Guest Editorial
Design of Energy-Efficient Distributed Power Generation Systems

THE REQUIREMENT for environmentally friendly power generation systems combined with the increased cost of fossil fuels and the growing complexity-size of power grids, has led to new and emerging concepts in the generation, transmission and distribution of power. One of the proposed solutions is by using distributed generation (DG) that employ renewable energy sources (RES). The use of such a concept has dramatically changed the structure of modern power systems where interconnected power electronic converters are extensively used under different interconnection schemes. In order to maximize the benefits of DG, microgrids are employed where various sources and loads can either operate as an isolated island or be connected to the main grid. When equipped with the necessary information technology, a microgrid can be considered to be a local smart grid powered by local sources and storage elements and supplying end-user appliances. Power converters are necessary to connect these local sources to the loads and storage elements or several microgrids together or even to the main power grid. These converters must operate with high efficiency and reliability in a wide operating range of system parameters. For example the occurrence of high current ripple in a converter can greatly deteriorate the performance of a fuel cell or the MPPT controller of a PV panel and can significantly reduce their life time; also it is possible that the converter may suddenly operate in a undesirable high current/voltage area and hence may cause considerable damage to the RES. In interconnected schemes, some converter stages can act for others as a nonlinear load and hence create undesirable destabilizing effects. Traditionally, power converters have been studied as linear systems operating in a small area around the desired point as the dynamic behavior was represented by an averaged model and it was assumed that the input voltage and load variations are small or even negligible. However, using power converters in DG including RES nulls the aforementioned argument as for example a PV panel may provide from full power of several kilowatts during the day to zero power during the night or a local load may arbitrary consumes from zero to a high power value. Hence the converter must operate in a wider area and therefore various nonlinear phenomena can take place. An appropriate functioning of the system is possible only if suitable control strategies are applied to the different components of the distribution network. To implement these strategies, a complete dynamical modeling and analysis of the distributed generation system is required. Therefore it is imperative that these converters are studied in great detail and subsequently properly designed to provide the best possible performances. Furthermore, new converter topologies must be proposed that are capable of tackling the challenging tasks of a power converter operating in DG systems. For example multilevel or multi input converters operating in interleaving operation with advanced control strategies may be often required. Another crucial issue of DG systems is to use network theory (like directed graphs) and hence study their performance and stability not concentrating on each device separately but on the overall microgrid as a whole. This can be beneficiary in order to determine the optimum location operation and design of the aforementioned local sources and loads as well its connection (or not) to the main power grid.

Therefore, this special issue focuses on circuit topologies, dynamics, control aspects, stability analysis, efficiency study and design of power converters for distributed power generation systems and aspects related to control of power systems from a network perspective. We received a total number of 31 submissions. The papers were contributed by researchers from both academia and industry and it was decided to decline some of them, in order to accommodate adequate number of high quality accepted papers. This issue finally features a total number of 17 papers selected through a highly competitive peer-review process. The first nine papers focus on the nonlinear behavior, bifurcation prediction and stability analysis of switched-mode power converter systems.

The first paper is entitled "A Review on Stability Analysis Methods for Switching Mode Power Converters," by El Aroudi *et al.* presents four different methods for analyzing the stability of the fundamental periodic orbit of a switching converter and uncovering the different bifurcation phenomena that can undergo. The main properties of these methods are pointed out and a brief explanation of how they can be used in applications that involve power converters is presented. Finally, the paper ends by describing some of the future challenges that exist in the area of accurate stability analysis of power converters especially when these are employed in distributed generation applications.

The paper entitled, "Bifurcation Analysis and Experimental Study of a Multi-Operating-Mode Photovoltaic-Battery Hybrid Power System," by Xiong *et al.* considers the stand-alone photovoltaic-battery hybrid power system which is studied for illustrating the possible complex scenarios that can take place. Authors reveal slow-scale Neimark-Sacker bifurcation, fast-scale period-doubling bifurcation as well as coexisting solutions. Discrete-time mapping model is used to identify these bifurcation phenomena and evaluate the stability boundaries of the system and experimental validation is provided.

The paper entitled, "Nonlinear Analysis of Interconnected Power Converters: A Case Study," by Benadero *et al.* deals with

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the nonlinear dynamics of interconnected power converters in an islanded direct current DC microgrid is analyzed. The authors analyze the dynamical behavior that can arise from the interconnection of these devices on a common DC bus by using a simplified scheme based on two cascaded converters. They use a sliding mode controller for a DC-DC bidirectional power converter to control the DC bus voltage under constant power loads (CPLs). The authors show that this class of loads introduce a destabilizing nonlinear effect on the converter leading to significant oscillations in the DC bus voltage. Simulation results are shown to illustrate the validity of the nonlinear mathematical analysis.

