Power Electronics for Extending Lifetime and Robustness of Fuel Cell Systems

THE fuel cell is an electrochemical device that converts the chemical energy stored in a fuel directly into electrical energy, with only heat and water as by-products. Hence, it is one of the cleanest technologies for producing electric power. However, the durability of fuel cells is a main concern for the massive deployment of fuel cell technology for transportation and stationary power generation applications.

The fuel cell power generation system consists of a fuel cell stack and the balance of plant consisting of auxiliary units such as air compressor, cooling circuit, power converter, etc. The fuel cell's lifetime is closely related to its electrode/electrolyte material aging and degradation during its operation. Over time and with use, the degradation of fuel cell performance cannot be avoided; however, with well-designed balance of plant and control system, the rate of performance degradation can be minimized, and the robustness of the fuel cell systems can be improved.

Among the different causes for the degradation of fuel cell, the electrical load cycling and the thermal cycling (which is closely related to electrical load cycling) during fuel cell operation are known to be the main long-term degradation factors. The high dynamic load transient, as well as the high dc current ripple, can significantly affect the fuel cell's lifetime in a negative way. In particular, low-frequency fuel cell current ripple produced by ac side or nonlinear load (few hertz to several hundreds of hertz) has a direct impact on the relatively slow diffusion and charge transfer phenomena inside the fuel cell during the electrochemical reactions, and lead to observable performance degradation and hysteresis effect. On the other hand, high-frequency fuel cell current ripple produced by power electronic component switching (few kilohertz to hundreds of kilohertz) has less impact on the instantaneous fuel cell performance due to the presence of double layer capacitance at the fuel cell electrode/electrolyte interfaces. Nevertheless, their long-term effect on the fuel cell active material (catalyst) degradation cannot be neglected.

The purpose of this "Special Section on Power Electronics for Extending Lifetime and Robustness of Fuel Cell Systems" of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS is to present the recent progress and developments in power converter design, system control, and advanced analysis methods to improve the lifetime and the robustness of fuel cell power generation systems. This Special Section consists of seven accepted papers, which can be divided into two groups.

The first group of papers, which consists of items 1)–4) in the Appendix, focuses on the new topologies and control improvements of fuel cell power converters. Multiple approaches have been proposed to effectively reduce the low-frequency input current ripples produced by connected load and the high-frequency input current ripples produced by power switching devices.

In item 1) of the Appendix, a dc/ac boost inverter and its control scheme have been designed for fuel cell supplied single-phase UPS. In order to effectively reduce the current ripples produced by ac side and nonlinear load, the proposed boost inverter works under both differential mode and common mode. While the differential mode ensures the dc-to-ac conversion, the common mode helps us to reduce current ripple in dc input. Moreover, an interleaved pulse width modulation (PWM) design has been proposed to further reduce the harmonics at switching frequency. Experimental tests have been conducted with both linear and nonlinear loads. The results have demonstrated very good performance and effectiveness of the proposed converter topology with the controller to reduce dc current ripple.

In item 2) of the Appendix, an impulse commutated current-fed three-phase dc/dc boost converter providing galvanic isolation has been proposed for fuel cell dc applications. Soft-switching technique has been used with high variable switching frequency between 75 and 80 kHz. The authors have shown that the induced current ripple can be efficiently reduced under continuous conduction mode of the proposed converter. Furthermore, detailed analysis and discussions about the components stress, losses, and efficiency have been thoroughly provided under different operating conditions. Experimental results with a 1-kW converter prototype have also been presented.

In item 3) of the Appendix, an improved current-fed hybrid dual active bridge dc/dc boost converter has been designed especially for fuel cell applications. By using the proposed converter topology and control, the input current ripple can be effectively mitigated at maximum level due to the fixed 50% duty cycle for input side switches at any input voltage and for any type of load, and the presence of a notch filter in the voltage feedback path. In addition, soft-switching technique has been employed for all switches of the converter to further reduce the losses and improve converter efficiency. A 1-kW experimental prototype has been built to validate the proposed novel design. The measured maximum efficiency at 1 kW is higher than 95% at a switching frequency of 50 kHz.

Digital Object Identifier 10.1109/TIE.2017.2711758

In item 4) of the Appendix, a simple but robust design of a current-fed push–pull quasi-resonant dc/dc boost converter has been proposed using only three power switching devices. The authors have made a tradeoff between the topology simplicity and the converter efficiency. The soft-switching feature at input side can only be achieved at light load conditions. The converter losses and efficiency at different load conditions are presented both in simulation and in experimental results. An experimental 510-W prototype converter has been built and operated at a switching frequency of 100 kHz. Compared to similar converter topologies, the proposed converter can achieve similar power performance with fewer components.

