability and sustainability of power electronic devices and systems and of meeting the growing requirements for energy efficiency and environmental protection.

Developments and achievements in the field of new materials, nanotechnology, semiconductors, modeling, computational mathematics, information and communication technologies, artificial intelligence techniques, and data science make possible the creation and widespread implementation of smart power devices and systems. In this sense, they are designed, prototyped and equipped with innovative and cutting-edge management and control technologies to be able to self-adapt, optimize and provide the optimal and efficient management of energy flows. Intelligent power electronic devices and systems use sensors, software algorithms and communication technologies to provide a number of additional functionalities compared to classical ones [9–11], as they adapt to different conditions and loads and can regulate power, voltage and current, to ensure optimal real-time performance. The sensors and algorithms for intelligent systems monitor the condition of equipment and provide warnings or even predict potential problems before malfunctions occur. Smart energy systems are usually connected to other “smart” devices and integrated into the “Internet of Things” (IoT) for the coordinated and intelligent management of energy flow. By applying communication technologies, smart energy systems can be monitored and controlled remotely, allowing operators to respond quickly to various critical events.

On the other hand, the implementation and use of intelligent power electronic devices and systems brings risks and disadvantages that must be carefully considered, analyzed and managed [12–14], since they are connected and controlled remotely over the Internet, making them a potential target for hacker attacks. Such attacks can lead to the disruption of normal operations, data leakage or even physical damage to equipment. Intelligent systems are more complex and require specialized knowledge and skills to manage and maintain. This complexity can lead to difficulties in diagnosing and fixing problems, as well as increased demands on the personnel who manage them. Some smart systems use proprietary software and hardware, which limit the ability to modify or integrate with third-party products and may increase the dependency on specific vendors. They also require regular software updates to improve the functionality and address security vulnerabilities. This process is usually difficult and expensive, especially for large and complex systems. In this aspect, the introduction of smart technologies often requires a significant initial investment, and the payback can be realized gradually over time. Technological advances can quickly render some smart systems obsolete, necessitating their replacement or modernization. On the other hand, collecting and analyzing large amounts of data from smart devices can put the privacy of personal information and corporate data at risk, and smart devices can be vulnerable not only to cyberattacks, but also to physical damage caused by natural disasters, human error or intentional destruction.

Managing these risks and flaws requires a comprehensive approach, including rigorous security measures, regular maintenance and upgrades, and planning for future technological developments.

The main goal of the manuscript is to present the concept of a new generation of power electronic devices and systems in the light of the emergence and development of new technologies and materials, and also to outline the problems and challenges in their implementation. This manuscript is organized as follows: the first chapter presents the trends and challenges facing the development of power electronic devices and systems; the second chapter examines the application of wide-bandgap semiconductors in power electronic devices; the third chapter is devoted to the application of nanomaterials for the realization of the magnetic components in power electronic devices; the fourth part presents artificial intelligence (AI) techniques used in different stages of the life cycle of power electronic devices; the fifth part presents flexible power electronic devices implemented on the basis of using a modular principle; in the sixth, the concept of the model-based life-cycle-oriented design of power electronic devices is formulated; and the last seventh part presents conclusions and a discussion. The motivation for creating this manuscript is the existing gap in the scientific literature regarding the development trends of power electronics as a whole, such as element base, functional capabilities, new design concepts based on artificial intelligence and data science.

2. Wide Bandgap Semiconductors in Power Electronic Devices and Systems

Wide bandgap semiconductors (WBSs) are materials that have a larger energy bandgap than traditional semiconductors such as silicon (Si) and germanium (Ge). These materials offer a number of advantages in their use for controllable semiconductor switches in power electronics, including higher efficiency, higher operating temperatures, and higher withstand voltages and temperatures [15–19]. The main types of wide bandgap semiconductors include the following:

- Silicon carbide (SiC) is known for its high thermal and chemical stability. It is used to create powerful diodes and transistors for power electronics. Applications include inverters for electric vehicles, solar inverters and other power electronic devices.
- Gallium nitride (GaN) is used to create highly efficient RF (radio frequency) amplifiers, fast switching devices and powerful transistors. Applications include wireless communications, microwave amplifiers and LEDs for lighting.
- Aluminum Nitride (AlN) is used to create microwave amplifiers, ceramic capacitors and other power electronic components. It combines high thermal conductivity with electrical insulation.

In recent years, the literature has described in detail both the features of their application in power electronics, as well as their advantages and disadvantages compared to classical semiconductors. In this sense, active work is being conducted on the creation of methodologies for the design of power electronic devices that reflect the specifics of WBSs, as well as on the creation of adequate models to describe their properties.

Ultimately, WBSs have both advantages and disadvantages and limitations to their deployment. Their advantages are related to higher thermal stability and lower switching losses, which make them suitable for application in power electronics. This leads to higher efficiency and lower electricity consumption. WBSs can operate at higher temperatures than traditional semiconductors. This is extremely useful for power electronics applications exposed to high temperatures or requiring less cooling. In addition, WBSs can operate at higher voltages, which is important for applications where high voltage conversion or surge immunity is required, and WBSs also have faster switching times, making them suitable for high-frequency applications and high current switching. After all, for the same power, WBSs are smaller and lighter than traditional semiconductors, which facilitates their integration into various devices and systems.

On the other hand, they are also characterized by the following disadvantages, as WBSs are generally more expensive to manufacture than traditional semiconductors such as silicon. At the moment, this factor can affect the price of the devices that use them, but on the other hand, in the near future, according to Moore's law, it is expected that with an increase in their use and volume of production, the production costs and, accordingly,

the price of WBSs will quickly decrease. WBSs require more complex technologies and processes that make manufacturing more difficult and increase costs, and although WBSs have many advantages, they are not yet as widespread and standardized as traditional semiconductors. Ultimately, due to the differences in the capabilities and characteristics of WBSs and traditional semiconductors, the integration of these two types of materials is a challenge in the prototyping of power electronic devices and systems.

Figure 1 shows a visualization of the properties and a comparison between the main properties of different types of semiconductors and their applicability for typical applications [20].

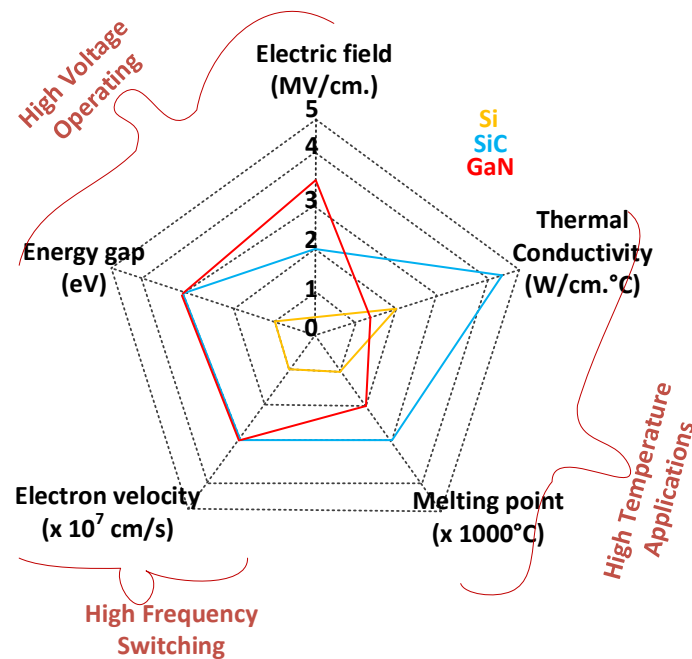


Figure 1. Comparison between the main parameters of Si, GaN and SiC semiconductor elements used for the design and according to the application [20].

Despite some limitations and drawbacks, WBSs have great potential for application in power electronics and for improving the electrical energy conversion efficiency for a wide range of applications at a time when the energy efficiency and performance of power electronic devices are of primary importance. On the other hand, the development of semiconductor manufacturing technology also leads to an evolution in the power circuit topologies used, increasing the application of resonant and multi-resonant circuits [21].

3. Use of Nanomaterials in Power Electronic Devices and Systems

The development and commercialization of new materials also has its impact on the development of power electronics. In this sense, new generations of magnetic components play an important role in power electronic devices and systems, offering more efficient and compact solutions for managing energy flows. Some of the key innovations and trends in this field including those described in [22,23] are related to the development of magnetic materials with higher saturation, which allows the creation of smaller transformers and inductances, and as a result, the creation of more compact and more efficient power electronic devices and systems. Manufacturers are developing integrated magnetic components, such as magnetic inductors and transformers, that combine the functions of several separate components into a single device. This improves the power density and efficiency. New low-loss materials reduce the heat loss in magnetic components and increase the efficiency of power electronics. With the development of high-frequency power electronics, magnetic components are designed and optimized specifically for high-frequency operation. The innovations in magnetic component development enable engineers to create devices that can

operate on both AC and DC signals, thus increasing the design flexibility. Some magnetic components are equipped with sensors and integrated control devices, which allow better monitoring and control of their operation.

A meminductor is a new type of electronic component that is used in the field of power electronics. It is the basis of memristor technologies, which are based on memristors—devices that have a resistance that can change depending on the magnetic field or the current that passes through them [24]. Meminductors function in a similar way, but focus on the change in inductance (L) of an electrical circuit as a function of external factors such as voltage, current or magnetic field. They can be used to create electrical power management devices with greater efficiency and better control. They can also be incorporated into high-frequency communication and data transmission circuits, where inductance control can improve the speed and efficiency of signal conversion.

