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Editorial

The Recent Development of Power Electronics and AC Machine Drive Systems

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Abstract: Currently, power electronics and AC machine drive systems are employed in numerous areas, such as in industrial processes, consumer electronics, electric vehicles (EVs), renewable-energy-source (RES)-based distributed generation (DG) systems, and electric power generation systems. As RESs such as wind and solar are attracting relatively more attention due to environmental issues caused by fossil fuel use, various RESs have been integrated into the utility grid (UG) as DG systems. As a result, the concept of a microgrid (MG), which constructs an electrical power system with DGs, energy storage systems (ESSs), and loads, has emerged. Recently, the DG-based MG has been regarded as a promising and flexible technology for those involved in constructing electric power systems. This article presents future technology and recent developments in applied power electronics. In this Special Issue, "The Recent Development of Power Electronics and AC Machine Drive Systems", four papers were published highlighting recent developments in this field. In addition, other topics beyond the coverage of the published articles are highlighted by a guest editor to address other trends and future topics related to the Special Issue. Through an in-depth investigation of recent development trends, this article seeks to encourage related studies in power electronics.

Keywords: AC/DC microgrid; distributed generation; grid-connected inverters; optimization of a power system; power electronics; renewable energy source; robust control of a power electronic converter

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1. Introduction

Over the last few decades, the demand for electronic devices and systems has increased significantly, mainly due to population and economic growth [1]. As a result, the development of power electronics and AC machine drives is increasing in many areas, such as industrial processes, consumer electronics, electric vehicles, renewable-energy-source (RES)-based distributed generation (DG) systems, and electric power generation [2,3]. On the other hand, introducing power generation based on RESs has become an important topic in the power system field, given that the excessive use of fossil fuels has contributed to global warming [4].

Several RESs, such as wind turbines, hydropower, and photovoltaic sources, are integrated into a DG system [5]. DG has been broadly developed as a potential solution to replace conventional fossil energy resources [6]. In addition to low pollution, DG is more flexible and efficient in development than conventional power plants [7]. To optimize the utilization of power supplied by RES-based DG, the installation of an energy storage system (ESS) is required to compensate for the intermittency of RESs [8]. However, interconnections among several power units, such as power sources, energy storages, and loads, are becoming challenging because each power system has different frequencies and voltages [9]. As a result, the concept of a microgrid (MG), which integrates several power systems, has emerged.

Generally, the MG concept has been introduced to connect several power units to a bus bar to exchange power among the electrical power units [10]. A bus bar can be used in either a DC system, referred to as a DC microgrid (DCMG), or in an AC system, called an AC microgrid (ACMG). According to the coordinating control strategy of the MG to achieve power sharing, MG control can be classified into three types: centralized control, distributed control, and decentralized control [11]. To optimize power-sharing, coordinating control should provide several energy management systems (EMSs) to overcome several uncertainties, including electricity prices, electric vehicle (EV) connections, and grid availability [12–14].

As an interface between MG and the utility grid (UG), a voltage source inverter plays an important role because most MG systems work in the grid-connected mode. As each power unit has a different voltage, the inverter is the key element in the microgrid to improve the quality and stability of the exchanged power among the power units, especially in the UG. Commonly, in grid-connected inverters (GCIs), an inductive–capacitive–inductive (LCL) filter is widely used as a filter to attenuate high-frequency harmonics caused by the pulse width modulation (PWM) switching frequency [15]. However, the complicated dynamics of LCL filters in an inverter system commonly lead to resonance behavior, which can affect the system's stability [16].

On the other hand, instead of focusing on the system's stability, studies of methods to increase the flexibility of renewable energy have also attracted much attention. In addition, there have been efforts to expand the use of renewable energy sources by reducing the system cost and hardware complexity. One potential solution is to reduce the number of hardware components by replacing possible hardware-based sensors with software-based ones [17]. If the use of hardware is minimized in the GCI configuration, DG systems may become much simpler and more economical. Moreover, the reliability of GCI systems is also increasing as these systems require less maintenance.