The second group of papers in this Special Section consists of items 5)–7) in the Appendix. Instead of focusing solely on fuel cell power converter design, these papers focus more on the fuel cell system top-level control optimization and system reliability improvement. Specific control strategies have been proposed for different types of fuel cell power generation systems. The primary control objective is to prevent the harmful operating conditions that lead to fuel cell degradation or even failure in severe cases.

In item 5) of the Appendix, the authors have proposed a nonlinear model-based predictive control strategy to: 1) maximize the use of cathode catalyst area during electrochemical reactions, and 2) prevent reactant gas starvation at different load conditions for transport applications. A multiphysical fuel cell model has been developed along with a state observer. The model has then been simplified and discretized for the implementation of nonlinear model predictive control. The proposed control scheme has then been tested with a case study using NEDC driving cycle profile. It has to be noted that the driving profile is simply adopted to validate the proposed control strategy, with no consideration of real fuel cell vehicle test conditions (type of vehicle, hybrid powertrain, etc.).

In item 6) of the Appendix, a real-world example of a diesel-powered fuel cell auxiliary power unit (APU) with onboard fuel reformer for truck applications has been presented. After a detailed presentation of APU system components and structure, the authors have thoroughly considered and discussed the main factors that impact the fuel cell system reliability during APU operation. Based on the reliability assessment, different control strategies have been proposed for system components, such as fuel reformer, cooling circuit, dc/dc converter, etc. The effectiveness and robustness of the proposed control have been validated under real operating conditions of the fuel cell APU.

In item 7) of Appendix, the authors have presented a hybrid power generation system which consists of a fuel cell and an ultracapacitor. The presence of a secondary energy storage component (i.e., ultracapacitor) can prevent the fuel cell to be operated under high dynamic transient load; thus, improving its lifetime. Although the hybrid fuel cell power system is not new in the literature, the authors have proposed a new nonlinear Lure–Lyapunov-based control strategy for energy management and power converter control in the hybrid system. The robustness of the proposed control has been discussed, along with experimental validations.

The Guest Editors hope that the papers presented in this Special Section will provide new ideas and pathways to mitigate the reliability and lifetime issues in the emerging and fast-growing fuel-cell-based power generation technologies for both transportation and stationary power generation applications.

Fei Gao, *Guest Editor*
Energy Department
University of Technology of Belfort-Montbeliard
90000 Belfort, France

Kaushik Rajashekara, *Guest Editor*
Department of Electrical and Computer Engineering
University of Houston
Houston, TX 77004 USA

Giuseppe Buja, *Guest Editor*
Department of Industrial Engineering
University of Padova
35122 Padova, Italy

Acknowledgment

The Guest Editors would like to thank the authors who have submitted their valuable contributions to this Special Section and the reviewers who have spent their valuable time providing insightful reviews. The Guest Editors would also like to thank the past Editor-in-Chief of the IEEE Transactions on Industrial Electronics, Prof. C. Cecati, for accepting our proposal to organize this Special Section and for his valuable suggestions during our preparation work. Finally, The Guest Editors would like to thank the current Editor-in-Chief of the IEEE Transactions on Industrial Electronics, Prof. L. G. Franquelo for his continuous support through the whole process and the Journal Administrators, R. Román, S. McLain, and S. Jacobs for their professional assistance and support.

Appendix
Related Work

1) N. Lu, S. Yang, and Y. Tang, “Ripple current reduction for fuel-cell-powered single-phase uninterruptible power supplies,” *Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6607–6617, Aug. 2017.
2) K. R. Sree and A. K. Rathore, “Impulse commutated high-frequency soft-switching modular current-fed three-phase DC/DC converter for fuel cell applications,” *Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6618–6627, Aug. 2017.
3) D. Sha, Y. Xu, J. Zhang, and Y. Yan, “Current-fed hybrid dual active bridge DC–DC converter for fuel cell power conditioning system with reduced input current ripple,” *Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6628–6638, Aug. 2017.
4) Q. Wu, Q. Wang, J. Xu, H. Li, and L. Xiao, “A high-efficiency step-up current-fed push–pull quasi-resonant converter with fewer components for fuel cell application,” *Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6639–6648, Aug. 2017.

5) J. Luna, E. Usai, A. Husar, and M. Serra, "Enhancing the efficiency and lifetime of a proton exchange membrane fuel cell using nonlinear model-predictive control with nonlinear observation," *Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6649–6659, Aug. 2017.
6) B. Pregelj, A. Debenjak, G. Dolanc, and J. Petrovčič, "A diesel-powered fuel cell APU—Reliability issues and mitigation approaches," *Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6660–6670, Aug. 2017.
7) S. Mane, M. Mejari, F. Kazi, and N. Singh, "Improving lifetime of fuel cell in hybrid energy management system by Lure–Lyapunov-based control formulation," *Trans. Ind. Electron.*, vol. 64, no. 8, pp. 6671–6679, Aug. 2017.

