Cardenas, Roberto and Perez, Marcelo and Clare, Jon C. (2017) Control and grid integration of MW-range wind and solar energy conversion systems. IEEE Transactions on Industrial Electronics, 64 (11). pp. 8786-8789. ISSN 1557-9948

Control and Grid Integration of MW-Range Wind and Solar Energy Conversion Systems

GLOBALLY, the energy provided by intermittent sources has been steadily increasing. For instance, the electrical energy now supplied worldwide by wind turbines is increased by a factor of more than three with respect to the 2008 figure. Solar based energy generation has increased by more than 10 times in the same period. In total, the worldwide electrical energy consumption increased by approximately 6340 terawatt-hours from 2003 to 2013. Of that increase, about 11% was covered by a combination of wind power (564.8 TWh) and solar power (122.8 TWh).

To meet the challenges created by intermittent energy generation sources, grid operators have increasingly demanded more stringent technical requirements for the connection and operation of grid-connected intermittent energy systems, for instance concerning fault- ride-through capability, voltage and frequency support, inertia emulation, etc. These considerations, combined with an ever-increasing push for lower cost, higher efficiency and higher reliability, are leading to a steady technological evolution in the areas related to intermittent energy conversion systems. Ongoing developments include new or improved high voltage converters, power converters with higher power density, control systems to provide ride-through capability, implementation of redundancy schemes to provide more reliable generation systems and the use of High Voltage Direct Current (HVDC) links for the connection of large off-shore intermittent energy systems. In all of these technological advances, industrial electronics is undeniably a key core contributor. For that reason, the Guest Editors proposed this "Special Section on Control and Grid Integration of MW-Range Wind and Solar Energy Conversion Systems". This Special Section has received the attention of the research community studying industrial electronics applications in solar and wind energy, and a good number of papers have been submitted. About 30% of these papers were accepted for inclusion in this Special Section. Below a short discussion of each of the works is presented.

Some of the submitted papers discuss control systems and power electronic topologies for high power Wind Energy Conversion Systems (WECSs). For instance, in item 1) of the Appendix the control systems required to compensate the oscillations in the electrical torque produced by multi-channel wind turbines are investigated. The design of a 9-phase PMSG multichannel generator, interfaced to the grid using three back-to-back converters, is introduced, highlighting the advantages of this topology in terms of increased reliability and fault redundancy in both the generator and power electronics. A control system to eliminate the oscillations in the generator torque is proposed and discussed in the paper. This algorithm is required in case of an asymmetrical fault in one the three phase windings. The proposed methodology is experimentally validated using a 20kW prototype. A CAN-based network with a bus speed of 800 kb/s is used to communicate and synchronise the back-to back converters. Several experimental results, highlighting the performance of the proposed control methodology are presented and discussed in item 1) of the Appendix.

In item 2) of the Appendix the control systems and hardware requirements for a Wind Energy Conversion System (WECS) interfaced to the grid using a Modular Multilevel Matrix Converter (M3C) are presented. In this work it is proposed to regulate the voltage in the M3C capacitors using a balancing algorithm based on a two-stage α-β-0 transformation. The design of the control system is based on a small signal model which relates the dynamics of the capacitor voltages to the instantaneous power in each of the converter clusters. It is claimed in item 2) that the proposed control strategies enable decoupled operation of the converter, providing maximum power point tracking (MPPT) capability at the generator-side, grid code compliance at the grid-side [including Low Voltage Ride Through Control (LVRT)], and good steady state and dynamic performance for balancing the capacitor voltages. Experimental results obtained with a prototype composed of 27 full H-bridge cells are presented and discussed in item 2) of the Appendix.

In item 3) of the Appendix a novel concept of wind turbine with a planetary gearbox is presented. The power extracted from the wind is split into two parts by a free running planetary gearbox. Most of the mechanical power is delivered to a synchronous generator, which is directly connected to the grid without using a power electronic interface. A relatively small fraction of the wind power is delivered to a servo-machine, which is controlled by a small back-to-back converter. This servo-machine operates the sun gear of the planetary gearbox. In order to show the variable speed operation with maximum power point tracking of the wind turbine at both low and high wind speed, a 200kW experimental system was implemented and several experiments were performed and discussed in item 3) of the Appendix. The experimental results, in both the steady state and transient states, validate the performance and power split behaviour of the wind turbine.