This Special Issue, entitled "The Recent Development of Power Electronics and AC Machine Drive Systems", aims to present most of the aforementioned advances related to recent developments in this field. The entire set of topics of interest for publication in the Special Issue is summarized below.

- Power conversion of renewable energy;
- System structure of an AC/DC microgrid;
- Integration of the vehicle-to-grid issue;
- Digital control of an AC machine drive system;
- Design of a DSP-based digital controller;
- Robust or adaptive control of a power electronic converter;
- Optimization of the converter system.

This publication is organized into four sections: Section 2 highlights the research trends and future developments related to the issue of power electronics and AC machine drive systems. Section 3 presents a short review of the contributions thus far for this Special Issue. Finally, a summary of the work is given in Section 4.

2. Research Trends and Future Developments

The topics addressed in the articles included in this Special Issue reflect some current trends in the power electronics field. By narrowing down the field to better classify the articles presented, they can be framed within the following two main application topics:

- Control of power electronic converters;
- Integration of multiple agent systems in a microgrid.

The following subsections describe and specify the role of every article in advancing the state of the art concerning the corresponding topics.

2.1. Control of a Power Electronic Converter

RESs from solar and wind play a key role in gradually replacing conventional energy sources such as fossil fuels. High reliability and high efficiency of the power electronics interface are crucial when converting electric power to ensure the sustainability of a renewable energy system. Special attention has been paid to investigations of the main challenges to integrating RESs into the main UG in several studies [6,15,18–21]. The major issues considered in those research works are listed below.

- Attenuation of the current harmonics caused by the PWM switching frequency;
- External disturbances from the main grid, including low-order distorted harmonics, grid frequency variations, and weak grid conditions;
- Internal uncertainties caused by aging or environmental factors, which impact the nominal parameters and performance of the power electronics components;
- Potential instability of an actual conversion system;
- Low-cost solutions for the conversion system.

To attenuate the current harmonics caused by the PWM switching frequency, LCL-type filters are more attractive due to their smaller physical size and better harmonic-attenuation capabilities. However, a third-order LCL filter introduces a resonant peak into the system, which may cause output resonance.

To ensure the stable and reliable operation of the converter system, several studies [17,22] focused on a three-phase GCI system and an active damping strategy based on an LCL filter. The mathematical model of a three-phase GCI based on an LCL filter in the synchronous reference frame (SRF) was established preliminarily, after which a full-state feedback controller was discussed for active damping. However, these controllers [17,22] cannot compensate for external disturbances from the main grid, including low-order distorted harmonics, grid frequency variations, and weak grid conditions. To offset external disturbances from weak grid conditions, one study [23] presents a hybrid damping method that combines passive damping and active damping. Passive losses, the effects of capacitor resistances, and robustness against grid impedance variations have all been addressed. As a result, the resonant frequency and the Q-factor of the capacitor resistor can easily be calculated.

On the other hand, other works [21,24] present an active damping method for robust current control of GCIs with LCL filters affected by inductor magnetic soft-saturation, uncertain grid impedances, grid frequency variations, and low-order distorted harmonics. One of these studies [24] presents a controller designed in the SRF of a GCI system with a linear-quadratic-regulator (LQR)-based current controller. This control method was constructed using the internal model principle in the SRF to augment integral and resonant states into a state feedback control. As a result, the control scheme successfully produces high-quality injected currents without negative effects from the LCL filter resonant phenomenon or distorted grid voltages. In another work [21], the authors present the contribution of a systematic procedure for the robust control design of a GCI. First, linear time-varying polytopic models are presented to consider the LCL filter and grid impedance. Second, robust control gain is realized using the linear matrix inequalities approach. The performance of the inverter system is validated under several severe disturbance conditions to prove the stability and robustness of the proposed control scheme.