Fei Gao (S'08–M'10–SM'15) received the Master's degree in electrical and control system engineering and the Ph.D. degree in renewable energy with distinguished youth doctor reward from the University of Technology of Belfort-Montbeliard (UTBM), Belfort, France, in 2007 and 2010, respectively.

He is currently an Associate Professor in the Energy Department, UTBM, and he is also a member of the French National University Council. His research interests include fuel cells and their applications in transportation, multiphysical modeling, and real-time simulation systems. He is the holder of the French research expertise bonus from the French Ministry of Higher Education and Research with A rank. He is the Head of the Energy Production Division of the Energy Department of UTBM, and the Chair of the fuel cell modeling axis of the Fuel Cell Research Federation in France. Since 2014, he has also been an Adjunct Lecture Professor at the School of Automation, Northwestern Polytechnical University, Shaanxi Sheng, China.

Dr. Gao is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS and IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION and Editor of the IEEE TRANSPORTATION ELECTRIFICATION NEWSLETTER and *Renewable Energy and Sustainable Development*. He was nominated in 2017 as Conferences/Workshops Committee Chair of the IEEE Transportation Electrification Community. He was elected as Secretary in 2013 and as Vice-Chair of the Technical Committee on Transportation Electrification of the IEEE Industrial Electronics Society in 2016. He also serves as Technical Track Chair and Member of Organizing Committee of many IEEE international conferences (IECON, ITEC, APEC, ISIE, ICIT, etc.).

Kaushik Rajashekara (F'99) received the Ph.D. degree in electrical engineering from the Indian Institute of Science, Bengaluru, India, in 1984.

He joined the Delphi Division of General Motors Corporation, Indianapolis, IN, USA, as a Staff Project Engineer in 1989. At Delphi and General Motors, he held various technical and managerial positions, and was a Technical Fellow and the Chief Scientist for developing electric machines, controllers, and power electronics systems for electric, hybrid, and fuel cell vehicle systems. In 2006, he joined Rolls-Royce Corporation as a Chief Technologist for More Electric architectures and power conversion/control technologies for aero, marine, defense, and energy applications. In August 2012, he became a Distinguished Professor of Engineering at The University of Texas at Dallas. Since September 2016, he has been a Distinguished Professor of Engineering at the University of Houston, Houston, TX, USA. He has published more than 150 papers in international journals and conference proceedings, and is a holder of more than 45 patents. He has given more than 150 invited presentations at international conferences and universities. He has coauthored one IEEE Press book on sensorless control of ac motor drives and contributed individual chapters to six published books. His research interests are in the areas of power electronics, drives, transportation electrification, and energy management of microgrid systems.

Prof. Rajashekara was elected as a Member of the National Academy of Engineering in 2012 for contributions to electric power conversion systems in transportation. He was also elected as a 2015 Fellow of the National Academy of Inventors and 2013 Fellow of the Indian National Academy of Engineering. He has received the IEEE Richard Harold Kaufmann Award for outstanding contributions to the advancement of electrical systems in transportation; IEEE Industry Applications Society Outstanding Achievement Award, and IEEE IAS Gerald Kliman Award for contributions to the advancement of power conversion technologies through innovations and their applications to industry. He is a Fellow of SAE International.

Giuseppe Buja (M'75–SM'84–F'95–LF'13) received the "Laurea" degree with honors in power electronics engineering from the University of Padova, Padova, Italy.

He is currently a Full Professor at the University of Padova. He has carried out research in the field of power and industrial electronics, originating the modulating-wave distortion, and the optimum modulation for PWM inverters, pioneering the introduction of the DSP in power electronics systems, conceiving advanced techniques for control and integration of electric drives, and developing electric powertrains with fuel cells, supercapacitors, and wheel motors. His current research interests include wired and wireless charging of electric vehicles and power conversion for renewable energies.

Prof. Buja received the IEEE Industrial Electronics Society (IES) Eugene Mittelmann Achievement Award "in recognition of his outstanding technical contributions to the field of industrial electronics," and the 2016 Best Paper Award from the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS. He has served the IEEE in several capacities, including as General Chair of the 20th IECON in 1994. He is an Associate Editor of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, a Member of the Editorial Board of the *Chinese Journal of Electrical Engineering*, and a Senior Member of the Administrative Committee of the IES.