The paper entitled "Nonlinear Analysis of Discretization Effects in a Digital Current Mode Controlled Boost Converter," by Singha *et al.*, presents an analytical framework to investigate sub-harmonic oscillations in a digitally current mode controlled boost converter. Authors first derive a discrete-time models for multi-sampled current loops and uniform sample with compensating ramp for the system working under continuous conduction mode. Authors show that the discrete-time maps for such systems are discontinuous in nature. Test results from experimental measurements demonstrate close agreement with the mathematical analysis.

The paper entitled "Stability Analysis of Multi-Phase Synchronization in Paralleled Buck Converters with Winner-Take-All and Loser-Take-All Switching Rules," by Ohata and Saito studies paralleled systems of buck converters with two kinds of switching rules. First, the system is controlled by the winner-take-all and current threshold switching rules. The authors show that as parameters vary, the multi-phase synchronization loses stability and the system exhibits chaotic behavior in which unstable multi-phase synchronization is embedded. Second, the system is controlled by winner-take-all and loser-take-all switching rules. It is shown that the system can generate stable multi-phase synchronization in a wide range of parameters. Using simple piecewise linear models, the stability of the synchronization phenomena is studied and stability condition in terms of the system parameters is derived. The stable synchronization phenomena are confirmed experimentally.

The paper entitled "Applications of Computation Algorithm of Bifurcation Values to Resonant Converter Designs: Design of DC-DC Converter with Phase-Controlled Class-D ZVS Inverter and Class-E Rectifier," by Yamada *et al.* presents a design methodology of switching power converters with visualizations of converter characteristics on a system-parameter space. The authors use a resonant converter with the class-D zero-voltage-switching (ZVS) inverter as a design example. The validity and effectiveness of the proposed design strategy was confirmed by showing the quantitative agreements between PSpice-simulation and experimental results.

The paper entitled "Synchronization Phenomena in Microgrids with Capacitive Coupling" by Mandal and Banerjee considers a cascade connection of two switching converters for microgrid applications. In particular, the authors show that the nonlinearity present in all power electronic systems offers a way to synchronize spontaneously the clocks of the different stages if appropriate coupling exists among the converters. The authors also show that desirable periodic synchronization is achieved over specific ranges of the intermediate bus capacitance that depend on the frequency ratios of the converters in the uncoupled state.

The paper entitled "Modular Control Design and Stability Analysis of Isolated PV-Source/Battery-Storage Distributed Generation Systems," by Krommydas and Alexandridis, considers a distributed generation (DG) system with a photovoltaic (PV) source supported by energy storage devices and feeding DC- and AC-loads in islanded-mode operation. As all the DG parts are interfaced through power electronic DC-DC or DC-AC converters, a control strategy is introduced which is applied directly on each individual duty-ratio converter input. The particular controllers are implemented by applying the standard local cascaded structure with the inner-loops being fast nonlinear proportional-integral current-mode controllers. A rigorous novel stability analysis is developed by constructing the appropriate Lyapunov function in a new sequential manner. Finally, the cumbersome analysis that ensures system stability and convergence to the desired equilibrium, is further verified by simulation and experimental results.

In the paper entitled "Stability Criteria for Nonlinearly Perturbed Load Frequency Systems with Time-Delay," by Ramakrishnan and Ray, new criteria are presented for ascertaining delay-dependent stability of networked multi-area load frequency control (LFC) systems with feedback loop delay in presence of unknown and time-varying exogenous load disturbance. The proposed stability criteria are based on Lyapunov Krasovskii (LK) functional approach, and they are expressed in linear matrix inequality (LMI) framework. The proposed results are illustrated on standard benchmark LFC systems, and validated by simulation results.

Two papers are devoted to control and stabilization methods for distributed energy generator systems. The paper entitled "Design of Robust Higher Order Sliding Mode Control for Microgrids," by Cucuzzella *et al.* deals with the design of advanced control strategies of sliding mode type for microgrids. In particular, a second and a third order sliding mode (SOSM) control are proposed for different operating modes. The authors show that the microgrid controlled via the proposed sliding mode control laws exhibits appreciable stability properties and when compared with traditional PI control laws, they show the beneficial effects of the proposed strategies whole complying with the IEEE recommendations for power systems.

