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Editorial

High-Efficiency and High-Performance Power Electronics for Power Grids and Electrical Drives

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1. Introduction

Since the invention of the light bulb by T. A. Edison, the use of electricity has kept growing during the recent century. In fact, electrical energy is the most versatile among the various forms of energy. It can be easily generated, transmitted across long distances, distributed as AC or DC, and converted into other forms with high efficiency to be used on demand or stored for later use. In particular, power electronics is the enabling technology that allowed for the transition from rotating to static power conversion, thus radically transforming how we condition electrical energy in stationary and non-stationary applications. Currently, power electronic converters are available in many variants, each with pros and cons. They generally exhibit good efficiency, dynamic performance, and reliability, especially when they supply passive loads. The most recent power electronic converters are very sophisticated and cover different application domains: from grid-connected inverters for renewable energy sources (RESs) to optimal power flow controllers for microgrids under the supervision of an energy management system (EMS); from high-dynamics variable speed electrical drives (VSDs) for industrial applications to smart and efficient drives for e-mobility; and from wireless charging of electric vehicles to bidirectional converters for the integration of energy storage systems (ESSs) into AC or DC microgrids.

Although such applications have been successfully deployed, the urge for a sustainable future requires further performance increase in terms of efficiency, power density, power quality, cost, robustness to faults, as well as stable operation and high dynamic performance in several operating conditions. These results can be obtained by leveraging different approaches. For example, wide bandgap power devices such as silicon carbide (SiC) or gallium nitride (GaN) allow for faster dynamics, reduced power loss, and increased power density. In addition, advanced converter topologies such as multilevel/multiphase converters or partial power converters can also offer several benefits. The first can improve power quality and can reach higher power levels through modular design; the others allow for processing only a fraction of load power, thus achieving increased power density and, again, higher power levels.

Moreover, it is also possible to take advantage of innovative control techniques. For example, electrical loss minimization (ELM) techniques can reduce losses for a given load power, whereas maximum torque per ampere (MTPA) techniques for electrical drives can reduce the current needed to obtain a given load torque level. As a result, both techniques lead to increased efficiency; in addition, MTPA improves the dynamic performance.

Based on these premises, this Special Issue was launched to gather technical and scientific contributions on various techniques aimed at improving the efficiency and performance in power electronics applications for power grids and electrical drives. The Guest Editor of this Special Issue was pleased to observe a positive response from the scientific community, which contributed ten high-quality articles. Such a response confirms the importance of the subject and the need for investigating new solutions in this field. The articles published in this Special Issue contribute to expanding the scientific knowledge in the field of power electronics and will be briefly reviewed in the following section.

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2. Overview of the Contributions in This Special Issue

This Special Issue includes ten contributions on various techniques aimed at improving the efficiency and performance in power electronics applications for power grids and electrical drives [1–10]. Such articles were authored by international research teams from several countries and covered different topics. For the reader's convenience, they were grouped into three categories:

(a) Power converters used to interface RESs and ESSs with microgrids [1,3,5,7,8,10] or to recharge ESSs in electric vehicles [9];
(b) Performance increase in VSDs and direct online induction motors [4,6];
(c) Application of electrical loss minimization techniques to microgrids based on RESs [2].

In the following, after a short description of each contribution, some perspectives for future developments are briefly given.

As for category (a), the first three contributions deal with multilevel converters. The study presented in [1] by Wang et al. is focused on modular multilevel converters (MMC). Although such converters are well-suited for high-power and medium-voltage applications, they exhibit a quite complex topology based on several submodules (SMs). Therefore, their performance can be affected by SM failures, leading to unequal power distribution and undesirable internal dynamics. Wang et al. [1] studied the impact of SM failures on the MMC internal dynamics performance and proposed two implementations of auxiliary controllers that can regulate such dynamics. The performance of the presented techniques was assessed using time-domain simulations and through experiments. In general, the authors found that appropriate control countermeasures can minimize the adverse impact of SM failures in terms of control range, power quality on the AC and DC sides, and distribution of voltage stress across the SM capacitors and semiconductor switches. Furthermore, they presented the trade-offs of the two proposed control methods. The first control scheme is better than the second from the AC side viewpoint but pollutes the DC current with a fundamental frequency ripple. In contrast, the second scheme is better than the other from the DC side viewpoint; nevertheless, it increases the risk of DC injection into the AC grid and reduces the AC control range. Future development could be devoted to devising control strategies that can improve the performance on both the DC and AC sides without trade-offs.