Besides the stabilization problem of the LCL-filtered inverter system, other disturbance sources caused by filter parameter uncertainties, weak grid conditions, and a non-ideal grid environment should be considered in the inverter controller design process. Robust current controllers in GCI systems should produce high-quality injected currents, even under severe conditions. In the recent literature [5,6,16,19,25,26], the GCI is controlled by a robust control algorithm to realize an effective, flexible, and reliable power conversion system under non-ideal conditions. One of these studies [5] optimally obtains controller gains by solving the linear matrix inequality (LMI) derived from the stability conditions from the Lyapunov theorem. The LMI algorithm is an effective tool to use in designing a controller that considers system uncertainties. This scheme minimizes the effects of parameter uncertainties on the system controller and observer. In other studies [6,26], the researchers devote much attention to the model predictive controller (MPC) due to its superior reference tracking, straightforward concept, and excellent constraint-handling capability. This control scheme is solved online during each sampling period to calculate the optimal control inputs based on the predicted future model. However, the conventional MPC scheme is known to be susceptible to parameter discrepancies, which may degrade the performance. To address this problem, two methods [6,26] combine LMI-based optimization with an MPC to construct an optimal controller that is robust against system parametric uncertainties. These control methods guarantee excellent robust control performance under frequency variations, parameter uncertainties, and grid voltage imbalances. Moreover, to reduce the implementation costs, the full-state observer approach is utilized, which minimizes the required number of sensing devices. In one study [25], the heuristic design of observed-state feedback control is presented to deal with the system uncertainty problem. Owing to the superior features of the presented control schemes, these power conversion systems are expected to be more robust and reliable in the future.

The low-cost factor of renewable electricity is the key driver of the global energy transition from conventional power plants toward sustainable sources. Besides the maximization of renewable energy utilization, energy conversion systems with high performance and low cost have attracted much attention from researchers. One of the potential solutions to reduce the cost of hardware components in the inverter system is to replace all possible hardware-based sensors with software-based counterparts. Several studies of integrating a full-state observer to estimate the system states from limited measured inputs have been published [6,21,24]. As a result, control algorithms are accomplished by using one DC-link voltage sensor and two grid-side current sensors, while the synchronization process between the inverter and the main grid is based on the information from two grid voltage sensors. To reduce the cost and hardware complexity further, several studies [4,15,18–20,27] replaced grid voltage-sensing devices with control algorithms without harming the synchronization process.

One such study [27] combines a full-state feedback observer to estimate the inverter system states and a grid-phase angle estimator to obtain information on the grid voltages. In that study, the entire algorithm is realized by two grid-side current sensors and one DC-link voltage sensor. The system robustness is validated under various test conditions, i.e., a distorted grid, an unbalanced grid, and system parameter uncertainties. In another study [15], the authors present an approach for dealing with both internal and external disturbances that affect the LCL-filtered inverter system. The system's stability is maintained by a proposed control scheme that directly estimates and attenuates lumped disturbances. The study also offers a low-cost inverter system prototype that eliminates sensors for grid voltages, inverter-side currents, and capacitor voltages using a resonant extended state observer. Another paper [18] addresses the problems of non-ideal grid voltage environments, including those with distorted grid voltages, grid frequency variations, and grid-phase angle jumps. That study successfully eliminates the use of grid voltage sensors using a model-based disturbance observer for an LCL-filtered GCI. The evaluation results under several severe test conditions presented in that paper properly prove the stability of the synchronization process even without grid voltage measurements. The frequency-adaption issue was also considered in the control design process to ensure the stability of the inverter at different grid frequencies. Two studies [4,20] present a controller designed in the SRF for a GCI system based on the MPC method. The low-cost factor is considered in the design process by replacing all hardware-based sensors with full-state and disturbance observers. As a result, a control algorithm that reduces both the system cost and hardware complexity is achieved.

2.2. Integration of Multiple Agent Systems in a Microgrid System

The interest and growth over the past few decades in renewable energy have signified MG as a crucial aspect in integrating several power units, such as DG power sources, energy storages, and loads. Specifically, given the increased popularity of EVs, it is of paramount importance that an effective integrating system for MG is realized in the near future. Through in-depth investigations of this issue, several articles have contributed to the development of MG systems [7–14,28]. The main concerns in these studies are listed below.