The control of a virtual synchronous generator is discussed in item 4) of the Appendix. As stated in the paper, one of the methods for incorporating the increasing amount of wind power penetration into the grid, is to control the wind turbines to emulate the behaviour of conventional synchronous generators. However, energy balancing is one of the main drawbacks withholding WECSs from being truly dispatchable by power system operators. This paper presents a comprehensive methodology to emulate a synchronous generator, by controlling a WECS interfaced to the grid using a full power back-to back

Digital Object Identifier XX.YYYY/TIE.20XX.ZZZZZZZ

converter and an energy storage buffer. The proposed virtual synchronous generator control system allows both grid-connected and stand-alone operation of the wind turbine system. Power balancing of the WECS is achieved by controlling the rotor speed of the turbine according to the loading condition. Experimental results are presented to demonstrate the feasibility and effectiveness of the proposed methodology.

The control of Doubly-Fed Induction Generators (DFIGs) for grid voltage regulation is discussed in item 5) of the Appendix. This paper proposes a flexible reactive current-to-voltage [defined as "IQ−V" in item 5)] control scheme for rapid voltage regulation of wind power plants based on DFIGs. In the proposed control methodology, the controller dispatches different voltage set points to the DFIGs depending on their rotor voltage margins. The DFIGs inject reactive power using the rotor-side and grid-side converters. The IQ–V characteristic, varies with time depending on the current capability of the converters. Therefore to increase the reactive current during a fault, the active current has to be reduced in proportion to the dip value of the grid voltage. To avoid over voltages after the fault clearance, a rapid reactive current reduction scheme is implemented in the DFIG controllers. The performance of the proposed flexible scheme is verified under scenarios with various disturbances. It is claimed that the control methodology discussed in item 5) of the Appendix could increase wind power penetration without jeopardizing voltage stability.

The field of modular multilevel converters for multi-MW solar or wind energy applications is also very active. For instance in item 6) of the Appendix a novel diode-clamped modular multilevel converter with simplified capacitor voltage balancing control is proposed. In this topology, low power rating diodes are used to clamp the converter capacitor voltages. Only the top sub-module in each arm of the converter requires capacitor voltage control. Consequently, only a few voltage sensors are required for voltage regulation and the computational burden is much reduced with this topology. A simple voltage balancing control method with a carrier phase-shifted (CPS) modulation strategy is developed for this converter and discussed in item 6) of the Appendix. Experimental results obtained with a laboratory prototype are presented and analysed in this paper.

In item 7) of the Appendix a three-phase parallel-grid-connected multilevel inverter is proposed for feeding power from renewable energy sources to the grid. The multilevel inverter topology consists of n 2-level conventional inverters connected in parallel. Each of these 2-level inverters is fed from a renewable energy source; for a photovoltaic (PV) array through a DC–DC converter and for wind power through an AC–DC converter. An experimental system composed of a 6-level grid-connected multilevel inverter has been built to demonstrate the proposed topology. The application of a Pulse Width and Height Modulation (PWHM) technique has been investigated. Simulation and experimental results have shown a substantial reduction of the total harmonic distortion at the inverter output, minimising the switching stress and requiring fewer power switches than that required in other conventional power converter topologies.

The applications of modular multilevel converters for wind energy storage applications has also been analysed in this Special Section. In item 8) of the Appendix a medium voltage WECS with integrated storage is discussed. The WECS is connected to the grid using a modular multilevel converter. The proposed converter has the storage system integrated into its modular cell structure. The paper analyses the proposed topology and presents a dimensioning methodology for both the converter and the storage system in order to meet the new stringent grid-connection standards and fault ride through requirements. In order to verify the system operation, simulation results are presented in item 8) of the Appendix .