The innovations in magnetic components aim to improve the efficiency, reliability and compactness of power electronic devices and systems while reducing their power consumption and heat loss. They are essential for the development of modern technologies.

In this aspect, in order to improve the efficiency and reliability of electronic systems and devices, new generations of power capacitors have been developed. Some of the key developments and trends in power capacitors are related to the development of powerful capacitors with a higher energy density that combine high capacitance with smaller dimensions. This allows for more compact power electronics designs and greater stored energy. Supercapacitors are being developed and improved, especially for energy storage and use in high-frequency applications. They offer high charging and discharging speeds and have a long life compared to conventional cells. Newer materials and technologies reduce the losses in power capacitors, especially in high-frequency, high-voltage applications. Power capacitors are being developed that can operate at high temperatures and withstand extreme conditions, and in some applications the capacitors are integrated directly on the same board as other components, thus reducing the costs and increasing the reliability. New types of electrolytic capacitors are being developed that offer a longer life and lower current losses. Some models of power capacitors are equipped with sensors and condition monitoring systems that allow users to monitor the change in certain parameters and the efficiency of the capacitors.

Memcapacitors are electronic components that are based on the concept of memristors [24]. They are a special type of capacitor that can store information about electric charge in the form of an electric field or material topology. Like memristors, which store information by changing their internal resistance, memcapacitors can store information by changing their electric field or capacitance. These devices are used in various fields of electronics where it is required to save data or settings in an electrical form. They can be used in the same vein as conventional capacitors, to store energy and filter signals, but they also offer the ability to retain information, making them useful for applications such as non-flash memories, logic devices and more. Thus, memcapacitors have the potential to change the way that electronic devices are built and used, providing new possibilities for integrating memory and data processing into electrical circuits. Their unique characteristics make them suitable for various applications in power electronics and information technology. It is important to underline that the research related to the commercialization of meminductors and memcapacitors is just beginning to develop, and the initial results are very promising [24].

4. Application of Artificial Intelligence Techniques in the Various Stages of the Life Cycle of Power Electronic Devices and Systems

The applications of artificial intelligence (AI) are constantly expanding, and in this sense, it has been one of the most impactful areas of research in the last few decades. The goal of AI is, based on its application, that devices and systems acquire intelligence by becoming capable, like humans, of learning and reasoning. AI has tremendous advantages and has been successfully applied in many diverse fields, including image classification,

speech recognition, autonomous cars, computer vision and more. Due to its specificity as an interdisciplinary field, power electronics also benefits from the development of AI [25]. There are many different applications related to the optimal design of both individual elements of power electronics devices, as well as individual devices and entire systems. By implementing AI, power electronic systems gain self-awareness and self-adaptability capabilities, and therefore, system performance and performance are guaranteed and improved.

Meanwhile, the rapid development of data science, including sensor technologies, the Internet of Things (IoT), computer computing, digital twins [26,27] and large database analysis [28], provides a wide variety of data for power electronic systems through the various phases of their life cycle. The growing volume of data provides enormous opportunities and lays a solid foundation for the application of AI in power electronics. AI is able to use data to improve product competitiveness through global design optimization, intelligent management, system reliability and operability assessment, and more. As a result, the research in power electronics can be conducted from a data-driven perspective, which is particularly beneficial for solving the increasingly complex tasks and projects presented to practitioners and researchers [29].

Due to the specific challenges and characteristics of power electronic systems, for example, high speed and adaptability in control, high sensitivity in condition monitoring for prediction and aging detection, etc., the implementation of AI in power electronics has its own characteristics that are different from other engineering fields such as image classification. Therefore, there is a pressing need to both review AI techniques applied so far in power electronics and propose new ones to accelerate the synergistic research and interdisciplinary applications of power electronic devices and systems. Based on the in-depth literature review and analysis in [30], AI applications in power electronics are categorized into three aspects: design, control and operation.

In order to determine the trends in the application of artificial intelligence techniques in power electronics, a search was conducted using the keywords, “artificial intelligence” and “power electronics,” in two of the world’s most well-known databases of referenced publications, Scopus and WoS. Figure 2 shows the annual number of publications related to the application of AI for power electronics from their appearance at all until 31 December 2023 published in the Scopus database [31].

Documents by year

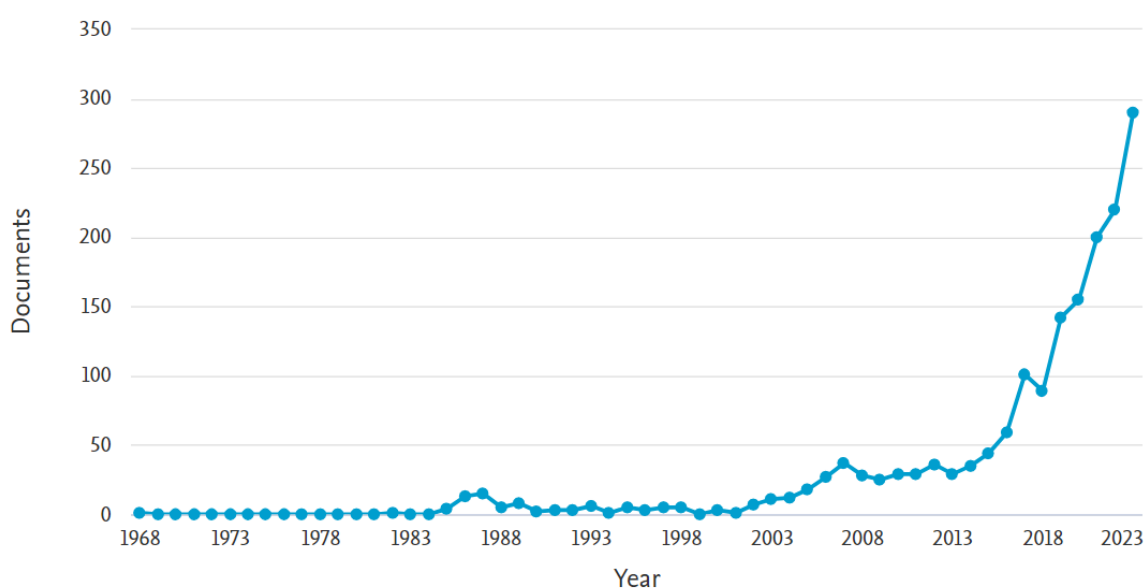


Figure 2. Annual number of publications in Scopus on the application of AI in power electronics from their appearance to 31 December 2023.

These statistics are based on all publications indexed in Scopus. As a result, a total of 1707 publications were identified. It is seen that AI implementation in the power electronics field has increased dramatically, with significant momentum observed, especially in the last few years. Of interest is the breakdown of this information by document type in the database, which is presented in Figure 3, namely predominant conference papers (over 54%) and journal publications (over 31%).

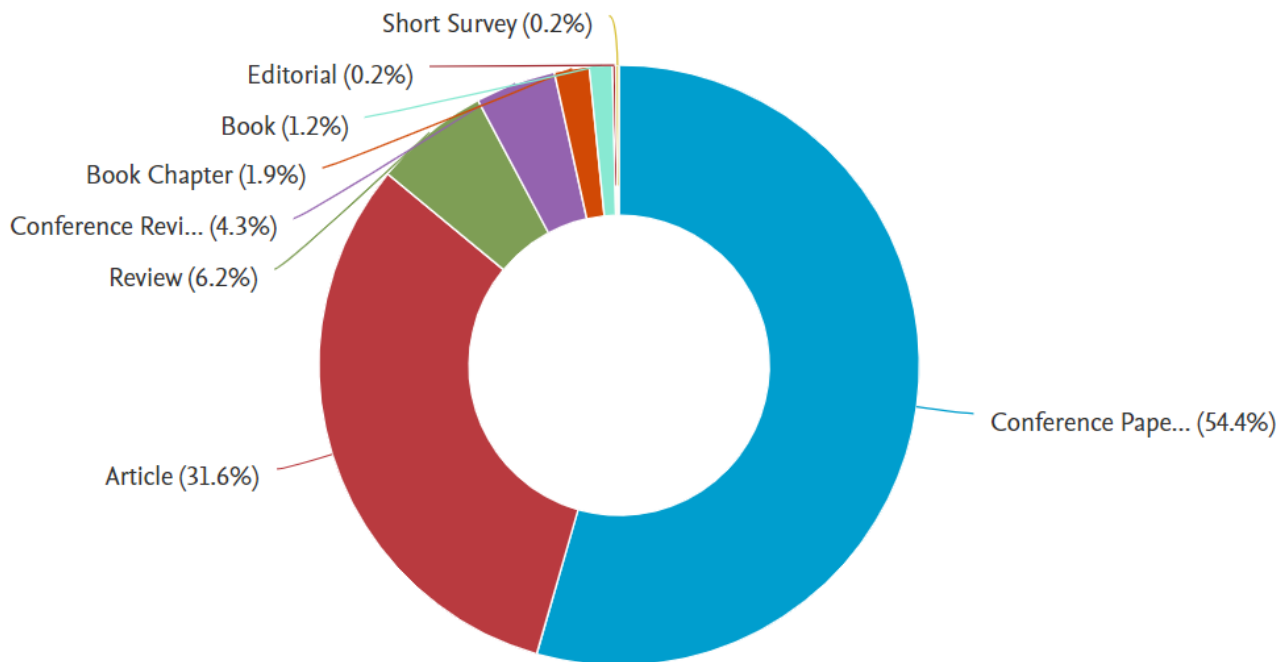


Figure 3. Type of documents regarding the application of AI in power electronics by field of science from their appearance as of 31 December 2023.