In [3], Di Benedetto et al. designed two multilevel converters that exhibited high efficiency and power density, as required for microgrid applications, as well as good performance in terms of quality of voltage and current waveforms using only silicon power semiconductors. In particular, the paper focused on a three-phase five-level E-type multilevel–multicell rectifier (3Φ5L E-Type MMR) and a three-phase five-level E-type multilevel–multicell inverter (3Φ5L E-Type MMI). The E-type topology was chosen because it allows for implementing an interleaved configuration using an intercell transformer, thus reducing the volume of the output filter. First, the proposed hardware design and control strategy were validated by simulations. Then, a prototypal 3Φ5L E-Type MMR plus 3Φ5L E-Type MMI was built using silicon MOSFETs or IGBTs switching at 20 kHz, and its performance was assessed experimentally. The results obtained showed excellent performance. The THDv and THDi were 0.88% and 1.95%, respectively. Furthermore, the converter exhibited a peak efficiency of nearly 99% using only silicon power semiconductors, a power density of 8.4 kW/dm^3, and specific power of 3.24 kW/kg. In comparison, a similar SiC-based converter proposed by another author exhibited the following figures of merit: 99.2%, 1.4 kW/dm^3, and 2.5 kW/kg; furthermore, another SiC-based converter proposed in the technical literature exhibited 99.26% efficiency and a power density of 4 kW/dm^3. This comparison shows that remarkable results can be obtained using an appropriate topology, even without using wide-bandgap devices. On the one hand, this concept could also be applied to other converter topologies. On the other hand, the performance of the converter proposed in [3] could have been even higher if SiC devices had been used.

Another contribution about multilevel converters was given by Foti et al. [5]. The authors presented a multi-input N-level power converter topology for grid-connected applications, which can perform independent management of N-1 power sources and an ESS without requiring additional DC–DC power converters. The proposed topology encompasses a three-phase neutral point clamped multilevel inverter (MLI), a three-phase transformer in an open-end winding configuration, and a conventional two-level inverter (TLI). The MLI can interface several DC sources such as photovoltaic (PV) modules and wind energy conversion systems with rectified output, providing active power to the grid. It operates at a low switching frequency (<1 kHz), thus featuring low switching power losses. The TLI is operated at a higher switching frequency but with a lower DC bus voltage, and its DC port can be connected to a bulk capacitor or an ESS. The TLI works as an active filter to compensate for the low-order harmonics generated by the MLI and for imbalances among the source voltages, provided that they do not exceed the DC bus voltage. The proposed topology reduces the complexity and cost of a multi-input power converter. Moreover, it exhibits reduced losses and lower switch count with the same power quality level. Both features contribute to increasing the efficiency and the power density of the converter. The validity of such a concept was confirmed first theoretically and then by simulations and experimental tests. Even when the N-1 input voltages were imbalanced, the THD was as low as 1.5%. Furthermore, the peak efficiency of the converter reached a maximum value of 95%. In future work, it could be interesting to apply the proposed concept to other application domains, such as electric vehicles and the aerospace industry.