A delta-connected multilevel converter for large-scale photovoltaic (PV) grid integration is presented in item 9) of the Appendix. In this paper a delta-connected Cascaded H-Bridge (CHB) is proposed as an alternative topology for large-scale PV power plants. The required voltage and current ratings of the converter are analytically developed and compared against the alternative topologies. It is shown that the delta-connected CHB converter extends the balancing capabilities of the star-connected CHB and can accommodate power imbalances with relatively small overrating. Experimental results from a laboratory prototype are provided to validate the operation of the delta-connected CHB converter operating under various scenarios.

A modular medium voltage converter for PV applications is presented in item 10) of the Appendix. In this paper a new concept for modular magnetic-links is proposed for high-power transmission with galvanic isolation between the low and the high voltage sides. In the topology, a high-frequency common magnetic-link made of amorphous material, as a replacement for conventional common-dc-link, is proposed. Pulse width techniques considering third harmonic injection are reviewed in this work for the modulation of the signals to be synthesised by the converter. The modelling and analysis required to estimate the switching and conduction losses in the converter are also addressed. An experimental system based on a 5 kVA, five-level converter rated at 1.2 kV is designed using two identical 2.5kVA high-frequency magnetic-links. Experimental results, validating the topology and control systems are presented in item 10) of the Appendix.

A multilevel transformerless topology for PV applications is discussed in item 11) of the Appendix. In this paper, a new multilevel converter interfaced to the grid, without using isolation transformers, is proposed. It is claimed that this topology completely eliminates common-mode leakage by connecting the grid neutral point directly to the PV negative terminal, thereby bypassing the PV stray capacitance. It is a low-cost solution consisting of only four power switches, two capacitors and a filter inductor. Compared to half bridge topologies, it is claimed that this multilevel converter can synthesise a substantially higher output voltage considering the same DC link voltage. A modulation algorithm is also discussed in item 11) of the Appendix. Simulation and experimental results are presented in this paper.

Control systems for Low Voltage Ride Through (LVRT) control of power converters, interfacing PV generation to the grid, are presented in item 12) of the Appendix. It is claimed that this LVRT strategy can effectively mitigate the double grid fundamental frequency oscillations in the active power and the dc-link voltage during unbalanced grid faults. Using the proposed algorithm, the PV inverters can still inject sinusoidal currents even when unbalanced grid faults are presented. In addition, a current limitation method is introduced, which can restrict the injected currents to the rated value during faults. The performance of the proposed control strategy is verified by simulation and by experiments.

The application of multilevel converters for HVDC grid integration is also discussed in this Special Section. In item 13) of the Appendix a modular-multilevel-dc-link dc transformer based on a high-frequency dual active phase-shift method is presented. The proposed system employs a modular multilevel converter to operate the HVDC active front-end interface and the high-frequency power-transfer links. It is claimed that the proposed converter topology has good modularity, appropriate flexibility and good fault handling capacity. The topology and its operating principles are discussed. The electrical performance and control design are presented and analysed comprehensively in the paper. Finally experimental results obtained with a prototype are presented in item 13) of the Appendix.

A solid-state smart transformer to interface large PV and wind systems to weak grids is proposed in item 14) of the Appendix. It is stated in this paper that the magnetic characteristic of a conventional power transformer implies a slow dynamic response and produces high grid current harmonics when the wind speed is low and/or irradiance is weak. The paper proposes a parallel connection of a solid-state transformer-based smart transformer and a conventional power transformer to reduce the power rating, improve the regulation of the voltage amplitude and to improve the grid current quality. Simulation and experimental results are presented in item 14) of the Appendix.

The application of multilevel converters to interface wind farms is also discussed in this Special Section. In item 15) of the Appendix a DC collection grid architecture to process the energy captured from off-shore WECSs is presented. The system can be connected with the shore via an HVDC network. In the approach presented in item 15), each WECS output voltage is rectified and converted to a medium frequency signal. Subsequently, a transformer-based isolation stage is used, followed by a boost rectification stage. The boost rectification stage is controlled to emulate a resistive load, forming a medium-voltage dc interconnection. It is claimed that this type of control is simple and effective, even in the presence of varying wind conditions. A system design example, analysis of the losses and dimensioning of the converter, and a transformer finite element analysis are discussed in the paper. Simulation results demonstrate the functional capability of the system. Experimental results from a scaled down prototype are presented in item 15) of the Appendix.