The results obtained from the analysis of the publications in the other WoS database are similar. Figure 4 shows the number of publications by year for the period from 2009 to 2023 inclusive [32]. The years of publication are indicated on the horizontal axis, and the number of publications for the respective year are shown on the vertical axis.

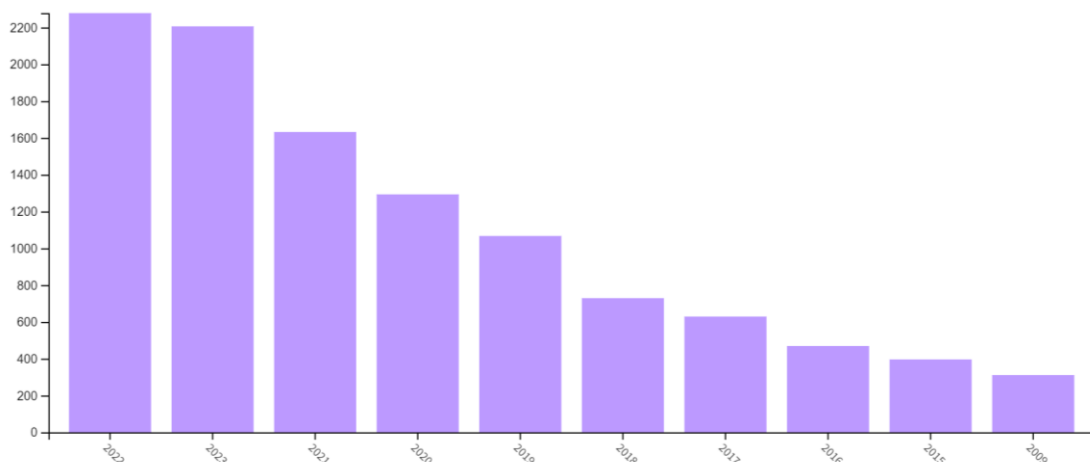


Figure 4. Number of publications, by year, in the WoS database, with the subject of applying AI in power electronics.

As of 31 December 2023, a total of 12574 publications had been published on the subject related to the application of artificial intelligence techniques in power electronics. Here, too, there has been a steady growth in the number of publications in recent years.

Another classification is by post type. And on this basis, the figures are dominated by journal publications and conference papers. This is evident from the data shown in Figure 5.



Figure 5. Type of documents indexed in WoS on the AI application in power electronics.

As a result of the increasingly widespread application of various artificial intelligence techniques in power electronics, several detailed reviews have been published that examine and summarize the achieved results and possibilities for expanding the scope of application [25,30,33–35].

Figure 6 summarizes the AI methods, functions and applications for power electronics. AI is seen to be widely applied in the three distinctive phases of the life cycle of power electronic systems, including design, control and operation.

As a functional layer between AI and the applications of power electronic devices and systems, the main functions of AI are categorized as follows:

- **Optimization:** This is used to find an optimal solution that maximizes or minimizes predefined objective functions, taking into account specific constraints, equalities or inequalities that the solutions sought must satisfy. In the design task, optimization selects an optimal set of device parameters that maximize or minimize the design goals and constraints.
- **Classification:** Data classification in the context of machine learning and artificial intelligence is the process of sorting data into predefined categories. This is a type of supervised learning task where an algorithm is trained on an input data set already labeled with the correct answers, and then uses that training to classify new, unseen examples. In power electronics, this tool is useful for anomaly detection and maintenance fault diagnosis, and is also used for condition monitoring.
- **Regression:** Regression is a method of modeling the relationship between one or more independent variables (predictors) and a dependent variable (outcome). The purpose of regression analysis is to determine the strength and nature of the relationship between predictors and the outcome, and to make predictions about the outcome at new values of the predictors. By identifying the relationship between the input variables and the target variables, the purpose of regression is to predict the value of

one or more continuous target variables, given known input variables. In this sense, a regression model between the input and output signals is often used in the synthesis of intelligent control.

- Data structure exploration: This consists of data clustering, which finds groups of similar data within a data set, finding the density distribution of data from an input space and data compression, which projects high-dimensional data to low-dimensional data with the purpose of reduction. For example, in maintenance, degradation state clustering is in the data structure research category.

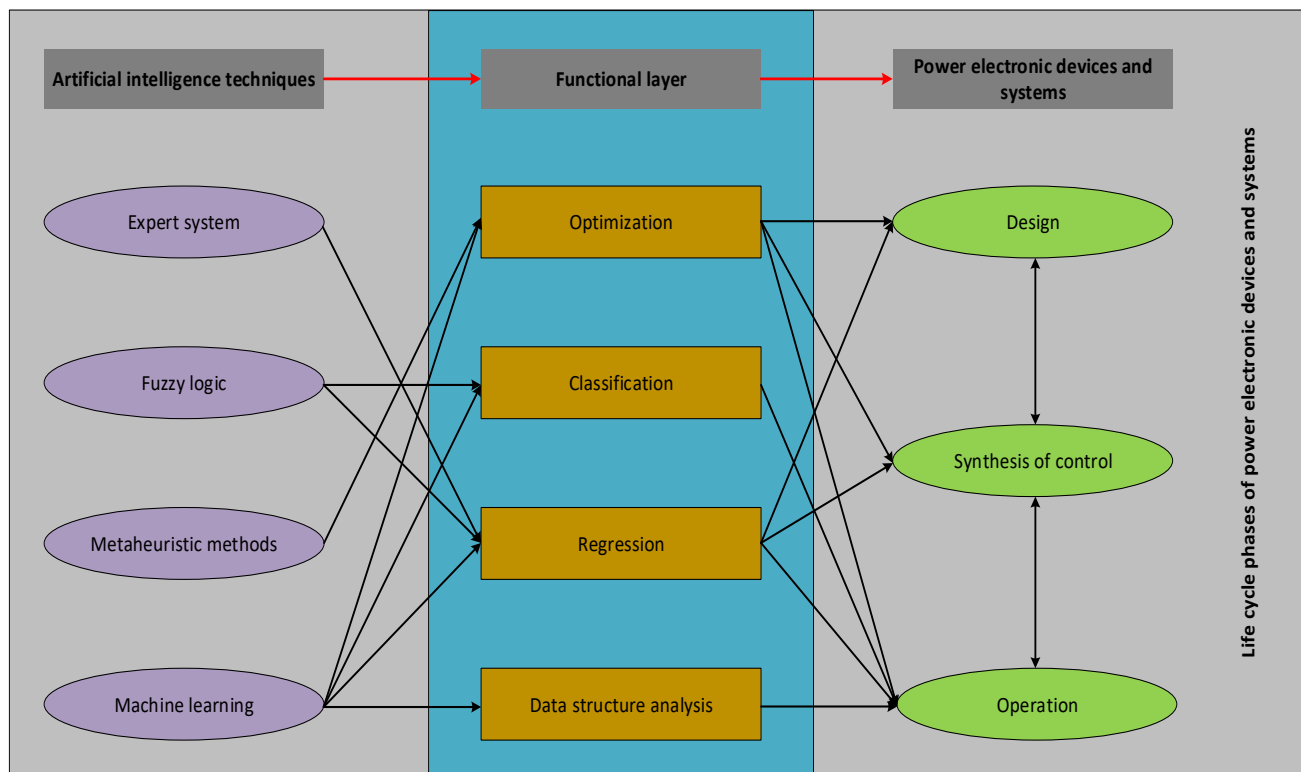


Figure 6. Application of artificial intelligence in the life cycle of power electronic systems.

In this aspect, the optimal design of power electronic devices is realized through various artificial intelligence (AI) techniques as follows:

- Genetic algorithms (very commonly used artificial intelligence techniques that are based on the principles of evolution and natural selection in living nature). Genetic algorithms are applied to optimize the parameters of power electronic devices, such as the configuration of electronic components, select appropriate materials and parameterize electrical circuits to achieve better efficiency or performance, resulting in more efficient and economic decisions; in power electronic devices, where it is important to control the energy distribution, genetic algorithms can be used to optimize this process. This can also include both optimal input and power management and output for load balancing; improvement of electrical circuits, by choosing the appropriate configurations and parameters that maximize the desired characteristics of the devices, such as efficiency, dynamics or reliability; and managing the thermal characteristics of power electronic devices by finding the suitable configurations of cooling systems or optimizing the heat distribution in the device.
- Machine learning (ML) is used to analyze data from multiple measurements, predict the performance or reliability of devices, and optimize design, prototyping, and manufacturing processes. In this regard, machine learning is an important tool based on the application of artificial intelligence that can be used for the optimal design of power electronic devices. ML is used in this context as follows: to analyze data

from previous measurements and tests to predict the performance and reliability of various configurations of power electronic devices. This can help engineers select the best designs for specific applications; machine learning can be used to optimize the energy efficiency of power electronic devices by analyzing the energy consumption and identifying the optimal operating modes; machine learning can be used to create models that automate the verification and testing of power electronic devices. These models can predict the behavior of devices in different conditions and detect potential problems in advance, before emergency events occur.