Other contributions that fall into category (a) are [7,8] by Luna et al. These papers were focused on the use of bidirectional DC–DC converters to integrate an ESS into a DC microgrid, ensuring stable operation and good dynamic performance. The authors showed that this integration deserves careful design because the ESS converter is required to work in different scenarios depending on the microgrid configuration. They chose the Split-Pi converter as a case study because it presents several merits at the only cost of non-isolated operation; however, the proposed approach has general validity. In [7], the authors analyzed the five possible operating scenarios, showing how to model the equivalent load of the ESS converter, and devised the state-space model of the ESS converter supplying such a load. Each scenario requires a different control scheme with reference to the number of control loops and the controller design procedure to obtain high performance. Proportional-integral-derivative (PID) controllers were employed, and the related design criteria were given. Then, in [8], the authors validated the theoretical analysis presented in [7] by performing several simulations and experimental tests. Future development of this work could be devoted to designing unconventional control systems for ESS converters suitable for operating in more than one microgrid scenario or, possibly, in all the scenarios.

The main objective of the work by Aouichak et al. was to present and experimentally validate a bidirectional DC–AC converter for ESSs, connected to the AC grid and operated under the supervision of a smart home electricity management system (HEMS) to reduce the cost of electricity [10]. The proposed converter can operate in both grid-connected and off-grid modes. It is based on two cascaded bidirectional stages and can generate a full sinusoidal wave from a sinusoidal half wave thanks to the high performance of wide bandgap devices. First, a modified half-bridge DC–DC stage regulates the DC voltage and establishes the positive half of the AC waveform; such a stage is based on two SiC power MOSFETs controlled at a high frequency (150 kHz). Then, an H-bridge DC–AC stage periodically reverses such a waveform; this stage is composed of four MOSFETs on a silicon substrate, controlled at line frequency (50 Hz). The converter was validated experimentally in inverter mode and in rectifier mode with power factor correction (PFC). The use of SiC switches combined with appropriate control strategies allowed for an increase in the compactness of the converter while ensuring good performance, especially in terms of efficiency, which exceeded 95% over the entire power range from 100 W to 1.5 kW. The main advantages of the proposed converter are twofold: (1) it is based on a reasonably complex topology and, thus, can be recommended as an alternative solution for HEMS applications; (2) in stand-alone operations, it does not require a bulky output filter, so it is more compact than a traditional H-bridge inverter. Future development could be focused on analyzing the electromagnetic compatibility aspects related to the high switching frequency to ensure a safe connection to the AC grid.

The last contribution falling into category (a) is the one by Madzharov et al. and discusses the application of the energy dosing technique to improve the performance of a charging station for electric vehicles based on a resonant DC–DC converter [9]. The proposed converter comprises a half-bridge resonant inverter with energy dosing (RI with ED) without reverse diodes, a high-frequency matching transformer, and an output rectifier with a capacitive filter. The switching devices operate with zero current switching (ZCS) and zero voltage switching (ZVS). The main advantage of the energy dosing schemes is that the power does not depend on the load resistance value but is a function of the operating frequency, the resonant capacitance, and the supply voltage. Therefore, the power transferred to the vehicle can be kept constant despite variations in the magnetic coupling coefficient during stops and driving. The characteristics of the RI with ED were compared with two other competing schemes often used in charging stations as high-frequency sources. The proposed converter presents a higher intrinsic regulation capability because the frequency variation required to maintain the nominal power against load variation is lower. A further extension of this work could include optimizing the component size to achieve different goals, such as minimum losses, maximum efficiency, and minimum weight and volume.