In item 16) of the Appendix a control methodology for optimised power redistribution of off-shore wind farms, after on-shore converter outage, is proposed. It is claimed that the proposed control topology enhances the frequency stability of on-shore ac grids. Two scenarios of power redistribution after on-shore converter outage are analysed; self-distributed type and non-self-distributed type. For the self-distributed scenario, the proposed power redistribution method involves three steps which are extensively discussed in item 16) of the Appendix. For the non-self-distributed scenario, a combined off-shore wind farm control strategy composed of inertia emulation and pitch angle control is proposed to alleviate the adverse effect of the excess power on asynchronous grids. Verification is carried out through simulation studies on a modified New England 39-bus system incorporating a seven terminal VSC-HVDC transmission network.

ROBERTO CÁRDENAS, *Guest Editor*
University of Chile
Avda. Tupper 2007, Santiago, Chile.

MARCELO PÉREZ, *Guest Editor*
Santa María Technical University
Avda España 1680, Valparaiso, Chile

JON CLARE, *Guest Editor*
University of Nottingham
Nottingham, NG7 2RD, UK.

APPENDIX
RELATED WORK

1) L. Trilla, J. Pegueroles, J. Urresty, C. Muniz, and O. Gomis-Bellmunt, "Generator Short-Circuit Torque Compensation in Multi- Channel Wind Turbines," *IEEE Trans. Ind. Electron.*, no. November, 2017.
2) M. Diaz, R. Cardenas, J. Clare, and P. Wheeler, "Control of Wind Energy Conversion Systems Based on the Modular Multilevel Matrix Converter," *IEEE Trans. Ind. Electron.*, no. November, 2017.
3) Q. Liu, R. Appunn, and K. Hamyer, "Wind Turbine with Mechanical Power Split Transmission to Reduce the Power Electronic Devices: an Experimental Validation," *IEEE Trans. Ind. Electron.*, no. November, 2017.
4) Y. Ma, W. Cao, L. Yang, F. Wang, and L. Tolbert, "Virtual Synchronous Generator Control of Full Converter Wind Turbines with Short Term Energy Storage," *IEEE Trans. Ind. Electron.*, no. November, 2017.
5) J. Kim, E. Muljadi, J. Park, and Y. Kang, "Flexible IQ–V Scheme of a DFIG for Rapid Voltage Regulation of a Wind Power Plant," *IEEE Trans. Ind. Electron.*, no. November, 2017.
6) X. Liu., J. Lv, C. Gao, Z. Chen, Y. Guo, Z. Gao, B. Tai, "A novel diode-clamped modular multilevel converter with simplified capacitor voltage balancing control," *IEEE Trans. Ind. Electron.*, no. November, pp. 1–1, 2017.
7) S. Amamra, K. Meghriche, A. Cherifi, and B. Francois, "Multilevel Inverter Topology for Renewable Energy Grid Integration," *IEEE Trans. Ind. Electron.*, no. November, 2017.
8) B. Novakovic and A. Nasiri, "Modular Multilevel Converter for Wind Energy Storage Applications," *IEEE Trans. Ind. Electron.*, no. November, 2017.
9) G. Konstantinou, Y. Yu, C. Townsend, R. Aguilera, and V. Agelidis, "Delta-Connected Cascaded H-Bridge Multilevel Converters for Large-Scale PV Grid Integration," *IEEE Trans. Ind. Electron.*, no. November, 2017.
10) A. Rabiul-Islam, M., Mahfuz-Ur-Rahman, M. Mazharul-Islam, Y. Guo, and J. Zhu, "A Modular Medium Voltage Grid Connected Converter with Improved Switching Techniques for Solar Photovoltaic Systems," *IEEE Trans. Ind. Electron.*, no. November, 2017.
11) A. Kadam and A. Shukla, "A Multilevel Transformerless Inverter employing Ground Connection between PV Negative Terminal and Grid Neutral point," *IEEE Trans. Ind. Electron.*, no. November, 2017.
12) E. Afshari; G. R. Moradi; R. Rahimi; B. Farhangi; Y. Yang; F. Blaabjerg; S. Farhangi,, "Control Strategy for Three-Phase Grid-Connected PV Power Converters Enabling Current Limitation under Unbalanced Grid," *IEEE Trans. Ind. Electron.*, no. November, 2017.
13) B. Zhao, Q. Song, L. Jianguo, and W. Liu, "A Modular-Multilevel-DC-Link Front-to-Front DC Transformer Based on High-Frequency Dual Active Phase- Shift for HVDC Grid Integration," *IEEE Trans. Ind.*