- Simulation models play a key role in the field of power electronics, providing a powerful tool for the design, analysis and optimization of power electronic systems. These models help designers understand and predict the behavior of power electronic components and systems under various operating conditions without having to build and test physical prototypes, greatly reducing the development time and costs. The applications of simulation models in power electronics include, but are not limited to, the following key aspects: Simulation models allow engineers to design and optimize power converters by experimenting with different topologies, components, and control schemes to find the most efficient, rational, and reliable solutions; simulation models support the analysis of the thermal behavior of these components, which is critical to prevent overheating and increase the reliability and lifetime of the devices; simulation models are used to study the electromagnetic characteristics of power electronic systems, including electromagnetic interference (EMI) and compatibility (EMC). This is important for developing systems that meet regulatory requirements and do not cause interference to other electronic devices. Simulation models are invaluable for studying the dynamic behavior of power electronic systems under various load conditions and input signals. They help develop management strategies that optimize real-time productivity and efficiency. The modeling and simulation of power electronic systems allow engineers to assess the robustness and reliability of these systems under various operational and extreme conditions. This is critical for identifying potential points of failure and preventing failures in critical applications.
- AI techniques are successfully used to automate the validation and testing processes of power electronic devices, as these are critical processes that ensure their reliability, safety and efficiency. In the context of the rapid technological development and increasing complexity of power electronic systems, the automation of these processes is becoming increasingly important. Here are some key aspects and applications of automated verification and testing: Automated test systems execute predefined test procedures without continuous human intervention. This includes automatically applying input signals, measuring outputs, checking for compliance with specifications and generating test reports. This automation enables faster and more efficient device testing; automated verification tools analyze and verify that the design of the power electronic systems meets the specified specifications and safety requirements. They may use formal verification methods or simulation tests to identify the potential problems in the project; automated testing systems subject power electronic devices to a variety of stress tests, including extreme temperatures, humidity, vibration and electrical loads. This helps in assessing the reliability and durability of the devices under severe operating conditions. Functional testing verifies that power electronic devices perform their intended functions under normal operating conditions. Automated testing tools can facilitate the execution of complex test scenarios, thereby providing higher test coverage and better functionality verification; automated integration testing verifies the interaction between the different components or subsystems in power electronic systems. This is especially important in complex systems where the components must work harmoniously together; when changes are made to the system, automated regression testing can quickly identify unforeseen problems that those changes may have caused. This ensures that the new or changed schematic element or code does not break the existing functionality; for products that must demonstrate

long-term reliability, automated systems can conduct continuous monitoring and testing for periods of time that are not feasible for manual testing.

Automating the validation and testing of power electronic devices not only increases their efficiency and reduces the time to market, but also improves the product quality by minimizing the possibility of human error in the testing process.

The application of AI techniques in the control synthesis of power electronic devices and systems is an area that is undergoing rapid development and offers significant advantages over classical methods. AI and machine learning can help optimize the performance, efficiency and reliability of controllers in ways that traditional methods cannot. The most significant applications of AI in control synthesis are related to the implementation of adaptive control systems that can adapt to the changing environmental conditions, and changes in the characteristics of building elements and loads in real time. For example, neural networks are trained to optimize the performance of inverters in photovoltaic systems depending on the changing conditions of illumination and temperature. In addition, such a system can predict the change in road conditions for the optimal distribution of energy consumption between the battery and the capacitor in electric vehicles. Machine learning techniques can analyze sensor data in real time to identify the conditions that precede failures. This allows preventive measures to be taken to avoid system shutdowns and reduce the downtime. Also, AI algorithms are applied to analyze operational data and to optimize the performance of power electronic systems to achieve the maximum energy efficiency. This is particularly important in applications such as electric vehicles and energy system management for decentralized power generation, where the efficiency directly affects the productivity and operating costs. In modular power electronic devices and systems operating autonomously or integrated into networks, AI techniques support their dynamic control and load balancing. This includes automatically both reconfiguring energy storage devices and operating with the optimal number of modules for the specific needs, as well as managing the energy distribution in response to the changing load needs. AI can also be used to automatically generate and optimize the control algorithms for power electronic systems. This includes the development of innovative control strategies that are tailored to the specific applications and requirements, using genetic algorithms or other optimization methods. AI techniques can analyze the real-time data from various sensors and identify the power quality issues such as power surges or harmonics. They can then manage the power electronics in such a way as to correct these problems in real time, thereby improving the overall power quality and performance relative to the power grid. Machine learning and optimization algorithms help to successfully integrate renewable energy sources into electricity networks by optimizing the generation and distribution of energy from these sources depending on the demand and other energy sources, which is one of the possible solutions for the realization of electrification.

The application of AI techniques in power electronics offers the possibility of significant improvements in the control, efficiency and reliability of power electronic devices and systems, thereby meeting the growing demands for sustainable and efficient energy management in the modern world.

The operation of power electronic devices is an area that includes reliability, condition monitoring, remaining useful life (residual resource) prediction, etc. One of the main areas where AI is used is the analysis of the data from the sensors mounted on power electronic devices to extract information about their current state and load. This analysis can include various parameters such as temperature, voltages, currents and vibrations. Using sensor data and machine learning algorithms, AI can predict the likelihood of the failure of power electronic devices. This allows the operators to plan preventive maintenance actions before problems occur. Artificial intelligence can be used to optimally manage resources and inventory, such as replacing components or performing maintenance at optimal times to extend the useful life of devices while minimizing the downtime losses. Based on AI predictions, the system can generate warnings about potential dangers or problems with devices and even take automatic actions to prevent damage or malfunctions. Overall, the

use of AI in this context can help improve the reliability of power electronic devices while providing more efficient and proactive life cycle management.

5. Flexible Power Electronic Devices and Systems

Modular power electronic devices and systems are composed of a set of modules or components that can be connected and combined in various ways to achieve a desired functionality or configuration. These devices and systems offer flexibility and scalability, allowing users to create customized solutions according to their specific needs and requirements. Some of the main characteristics and applications of modular power electronic devices and systems [36,37] are related to flexibility and scalability. Modular power electronic devices allow users to choose and combine modules according to their needs and preferences. This allows flexibility in creating solutions and easy expansion or modification of the system in the future. In addition, modular systems are often designed with standardized interfaces and communication protocols, making it easier to integrate and configure the various components. Power electronic devices that must operate over a large load range face specific challenges related to their design, control and reliability. Typically, these devices are critical components in many applications, including industrial equipment, renewable energy converters, electric vehicles and power systems. One way to successfully solve these challenges is to implement modular structures. By using a modular structure, these systems are often easier to maintain and troubleshoot, as damaged or worn modules can be easily replaced without having to shut down the entire system. Modular power electronic devices and systems allow users to create customized solutions by choosing only those modules that are necessary for their specific tasks or applications, and due to these qualities, they are used in various fields such as home automation, industry, robotics, energy systems, IoT (Internet of Things) devices and more.

Ultimately, regardless of the specific application and requirements, modular power electronic devices and systems represent a powerful tool for creating innovative and customized solutions that can meet a variety of needs and requirements.

In this sense, by surveying the multiple approaches used to formulate and formalize modularity in power electronics, the most common one is based on a broader identification of the conversion modules, as opposed to those that only consider the topology of the power circuits. Thus, with a view to conducting a complex assessment of the design process of power electronic devices and systems, the concept of “power electronics technology space” (PETS) was introduced [37]. The application of PETS is useful for presenting, on the one hand, the whole range of possible technologies for the realization of power electronic devices, and on the other hand, their applications and required powers. The power electronics technology space concept is visualized in Figure 7, with power electronic devices and their application areas systematized according to their use in the various stages related to the collection, distribution, storage and consumption of electrical energy.

From this point of view, the concept of power electronics technology space is defined by three main components as follows:

- (1) Converted power level. Due to the diverse nature of the applications, power electronics covers a very large range of power levels, with the lower limits being milliwatts (for micro-power supplies of sensors and sensor networks) up to gigawatts (in power and energy systems). Therefore, one axis of the technological space is chosen as the level of the converted power.
- (2) Functions. Power electronic devices convert electrical energy throughout the cycle of its production, distribution, storage and consumption. A relevant classification on this basis is power electronic devices with applications for: energy harvesting (oriented to energy sources); energy transmission and distribution (grid oriented) and efficient energy consumption (load oriented). The requirements and, accordingly, the prototyping technology of each individual device of these three families are very different, which leads to the definition of the second axis of the technology space as functions.

- (3) Application. The power electronic devices are located along the entire energy cycle as follows: on the source side, on the load side and in the supply network; at the same power level, the operating conditions, environmental and regulatory requirements and standards are very different depending on the application, so the third axis of the technology space is formed according to the type of application.