- Coordination of various power units in MG systems to achieve a power balance;

- Power flow control of MG under various uncertain conditions, including wind power and load demand variations, battery SOC, and grid availability issues;
- Stability and reliability issues of MG systems to maintain the bus bar during various transitions;
- Scalability issue of MG systems;
- Optimal energy management system of MG in grid-connected mode and integration of an EV with consideration of the electricity prices;
- Protection algorithm for the MG system during emergencies.

With the increased numbers of power units such as DGs and ESSs in the overall system, the burden of the MG to manage the power units also increases. To coordinate all power units, MG control strategies can be classified into three types: centralized control, distributed control, and decentralized control.

In the centralized control strategy, several power units are controlled by a central controller through a communication line. This approach has been the topic of several studies [10,28] to ensure a proper system power balance. One study [10] introduces a power flow control strategy (PFCS) to ensure the power balance in a DCMG system. The PFCS determines the control operations of each power unit in the MG system by considering several conditions, such as UG availability, the ESS state-of-charge (SOC) level, and variations in DG power and load demand levels. Moreover, this study also introduces a load-shedding (LS) algorithm to protect the MG system in critical cases, as well as a load-reconnecting (LR) algorithm to reconnect loads that were initially disconnected due to critical cases. However, in spite of the effectiveness of the control strategy to achieve a power balance under various power unit conditions, the centralized control scheme has several drawbacks, such as communication network delays that affect the stability of the system. Another study [28] proposes a robust control strategy to overcome the communication network delay problem in the MG system. The stability of the MG system in the presence of a time delay is guaranteed by selecting an appropriate Lyapunov–Krasovskii function. Moreover, the robustness of the MG system was achieved by a robust $H\infty$ control to handle the disturbance-attenuation criterion. Then, to find the optimum solution, LMI convex optimization with certain constraints is employed. The control performance is verified in a simulation and experiments under load variations and input voltage disturbances in three delay scenarios. The results clearly confirm that the proposed control strategy can feasibly maintain the stability of the DC-link voltage of an MG system.

On the other hand, to avoid single-point failures in the centralized control scheme, distributed control was presented [13]. In the distributed control scheme, each power unit receives the necessary global information by communicating only with its neighboring power unit. The information collected from communication links and sensors is processed in a power converter interface to determine the operating modes of each power unit. In one study [13], distributed control based on a consensus algorithm is proposed. Essentially, the consensus algorithm provides a decision based on the convergence value of the information collected from other power units. Based on the decision, each power unit independently determines the operating modes to maintain the power flow of the bus bar under various conditions of load demand and DG power.

However, in a large-scale system, the use of many communication links may not be economic or practical, as doing so can lead to certain communication delays or failures. To overcome the problem, decentralized control was introduced [7,8]. In these studies, the droop control method is implemented to achieve a power balance and power-sharing without a communication link. Basically, droop control utilizes the behavior of the bus bar to determine the power reference and operating modes of each power unit. For instance, in one study [7], an increase in the DC-link voltage indicates surplus power within the DCMG system. In response to this, droop control automatically reduces the power supply into the DCMG until the DC-link voltage maintains a constant value to prevent a collapse of the DCMG system. Despite the good power-sharing characteristic of droop control, deviation of the DC-link voltage is the main disadvantage of this control method, which affects the power quality delivered to the load. To overcome this limitation, other work [8] proposes a compensator to eliminate the deviation of the DC-link voltage in droop control via a simple approach that greatly improves the performance of the existing decentralized MG system.

Instead of coordinating control strategies, the energy management system has also drawn much attention as part of the effort to minimize operational costs and maximize profits. In one study [9], the electricity price condition is determined by a real-time pricing (RTP) method that consists of two conditions, referred to as the high-cost and low-cost conditions. When the electricity price is in the high-cost condition, the MG minimizes the use of electric power from the UG and supplies the maximum power from DGs and ESSs into the MG. In contrast, in the low-cost condition, the MG maximizes the use of electric power from the UG. To utilize EVs as energy storage units, an EV that can be operated in both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes is taken into consideration for power transfers in other work [14]. An autonomous real-time energy management controller is proposed for use in the MG system to minimize the energy cost at workplaces while providing cost benefits to EV owners to encourage their participation in the workplace.