The paper entitled "Direct and Optimal Linear Active Methods for Stabilization of *LC* Input Filters and DC/DC Converters under Voltage Mode Control" by Wu *et al.* presents two linear active methods, the direct method and the optimal method, for the DC/DC buck converter under voltage mode control are proposed. In these two methods, feedforward loops are designed to modify the input impedance of the DC/DC converter to stabilize the system. Comparing with the direct method, the optimal method can achieve a shorter settling time and has smaller undesirable damped oscillation on the output voltage. Experimental results are reported to verify the effectiveness of these two methods.

Three papers are devoted to new converter/inverter topologies and their control for distributed energy generation using renewable energy resource.

The paper entitled "Dual-Input Switched Capacitor Converter Suitable for Wide Voltage gain Range," by Pillonnet *et al.* proposes a multiple input single output switched capacitor converter (MISO-CSC) to provide flatness efficiency over a large voltage gain range. By using two power supplies, the MISO converter produces 18 ratios instead of three in SISO (single input single ouput) mode. The autors show that by using a CMOS 65 nm technology, the transistor-based simulations exhibit an average 15% efficiency gain over a 0.5–1.4 V output voltage range compared to the SISO-CSC

The paper entitled "Efficiency Comparison of Inductor-, Capacitor- and Resonant-based Converters Fully Integrated in CMOS Technology," by Pascal and Pillonnet presents a method to compare the efficiencies of CMOS integrated capacitive-, inductive-, and resonant-based switching converters. The authors show that their models can be used to accurately predict converter efficiency in the early design phase. They also apply their method to design, optimize and compare fully-integrated power delivery requirements on a 1 mm^2 on-die area in 65 nm CMOS technology and the results underline the high efficiency of the promising resonant-based converter.

The paper entitled "New Three-Phase Symmetrical Multilevel Voltage Source Inverter," by Salem *et al.* presents a new design and implementation of a three-phase multilevel inverter (MLI) for distributed power generation system using low frequency modulation and sinusoidal pulse width modulation (SPWM). The author also propose a factor, which is developed to define the number of the required components per pole voltage level. A detailed comparison based on this factor is provided in order to categorize the different topologies of the MLIs addressed in the literature. Experimental results show a well-matching and good similarity with the simulation results.

The final three papers focus on different aspects related to control of power systems from a network perspective. In particular, the paper entitled "Consensus-Based Secondary Frequency and Voltage Droop Control of Virtual Synchronous Generators for Isolated AC Micro-Grids," by Lu *et al.* focuses on the secondary control of isolated ac microgrids. Stability of the closed-loop system is ensured by the transient energy function under certain mild conditions. Numerical experiments of a 14-bus/6-distributed iInterface converters-based micro-grid on real-time simulators are performed to validate the effectiveness of the proposed control mechanism.

The paper entitled "Assessment of Robustness of Power Systems from a Network Perspective," by Zhang *et al.* investigates the robustness assessment of power systems from a network perspective. The authors assess robustness of the IEEE 118 Bus, Northern European Grid and some synthesized networks. Simulation results show that the connection with short average shortest path length can significantly reduce a power system's robustness, and that the system with lower generator resistance has better robustness with a given network structure. The authors also propose a new metric based on node-generator distance (DG) for measuring the accessibility of generators in a power network which is shown to affect robustness significantly.

The paper entitled "Analytical Approximation Critical of Clearing Time for Parametric Analysis of Transient Stability in Power Systems," derives an analytic approximation for the critical clearing time (CCT) metric from direct methods for power system stability incorporating as many features of transient stability analysis as possible such as different fault locations and different post-fault network states. The authors demonstrate the performance of this metric to measure stability trends on an aggregated power network, the so-called two machine infinite bus network, by varying load parameters in the full bus admittance matrix using numerical continuation and then compare their metric to two other expressions for the CCT.

We hope that the readers will enjoy the selected papers and that this issue will serve as a stimulus for opening up new research in the area of analysis, control and design of energy-efficient distributed power generation systems. We would like to express our sincere appreciation to authors of all the papers submitted to this special issue. The quality of the submissions was excellent in general and selecting a subset of the papers for publication was a major challenge. We sincerely thank the anonymous reviewers for delivering high-quality reviews in a timely manner that helped us address this challenge and improve the quality of the accepted papers. We would also like to express our gratitude to Prof. Manuel Delgado-Restituto, IEEE JOURNAL ON EMERGING AND SELECTED TOPICS IN CIRCUITS AND SYSTEMS (JETCAS) Editor-in-Chief, and Prof. Yen-Kuang Chen, the Deputy-Editor-in-Chief, and the editorial team of JETCAS for their constant support without which this special issue would not have been possible.

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