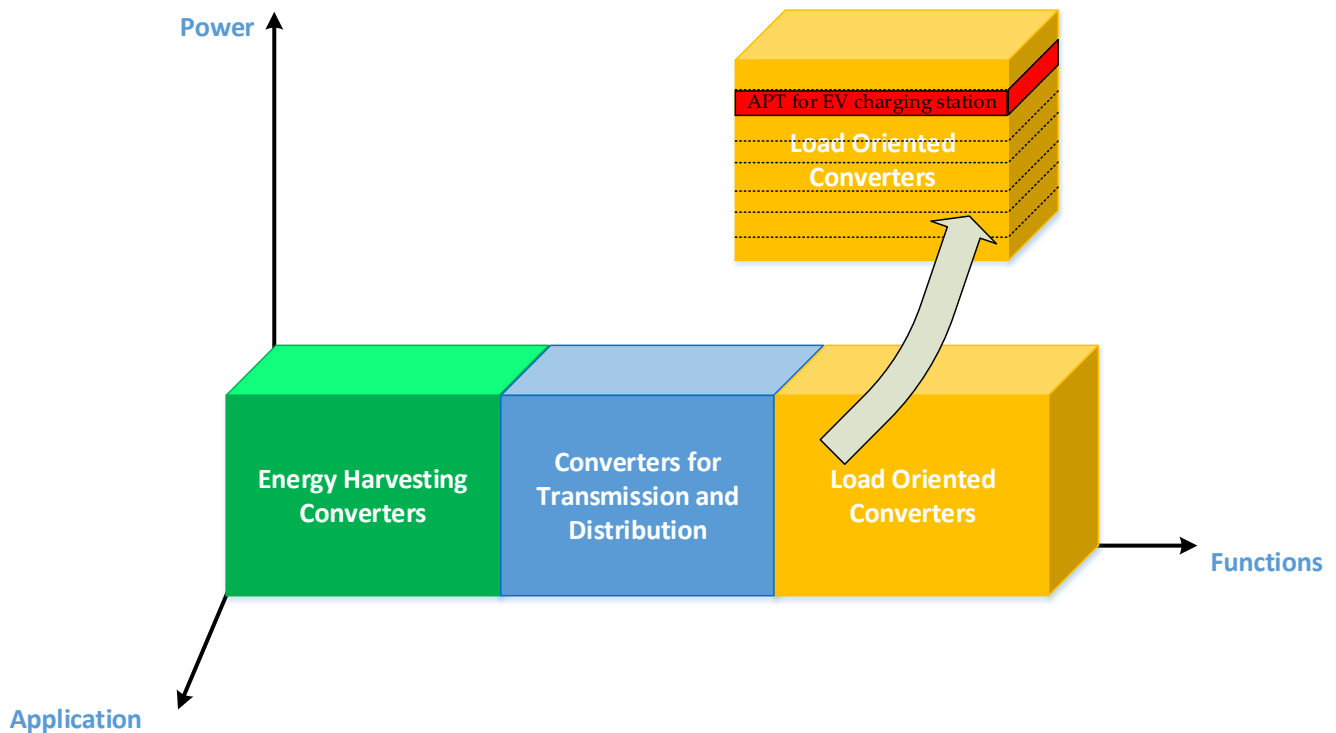


Figure 7. Technology space of power electronic converters.

In this sense, a specific power electronics technology from the Applied Technology Space (APT) is defined. Applying this approach allows different project-oriented APTs to be identified, such as powering a micro-chip, an induction heating system, for a photovoltaic generator or for an electric vehicle charging station. An APT for the realization of electric vehicle charging stations is shown in Figure 7. This space is obtained by choosing a task-relevant power and topology from the load-oriented converters.

The modularity in power electronics provides new opportunities in the implementation of power electronic devices and systems, and through this approach, such technical and economic indicators of the final product are achieved that would not be obtained when using a single device. A very characteristic example of the impact of modular structures on improving the performance of power electronic devices is given in [38], where the design of an ultra-fast charging (UFC) system for electric vehicles (EVs) is investigated. It is known that the charging infrastructure is the most critical point in terms of hardware technology accompanying the electrification of transport due to the problems related to the power grid and the financial sustainability of this process. In the considered example, the main goal is to propose a method to reduce the installed power of the DC-DC converters, while maintaining the possibility of charging each electric vehicle with maximum power in each stage of the charging process. To achieve this goal, the application of a modular approach is proposed. In practice, due to the wide variety of electric vehicles available on the market, their charging capacity varies over a very wide range. Figure 8 shows the dependences of the consumed power required for a charge depending on the SoC of the battery (Figure 8a) and as a function of the charge time (Figure 8b) for several representative brands of electric vehicles. It can be seen that the required power varies from 150 kW for Tesla to 45 kW for BMW. In this sense, this makes it difficult to choose the optimal size for

such a charging system: if a UFC station is sized for the maximum charging power allowed by electric vehicles, then it will operate most of the time at a lower power, thus leading to poor efficiency values, due to the incomplete load of the power electronic devices. On the other hand, insufficient installed power will create problems related to ensuring the necessary consumption by individual customers at any given moment of time. In the example, a charging station suitable for charging the seven types of electric vehicle indicated in Figure 8 is considered. The studied station consists of ten charging columns, each of which was chosen to provide 175 kW of power, and thus a total maximum power of 1.75 MW was obtained. This is the theoretical maximum peak power, assuming that ten vehicles, randomly selected from the seven models presented earlier, occupy the ten columns at the same time and all consume maximum power. After applying stochastic methods, it was found that a UFC plant with a maximum power of 1 MW is possible to satisfy more than 97.6% of the likely demand scenario. It is important to clarify that the calculated peak required power has no dependence on a specific time of day, and is a theoretical peak used to determine the base size of an ultra-fast charging station. Furthermore, the authors specify that the power conversion efficiency was not considered when constructing the probabilistic model. The main task is to find a solution to reduce the total installed power for the DC-DC converters, while maintaining the possibility to charge the electric vehicles at the maximum power at any given time.

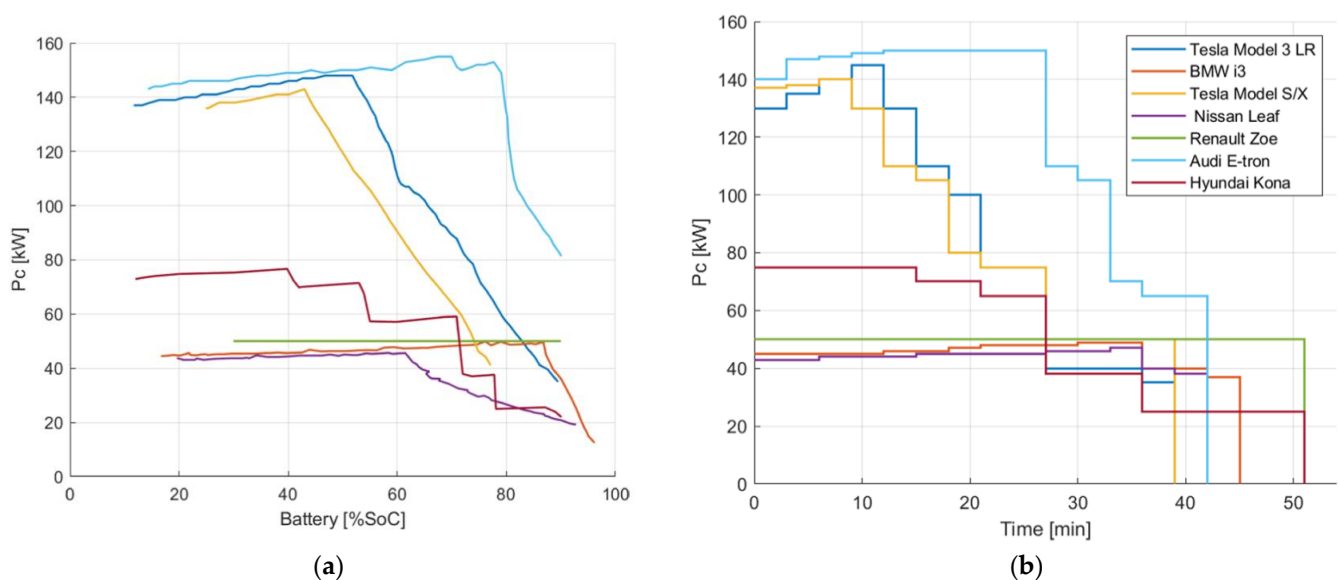


Figure 8. Dependence of the consumed active power (a) on the state of the battery; (b) from charging time [38].

By applying the modular approach for the realization of the station, a certain number of identical DC-DC converters (modules) are used, and different configurations are obtained using electronic switches, according to the power required to supply individual EV batteries. In this way, it is possible to simultaneously charge several electric vehicles with different power levels. The structure uses the concept of working on a common DC bus that integrates different types of renewable energy sources and energy storage systems.

In the proposed modular approach, the DC-DC part of the UFC station consists of 20 identical 50 kW modules that can be shared between adjacent charging ports depending on the possible power switch configurations. The size of the individual module of 50 kW has been determined with a view to achieving a charge of a maximally discharged vehicle with the lowest required power. An example configuration for charging two vehicles with different power and SoC of the battery is shown in Figure 9. Depending on the energy needs, the less charged EV (SoC 30%) uses three converters of 50 kW, and the better charged (SoC 70%) one of 50 kW. In this sense, one of the main tasks in the application of the

principle of modularity is the determination of the optimal size of the individual module, as this is related to the consideration of a range of technical and economic factors, such as the price per square meter of installed power, weight and dimensions, complexity of management, characteristic load efficiency, reliability, temperature regime, etc.