3. A Review of the Contributions in This Issue

This section discusses the articles published in this Special Issue to provide a quick review and summarize the main contributions clearly. Several control issues for power electronics converters have been presented for applications of GCIs, plug-in electric vehicles, and AC motor drives. This section provides a brief synopsis of these research articles in this journal thus far.

Four research papers presented various applications of power electronics techniques for energy and electric drive systems to enhance stability and performance levels. The first article, "Frequency adaptive current control scheme for a grid-connected inverter without grid voltage sensors based on the gradient steepest descent method" [29], written by T. V. Tran, M. Kim, and K.-H. Kim, presented a frequency-adaptive control scheme for an LCL-filtered inverter system without grid-voltage sensors. This control method ensures high-quality grid-injected currents, even under harmonic distortions and frequency variations of the grid voltages. The stability issue was also addressed in terms of the Lyapunov theory to guarantee the tracking performance of the estimated variables. Comprehensive simulation and the experimental results demonstrated the simplicity and effectiveness of this method against negative effects from the grid, even without grid-voltage sensors.

C. Volosencu published an article entitled "Reducing energy consumption and increasing the performances of AC motor drives using fuzzy PI speed controllers" to reduce the energy consumption in transient states by considering two main AC machines used in practice: induction motors and permanent-magnet synchronous motors [2]. In this study, a speed control structure with a fuzzy PI controller is presented for a vector-controlled asynchronous machine with an indirect orientation and a vector-controlled permanent magnet synchronous machine with an orientation of the rotor flux to address energy efficiency and enhance the quality of regulations. The evaluation results under various test conditions presented in this paper clearly demonstrate that the performance of the fuzzy PI controller for regulating the speed of AC electric motors is superior to that of a linear PI controller. This control algorithm is also more robust to errors when identifying electric machine parameters.

R. Sabzehgar, Y. M. Roshan, and P. Fajri published a research paper entitled "Modeling and control of a multifunctional three-phase converter for bidirectional power flow in plug-in electric vehicles" [12]. To perform multiple functions in electric vehicles (EVs), such as grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes, this paper presents a nonlinear sliding mode control design of a three-phase converter for plug-in electric vehicles (PEVs) with a bidirectional power flow. The stability of the proposed controller is also investigated by defining a proper Lyapunov function. The feasibility and usefulness of this control method were validated through both simulation studies and a hardware-in-the-loop (HIL) experimental testbed. The issue of current harmonic reduction was also considered during charging and discharging operations in this work to prove that the control scheme meets the IEC 61000-3-12 current harmonic limits.

N. Huh, H.-S. Park, M. H. Lee, and J.-M. Kim presented a paper entitled "Hybrid PWM control for regulating the high-speed operation of BLDC motors and expanding the current sensor range of a DC-link single-shunt" for a high-speed brushless DC (BLDC) motor drive system with DC-link single-shunt current measurements [3]. To improve the high-speed control performance and expand the current-sensing range in a high-speed BLDC motor drive system, this study introduced a hybrid PWM control method. Based on an analysis of the operating characteristics of most typical PWM methods for BLDC motors, this paper developed a PWM method suitable for high-speed operations. The developed PWM method was assessed experimentally.

4. Conclusions

As RESs are attracting more attention due to environmental issues, various RESs have been integrated into UGs as DG sources. Hence, power electronics techniques as interface tools are currently employed in numerous areas. This article presents research trends and recent developments in power electronics applied in efforts to construct an electrical power system flexibly and reliably. This Special Issue comprises four papers on current developments in power electronics and AC machine drive systems. Moreover, this article also discusses the trends and future developments related to the Special Issue to highlight the importance of research in the power electronics field. Contributors have shared many valuable insights on recent developments and the future of the field, and the guest editor has briefly summarized the details of each work while also highlighting important aspects, as well as an in-depth literature survey of related fields. The guest editor would like to thank all colleagues and reviewers for their contributions, and it is expected that this article will motivate significant implementations and spur the adoption of power electronics and AC power systems in the energy industry in the near future.

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