The two contributions that fall into category (b) focused on performance increases in VSDs and direct online induction motors (DOL-IMs). In [4], Di Benedetto et al. focused on implementing a high-performance power conversion system to reduce overvoltage in VSDs supplied by SiC-based inverters using long power cables. In particular, a three-phase two-level inverter with snubber circuits based on capacitors and diodes was investigated, designed, and tested to mitigate the overvoltage without sacrificing the conversion efficiency. Furthermore, an additional circuit was used to recover the energy from the snubbers avoiding increased losses. The proposed analysis was validated through experimental tests performed on a prototypal converter. The experimental results showed that, in the absence of the snubbers, the voltage at the motor terminals could reach twice the DC bus voltage when the cable length was equal to 15 m or 30 m: using a 400 V DC bus, the peak voltage at the motor side was 845 V, and the dV/dt was 9.95 V/ns. Instead, the proposed converter reduced the dV/dt to 1.47 V/ns and limited the overvoltage to 562 V. The power density was much higher than that for classical solutions such as the three-phase two-level inverter complemented by a bulky passive filter. The only drawback was a slight reduction in the conversion efficiency (0.976% against 0.982%). The proposed technique is promising, but further work should be devoted to finding a good compromise between the efficiency, dV/dt, and overvoltage of the entire electrical drive system.

In [6], Tornello et al. presented a technique to improve the performance of induction motors by exploiting an auxiliary winding set supplied by a partial power inverter. In fact, three-phase DOL-IMs are the most dominant solution in the industrial sector, providing a variety of constant speed and variable load applications where dynamic requirements are not critical. However, they exhibit a low power factor at partial loads, which is mitigated by adding suitable capacitors; moreover, a significant in-rush current is generated at start-up, leading to voltage dips, speed losses, torque pulsations, and possible activation of protection devices. In such applications, the additional cost implied by a VSD with a full-size inverter is not justified. However, the authors of [6] showed that it is possible to compromise cost and performance by using an auxiliary winding and a partial power inverter. The auxiliary winding features fewer turns than the main one and thus has lower voltage and power ratings. If suitably controlled by an inverter sized for a fraction of the motor's rated power and supplied through a floating capacitor, it allows for the following advantages to be obtained: (1) the machine power factor and, thus the efficiency, can be increased; (2) torque oscillations produced by the mechanical load or by distorted grid voltages can be mitigated; and (3) grid current peaks at motor start-up can be mitigated as well. The proposed technique was assessed by simulating a machine with a turn ratio of five. The results obtained showed that the power handled by the auxiliary winding and the inverter in the worst-case scenario was roughly one-fifth of the machine's rated power. Given that the inrush current mitigation depends on the capacitance of the floating capacitor, future extensions of this study could be focused on finding alternative approaches, such as performing the start-up at a higher DC-bus voltage to increase the energy stored in the floating capacitor.

Lastly, regarding category (c), Kumar et al. applied an ELM technique to a microgrid with power converters interfacing RESs such as solar photovoltaics (SPV) and wind turbine generators (WTG), as well as battery storage systems (BSSs) [2]. The authors' goal was to minimize the detrimental effect of active and reactive power losses in the microgrid to exploit the full potential of green energy generation and use. First, the optimal locations for accommodating the distributed generators (DGs) were obtained by considering two specific indices. Then, an optimization problem was formulated to perform the optimal sizing of the DGs for achieving the ELM. The problem was solved using a constriction factor-based particle swarm optimization (CF-PSO) technique, which has overtaken many algorithms, including the genetic algorithms (GA). Finally, a reliability analysis (RA) of the microgrid was performed by evaluating five indices and using the optimal location and sizing of the RESs and BSSs. The outcomes of the study showed an enhancement in the electrical loss minimization and an improvement in the bus voltage profile compared with a system without DGs. In addition, the RA was repeated considering the uncertainties in the reliability data of the SPV and WTG interfaced by power converters, including the failure rate and the time to repair. It was shown that the microgrid's reliability significantly improved by considering the reliability data of the optimally integrated DGs. Some perspectives for future developments include the extension of the analysis to include aspects such as CO_2 emissions, economics, system protection and reconfiguration, and system security.

3. Conclusions

This Special Issue is composed of ten papers that presented various techniques aimed at improving the efficiency and performance of power electronics applications in power grids and electrical drives. The contributions provided offer valuable insights into the recent developments in such a field. The Guest Editor briefly summarized each contribution and highlighted some perspectives for future developments. It is hoped that the proposed techniques will soon be implemented in the energy industry and further improved.

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