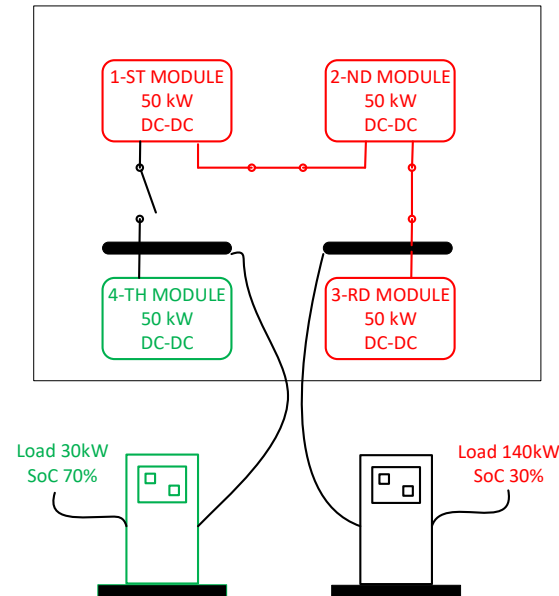


Figure 9. Example configuration of the modular system when working with two electric vehicles [38].

Two different switch configurations are offered. From the results obtained from their comparison, it is concluded that the second architecture, which uses more switches, has better performance in terms of power sharing and reducing the possibility to only 2.1% for charging a limited-power EV. However, both proposals allow greater flexibility in the charging of vehicles of different sizes and increase the utilization rate of the DC-DC converter and thus the efficiency of the entire charging system.

Another very important application of modular structures is in smart grids. SYNCRIS has developed and markets a modular and scalable microgrid technology based on modular and scalable inverters and storage combined with independence from the input energy sources. These systems are characterized by the fact that the inverters are modular and scalable from kW to MW using near-instantaneous (synchronization in microseconds) hardware-based self-synchronization technology with hot-plug capability, allowing the realization of multiphase systems (single-phase, two-phase, three-phase, multiphase) [39].

The modular concept for the realization of power electronic devices and systems has been applied very successfully in electronic technological systems with industrial application. UltraFlex Power Technologies has successfully applied it in the development of a series of power supplies for induction heating [40]. Ultraflex SmartPower™ Compac Systems offers a new modular concept in induction heating technology based on the Direct Digital Step™ control algorithm. The power supplies are thus configurable and upgradeable, with an output power range of 50 kW to 400 kW, with two output frequency ranges: 6 kHz to 60 kHz and 40 kHz to 200 kHz.

In the development of the modules, SiC transistor technology and refined digital control algorithms have been applied, thus providing an optimal balance between the performance and efficiency over a wide range of load variation. The modular structure achieves extremely flexible, wide-range load impedance matching through the use of multiple transformer ratios and configurable capacitor banks. The application of the modular concept achieves a durable and reliable design with built-in features for setup, safety and device diagnostics.

This modular and reconfigurable approach offers many advantages:

1. Facilitates repair and operation. Defective modules can be replaced without disrupting the functionality of the entire system.
2. Increases the flexibility needed to accommodate future expansions and the related power requirements. In the coming years, a significant increase in electric vehicles supporting fast and ultra-fast charge technology is expected. The modular approach makes it possible to increase the installed power of the station with minimal costs and efforts. In this way, the now-built charging infrastructure of ultra-fast charging stations will be adequate for tomorrow's needs and a lower cost of the initial investment will be obtained over the years, which will ultimately have a favorable effect on consumers.
3. Realizes optimal use of the installed capacity of the station. As shown in Figure 9, the modular approach realizes better control, for a given installed capacity. In this sense, it is implemented to successfully complete a larger number of simultaneous charges that require different power values.
4. Realizes high efficiency at a low station load. The characteristics of the EV and therefore the requested charging power can vary significantly between models and different SoC levels, so for this reason the converters of a conventional UFC station are sized for maximum power, but operate most of the time at a lower one, leading to low efficiency in the case of a light load. A modular topology seeks to improve this feature as it allows for a more distributed use of the installed power.
5. Improves the thermal management of the devices and hence their reliability, because it mainly depends on the operating temperature.
6. Achieving a lower cost due to the unification of production and the transfer of the design and development costs to a larger series of production.

Electrification and the growing need for clean and renewable energy necessitate a new concept in the production, distribution, consumption and storage of electrical energy—the concept of the Internet of Energy. This includes the integration of renewable energy sources, smart grids, energy storage devices and innovative energy management software solutions. Looking at the opportunities and challenges of this innovative technology, one of its key elements is an intelligent electronic transformer that allows the flexible and adaptive management of energy flows in the network [41]. In [42], a similar concept composed of flexible electrical equipment is presented: iPower+ Router, iPower+ Switcher and iPower+ Hub. The flexibility of the electronic transformer is achieved by using a modular structure, with individual modules connected to a common DC bus that facilitates power transfer.

6. Model-Based, Life-Cycle-Oriented Design of Power Electronic Devices

Sustainability in regard to power electronics is a new research topic that offers design solutions considering the circular and low-emission economy. The growing use of power electronic converters in all areas of modern societies leads to the creation of new products and growing production, which puts pressure on natural resources and the ecological balance in general. At this point, there is a lack of relevant studies focusing on reparability and the importance of integrating circuitry into eco-design requirements in power electronics. In this sense, it is necessary to apply an interdisciplinary approach in the design and prototyping of power electronic devices to guarantee the interaction of the production chain in terms of the materials used and circularity [43].

The main conclusions of the authors are as follows: to assess the sustainability from the point of view of power electronic converters, the whole life cycle, the whole eco-system along the value chain, etc. should be considered; it is necessary to develop and implement specialized methodologies for conducting life cycle management (LCM) on power electronic devices to compare the different technological solutions; standard indicators from LCM are not sufficient to design more environmentally and resource-sustainable power electronic converters. In this regard, additional indicators should be introduced related to the description of end-of-life scenarios, such as modularity, reusability, reparability, etc. In

this sense, circular economy studies are needed on the existing and future value chain of power electronic devices and their components.

Battery energy storage systems are key solutions in the field of highly efficient energy conversions to realize an ecological transition. Electrification and the integration of decentralized sources of electrical energy require an increasing use of power electronic devices and batteries. In this sense, the issues related to their impact on the environment are becoming increasingly acute, insofar as their production requires a significant use of materials, including critical and rare earth raw materials necessary for their prototyping and production, and at the end of their life cycle, they generate electronic waste. In this aspect, the power electronics and battery industry needs to transform from the traditional take-make-waste linear economy to a circular economy where the concept of reuse, remanufacture and recycling is an integral part of the product life cycle. In [44], the challenges and possible solutions for improving the sustainability of power electronics and energy storage devices through the concept of a circular economy are detailed, and they are considered from both a design and end-of-life management perspective. From this next point, the concept in the creation and application of the existing tools for the design of power electronic devices should also be changed.

In [45], the current state and application of various successful eco-design criteria for power electronic devices and the corresponding environmental impact assessment indicators are reviewed and systematized. On this basis, the authors have assessed the opportunities to improve the eco-design of power electronic devices by considering different design loop scenarios for the Sustainability Perspective.

In [46], a life cycle assessment of a powerful electronic DC-AC converter, with an output power of 150 kW, supplied by a 450 V DC bus, for a duration of 15 years with 10,000 operating hours is presented. An analysis was conducted of the various materials and resources used in the production of the device, with the most material-intensive part being the housing and the power module. The obtained results make possible the application of eco-design with the use of technologies capable of creating evolution in the production hotspots. The collected and analyzed information allows the consideration of scenarios involving a circular economy by creating maintenance, recycling and reuse loops in the device, combining them with modularity and self-diagnosis functions. Key hotspots are identified to offer recommendations to the designers and technologists responsible for product commercialization. On this basis, it was concluded that production and use are the two subsections of the life cycle with the greatest impact on the environment.

The time horizon for achieving the net zero emissions goals needed to limit global warming is too short to wait for the emergence of new revolutionary energy technologies to achieve substantial emissions reductions. This is due to the specific nature of energy systems, where technological development and scaling times are long, and the lifetime of already installed energy infrastructure is also long. Electronic converters with the highest achieved efficiency of 99% are already widely demonstrated for various applications, i.e., there is very little margin for improvement—less than 1%. This very high technological achievement is a consequence of the fact that, at present, the optimizations of power electronic devices are mainly from the point of view of efficiency, power density and operational reliability. New-generation power electronic devices can and should be improved in terms of their environmental footprint and their compatibility with the circular economy, i.e., to apply in their design a new type of design called “Eco-design” or “Circularity Design.” Therefore, in [47] a roadmap for the transition to a circular-economy-compatible power electronics is proposed by incorporating environmental compatibility assessment into the multi-objective optimization process applied in design. Ultimately, the addition of an environmental condition allows the optimal balance of design trade-offs to be achieved.

The main challenges in implementing this new eco-approach in design lie, firstly, in obtaining reliable and representative data on the environmental impact of the individual components that are used in power electronic converters, and secondly, in the need for a certain generalization for obtaining scalable environmental impact models. In this regard,

in the future, the performance tables provided by component manufacturers will not only contain data on their performance depending on operating conditions, etc., but also on the environmental footprint of the component. Thus, the need for ever deeper automation is growing, with artificial intelligence (AI) driving and evaluating device design based on the use of large result sets with multiple performance evaluations. In doing so, additional challenges related to design trade-offs such as between integration and reusability/recyclability or between reparability and reliability (long life) should be expected.

From a review of the current state of design in the field of power electronics, the conclusion follows that achieving optimal (in a certain sense) results in the design of power electronic devices is possible only through the application of innovative approaches that combine modern means of modeling, computational mathematics, artificial intelligence and information and communication technologies. One possible solution is Model-Based Design (MBD) [48]. The MBD of power electronic devices is an innovative approach to engineering and systems development that focuses on the use of computer models throughout the design process, from concept to final product. This method allows engineers and designers to simulate and test the various aspects of devices before their physical production, resulting in reduced development time and costs, as well as increased product quality and reliability.

The key aspects of model-based, life-cycle-oriented design are as follows:

- Concept and design phase. At this stage, computer models are used to explore different design concepts and to determine the most suitable device parameters. Modeling enables virtual experiments and the analysis of potential design challenges.
- Simulation and analysis. Using specialized software, engineers simulate the operation of the device in various conditions, which helps them identify and correct possible problems before the realization of a prototype.
- Design optimization. MBD facilitates design optimization by allowing fast and efficient design correction in response to the obtained simulation results or customer requirements.
- Prototyping and testing. Although MBD greatly reduces the need for physical prototypes, the production and testing of prototypes remains important to validate the models and their predictions.
- Production. The information generated through the MBD process helps to optimize production processes and to minimize the risk of errors.
- Maintenance and disposal. MBD also covers the maintenance and disposal stages of the devices, providing detailed information on their operation, maintenance and possibilities for recycling or refurbishment.

An advantage of the proposed system approach is that already at the first level of the design process, work is carried out in such a way as to fulfill the requirements of the assignment. The main disadvantage is the need for complex knowledge in a fairly wide area—electronics, electrical engineering, control theory, circuit engineering, etc.

MBD is based on the principles of system analysis, which means that the designed power electronics converters is considered as a hierarchical system composed of a certain number of sub-systems (building blocks) interacting with each other in the event of various disturbing impacts, which are expressed by the change in the load of the output of the power electronic devices, the input power sources and the environmental parameters. In this setting, the optimal design of the power electronics devices, taking into account the existing limitations, is considered as a task to reach set spatial coordinates. The state variables are the unknown parameters of the designed power electronic devices, which fulfill the design task and are in compliance with the conditions for the functioning of the building elements and the device as a whole. These are most often thermal limitations of the individual components (building elements), and recently also environmental requirements related to the circular economy. In this sense, the implementation of a model-based design of power electronic devices is related to the following:

- Rational choice of basic topologies and building elements;

- Use of hierarchical mathematical models of different complexity for power electronic devices, controllers, semiconductor elements, magnetic components, capacitors and energy sources;
- Creation of algorithms for the design of power electronic devices with guaranteed indicators in a certain area;
- Application of a suitable software environment to solve the above task.

The existing and widely applied methodologies for the design of power electronic devices have the following features:

1. They are based on dependencies that are obtained for quasi-steady mode operation; usually only the first harmonic of the source variables is taken into account.
2. The design algorithms used are linear, and in the case of the non-fulfillment of any of the requirements of the assignment or limitation, it is necessary to start the entire design procedure from the beginning, making a correction of the initial values of any of the parameters. Very often, there is no direct relationship in an explicit form between the values of the design parameters and the set constraints.
3. It is not possible to assess the influence of the tolerances of the circuit elements, the change in the load, the parameters of the working environment and the non-linearities of the elements on the operating mode of the device.
4. When choosing the values of the parameters of the power electronic device and operating modes, their influence on the dynamics of the system is not taken into account. The use of such evaluation is an effective approach to develop power electronic devices with improved dynamic performance and robust properties with respect to perturbations—changes in the parameters of the building blocks and external influences.
5. There is no assessment of the impact of the design on the life cycle of the product and the environment, and also no data from the operation of similar devices are used in the design.

6.1. Formalization of the Design Task

Due to the very wide scope of application of power electronic devices, they have an extremely large range of technical parameters: for powers from several watts to several thousand megawatts, voltages from several volts to hundreds of kilovolts and operating frequencies from 50 Hz to several hundred MHz. Different topologies are used and also different operating modes depending on the field of application. In this regard, it is necessary to use a unified approach for model-based design, which summarizes all the possible options for the purpose of the algorithmization and automation of the process. The formalization of the design task in power electronics requires the application of a structured approach that covers several key steps to ensure that the designed device or system meets the set requirements and standards. This process is divided into several main stages:

1. Defining the requirements and objectives of the project;

In this stage, based on the specification of the required power and energy, according to the application, the following are determined: output power, input and output voltages, frequencies, and currents; the maximum allowable power loss and target efficiency of the device; the environmental conditions in which the device will operate, including temperature, humidity and mechanical effects; and regulatory and safety requirements, and compliance with local and international standards and norms, including environmental ones.

2. Selection of appropriate topology, components and technologies;

This includes the choice of the appropriate topology and structure of the power scheme (application or not of modular structures), power semiconductor elements, control electronics and protections (drivers and controllers) and passive components (magnetic components, capacitors and resistors) that meet the requirements for power, efficiency, reliability, and environmental footprint.

3. Schematic and layout design;

This includes the schematic design to develop a circuit diagram that meets the set requirements and PCB design, including the component layout and path routing to minimize losses and electromagnetic interference.

4. Simulation and analysis;

In this stage, by means of various simulation tools, an analysis of the behavior of the scheme under different conditions is carried out as well as of the efficiency and thermal regime to ensure adequate cooling.

5. Prototyping and testing;

This part includes making a working prototype based on the designed circuits and PCB and performing various tests to check the functionality, efficiency and safety of the prototype in different operating modes.

6. Device design iterations and finalization.

This stage is composed of the following sub-stages: analysis of the test results and identification of problems; making the necessary adjustments and optimizations to the design; and verification of the final optimized design for compliance with all requirements and standards.

The design formalization in power electronics is a cyclical process that typically requires several iterations of design and testing to reach the desired result. The key to a successful project is careful planning and detailed precision at each stage of the process, as well as the use of artificial intelligence techniques to leverage the results of the work on previous projects.

6.2. Problem Statement for Model-Based, Life-Cycle-Oriented Design

The choice of scheme and building elements of a certain type of converter is made depending on the field of application. So, for example, for a consumer inverter, price is important, for a power electronic device in electric cars, efficiency and weight are important, etc. [48].

When designing power electronic devices, the following system of criteria is proposed:

1. Efficiency—this is determined by the losses in the device, which are directly related to the thermal conditions of the building elements— E ;
2. Volume/weight/dimensions—this criterion/restriction is important when developing devices with an application in transport and is essential for aircraft— M ;
3. Price—this is determining for power electronic devices with mass application, for example household electrical appliances— P ;
4. Functional characteristics—these are related to equipment used in industry, scientific research, telecommunications, energy, etc.— C ;
5. Reliability—this is a main criterion/limitation for power electronic devices in medicine, aviation and space, military affairs, etc.— R .
6. Ecological footprint—this is an additional criterion related to the ecological footprint of the components used in power electronics— G .

In this aspect, it is clear that it is not possible for all the above criteria to assume a minimum/maximum value at the same time. With the accepted statement that the quality of the product is evaluated according to several criteria, the use of multi-criteria optimization according to the Pareto method is proposed. The Pareto-optimal points (values of the elements) form a set—a set of the best or efficient points that meet the criteria, according to the imposed constraints. In such a setting, the task is undefined, and it is necessary to choose one of the solutions, i.e., the task is reduced to choosing a certain option, which is determined by the decision maker (designer/manager).

The label is entered as:

$$F \in \{E, M, P, C, R, G\} \quad (1)$$

i.e., the criterion in the optimal design can be any of the above or a combination of them, and X denotes the vector of parameters to be determined (values of capacities, inductances, switching frequencies, etc.), and vector X must be found such that:

$$\begin{aligned} F(X) &\rightarrow \text{extr} \\ \text{extr} &\in \{\min, \max\} \end{aligned} \quad (2)$$

For the different criteria, this will be min if the volume/weight/mass or cost and max if efficiency or reliability is used. When designing according to the criterion of functional characteristics, we may have both cases—for example, minimum pulsations, minimum sensitivity in relation to changes in the parameters of power electronic devices or preservation of functionality at maximum overload.

Figure 10 shows the concept of the model-based life-cycle-oriented design of power electronic devices. The main structural elements ensuring the functioning of this system are the databases for the following: the structures of power electronic devices; building blocks; control algorithms and controllers of power electronic devices; numerical methods; information about exploitation; and procedures for implementing various design algorithms. At the center of the concept is the power electronic device or system to be designed. The design should take into account the requirements and characteristics of the load, as well as the capabilities of the input power source. In addition, various technical, economic and environmental demands, standards and constraints related to the design should be added.

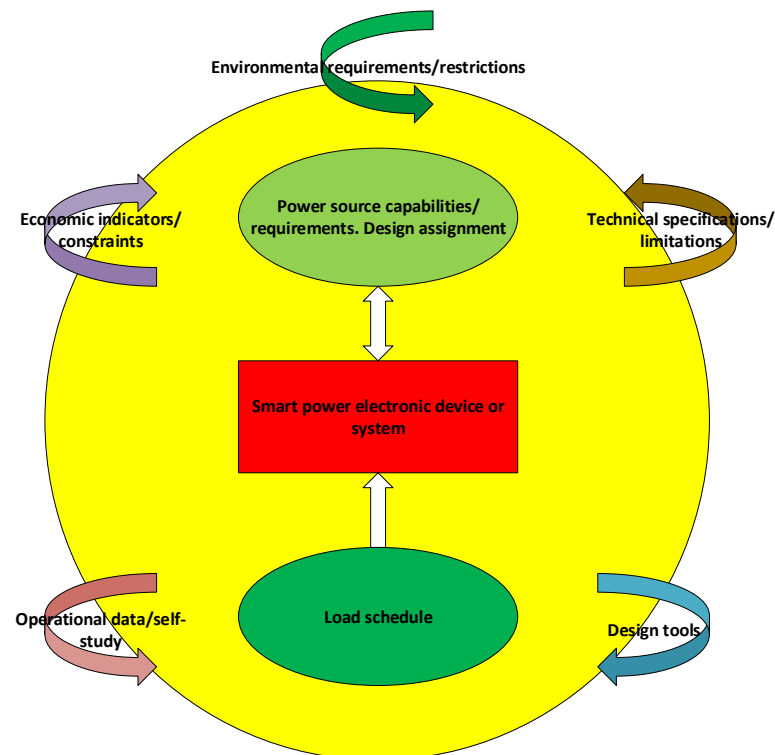


Figure 10. Concept of the model-based life-cycle-oriented design of power electronic devices.

Since the design, in addition to the search for minimum compatibility and satisfying the constraints of the assignment, is related to the very functioning of the powerful electronic devices, the design task is formulated in several variants:

Option 1

$$F(X) \rightarrow \min \quad (3)$$

$$\begin{aligned} K(X) &\leq 0 \\ H(X) &= 0 \end{aligned} \quad (4)$$

or

Option 2

$$\begin{aligned} F(X) &< \bar{U} \\ K(X) &\leq 0 \\ H(X) &= 0 \end{aligned} \quad (5)$$

where:

X —vector of the required parameters (values of the building elements, operating frequency, etc.) and fifth design;

K, H —vector functions of the constraints;

$\bar{U}$ is the upper limit of the minimum value of the solution.

We define:

The feasible region S is the set of determinable parameters for which constraints (4) or (5) are satisfied.

An estimate of the upper limit of $F(X)$ can in many cases be obtained very easily based on physical/technical constraints or by expert judgment. For example, the efficiency of the penalty cannot be greater than one, and the price for a specific power electronic device cannot be greater than that established on the market.

If it is assumed that criterion (3) is positive, then $U \in [0, \bar{U}]$, i.e., the solution U of the problem belongs to the interval from zero to the upper bound $\bar{U}$. Then, by a one-dimensional search, when changing in the set interval, its minimum value can be found, which satisfies the system of inequalities (3).

During the operation of power electronic devices in real conditions, under the influence of various factors, the parameters of the elements making up the device change, which is a consequence of the change in the load, the supply voltage and the parameters of the building elements. These changes are also due to the influence of the environment, the aging process of elements, etc. In the used methods with consistent selection of the parameters, these factors are not taken into account during the design. By introducing additional restrictions in system (3) or (5), it is possible to build power electronic devices with characteristics that take into account these restrictions, as well as additional ones introduced such as the environmental impact. The use of this approach requires the designer to have significantly more information about possible parameter variations, operating modes, environmental influences, exploitation data and about the effects of the elements on the environment. On the other hand, imposing too strong restrictions often leads to the impossibility of finding a solution.

6.3. Algorithm for Designing DC-DC Converters

In this part, an example algorithm for realizing the model-based life-cycle-oriented design of DC-DC converters is considered. The algorithm is based on the classic schemes of DC-DC converters without galvanic separation: Buck, Boost, Buck-Boost. The optimum values of filter elements L and C are sought.

1. Selection of the topology of the designed DC-DC converter according to the task.
2. Setting the parameter i (i —number of power schemes to be evaluated) and admissible areas where solutions meeting the conditions for optimization will be found.
3. Each filter element (capacitor or inductance) is described as a structure of the following type:
 - L_{ij1}, C_{ij1} —nominal value of the element;
 - L_{ij2}, C_{ij2} —tolerance of the nominal value;
 - L_{ij3}, C_{ij3} —maximum allowable voltage on the element;
 - L_{ij4}, C_{ij4} —active resistance of the capacitor/inductance series replacement circuit;
 - L_{ij5}, C_{ij5} —maximum permissible dissipated power/effective value of the maximum continuous current in the element;
 - L_{ij6}, C_{ij6} —in the presence of relevant data, a coefficient reflecting the ecological footprint of the element.

In the above notations, the first index i is for the sequence number of the scheme to which it refers, the second index is the number of the element in the group for the corresponding scheme, and the third index is the pledge characteristics of the element used for the needs of the design. The second index j is changed so that $j \in [1, n_i]$, where n_i is the number of circuit elements for the corresponding designed circuit.

4. Schematic elements are selected so that the conditions $[L_{ij1}, C_{ij1}] \in M_i$ are met, where M_i are the sets of available filter elements used in the design (according to the data from manufacturing companies);
5. The switching frequency of the power circuit is set or selected based on structural considerations.
6. By solving Equations (3) or (4), the quasi-steady modes of the device are found, from which the maximum voltages on the elements and the dissipated powers/effective values of the currents are determined. The elements for which the constraints on voltage and dissipated power/current are not fulfilled are removed from the sets M_i .

Two options as follows are possible if:

1. The region does not exist, then either the constraints introduced by (4) and (5) are weakened or it is passed to step 3 and new pairs of elements are selected.
2. There are several solutions in the domain S_i , then additional restrictions are imposed until only one unified pair of filter elements remains in it.

7. Discussion and Conclusions

An essential element of MBD is the construction and maintenance of databases for the topologies, mathematical models for each of the structures, and for the impact of the environment, information from exploitation and artificial intelligence techniques with a developed interface for connection between the user and the computer. This framework essentially constitutes the model-based, life-cycle-oriented design.

The advantages of the model-based design of power electronic devices are as follows:

- Efficiency and time and resources saving: it minimizes the need for multiple physical prototypes.
- Increase in quality and reliability: it allows the detailed analysis and testing of products before their production.
- Design flexibility: it facilitates the ability to make rapid design changes and adapt to new requirements.

Challenges to MBD of power electronic devices are as follows:

- Need for specialized software and highly qualified personnel with specific skills: the effective use of MBD requires specialized software and the training of engineers.
- Complexity of models: creating accurate and reliable models can be time-consuming and require considerable effort and expertise, although there are currently many developed models, both open access and commercial, of building blocks, devices, controllers and more as well as the construction and maintenance of databases for the topologies, mathematical models for each of the structures, and for the impact of the environment, information from exploitation and artificial intelligence techniques with a developed interface for connection between the user and the computer. This framework essentially constitutes the model-based, life-cycle-oriented design.

A model-based, life-cycle-oriented design offers a revolutionary approach to the development of power electronic devices, promising significant improvements in the efficiency, quality and sustainability of manufacturing processes. In this aspect, the use of artificial intelligence techniques for the automated optimization of the design of power electronic devices leads to finding more efficient, ecological and more economical solutions that meet the specific requirements of the project.

The innovative control of power electronic devices and systems plays a key role in achieving energy efficiency, reduced carbon dioxide emissions and a more reliable energy

infrastructure. These innovations are important for the future of the energy industry and are aimed at a more sustainable and intelligent energy sector.

Smart electronic converters are devices that perform the conversion of electrical signals from one form to another, while using advanced technologies and algorithms to more efficiently, reliably and intelligently manage this process. They are used in various areas of the power industry and are key to improving energy efficiency, and the integration of renewable energy sources and smart grids. Smart electronic converters are essential for modern power systems that strive for the greater efficiency, sustainability and smart management of energy resources. They are used in a wide range of industries and are expected to continue to evolve and innovate in the future.

The key role of power electronic devices for the realization of a sustainable and neutral energy transition to a carbon and hydrogen-neutral economy poses new challenges to designers in the field of power electronics. This is very well synthesized in the title of one of the key papers on the topic “efficiency is not enough”—that is, when designing power electronic devices and systems, not only technical, but also economic and environmental indicators should be taken into account, and not only during operation, but also throughout the life cycle of the product. The implementation of such a complex design process is not possible without the joint application of modern means of computational mathematics, modeling, AI techniques, and information and communication technologies. One possible solution is the application of MBD of power electronic devices, oriented towards the product life cycle. This concept combines classical design methods based on analysis in the quasi-steady mode, which serves to determine the initial values of the circuit elements, with which a series of numerical experiments with the device model is carried out over specified ranges of their changes. After that, an analysis of the obtained results and a selection of those that satisfy the pre-optimum task are carried out. This process is repeated until a unique combination of values and device parameters is obtained that is in accordance with the assignment. If such a combination of values and parameters of the device is not found, one/some of the limitations laid down in the design are weakened. New materials and wideband semiconductors are the future of the power electronics component base. Their combination with operational data and AI will result in power electronic devices with improved characteristics and guaranteed performance with a minimal ecological footprint on the environment.

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