Electron., no. November, 2017.
14) R. Zhu, G. De Carne, F. Deng., and M. Liserre, "Integration of Large Photovoltaic and Wind System by Means of Smart Transformer," *IEEE Trans. Ind. Electron.*, no. November, 2017.
15) H. Krishnamoorthy, M. Danioel, J. Ramos-Ruiz, P. Enjeti, L. Liu, and E. Aeoliza, "Isolated ac – dc Converter Using Medium Frequency Transformer For Off-Shore Wind Turbine DC Collection Grid," *IEEE Trans. Ind. Electron.*, no. November, 2017.
16) H. Dong, Z. Xu, P. Song, G. Tang, Q. Xu, and L. Sun, "Optimized Power Redistribution of Offshore Wind Farms Integrated VSC-MTDC Transmissions after Onshore Converter Outage," *IEEE Trans. Ind. Electron.*, no. November, 2017.

ACKNOWLEDGEMENT

The Guest Editors would like to thank Prof. Leopoldo Franquelo, Editor-in-Chief of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, for his tremendous support and Samantha Jacobs, Journal Administrator of the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, for her administrative assistance throughout the development of this Special Section. The Guest Editors would like also to thank the authors who supported this "Special Section on Control and Grid Integration of MW-Range Wind and Solar Energy Conversion Systems" by submitting papers with their important research results, and the world-class panel of reviewers, who provided valuable and meticulous comments and suggestions for each paper.

Roberto Cardenas (S'95–M'97–SM'07) was born in Punta Arenas, Chile. He received the B.Sc. degree in electrical engineering from the University of Magallanes, Punta Arenas, in 1988, and the M.Sc. degree in electronic engineering and the Ph.D. degree in electrical and electronic engineering from the University of Nottingham, Nottingham, U.K., in 1992 and 1996, respectively. From 1989 to 1991 and 1996 to 2008, he was a Lecturer with the University of Magallanes. From 1991 to 1996, he was with the Power Electronics Machines and Control Group, University of Nottingham. From 2009 to 2011, he was with the Electrical Engineering Department, University of Santiago. He is currently a Professor of power electronics and drives in the Electrical Engineering Department, University of Chile, Santiago, Chile.

Prof. Cardenas is an associate editor of the IEEE Trans. On Industrial Electronics. In 2005 he received the Best Paper Award in the IEEE Transactions on Industrial Electronics. His main research interests include control of electrical machines and variable-speed drives.

Marcelo A. Perez (M'07-SM'14) was born in Concepcion, Chile, in 1976. He received the Engineer degree in electronic engineering, the M.Sc. degree in electrical engineering, and the D.Sc. degree in electrical engineering from the University of Concepcion, Concepcion, Chile, in 2000, 2003, and 2006, respectively. From 2006 to 2009 he holds a postdoctoral position at the Universidad Tecnica Federico Santa Maria, Valparaiso, Chile, conducting research in the area of power converters. In 2009 he becomes an associate researcher and since 2015 he becomes an academic at the same institution.

Dr. Perez have received the 2012 Best paper award in the IEEE Industry Applications Magazine, he is Associate Editor of IEEE Transaction on Power Electronics, Chapter Coordinator of the IEEE-IES Region 9 Latin-America and the President of the IEEE-IES Chapter Chile.

His main interest are power converters topologies and control, multilevel converters, simulation, electromobility, smart grids and HVDC systems.

Jon C. Clare (M'90–SM'04) was born in Bristol, U.K., in 1957. He received the B.Sc. and Ph.D. degrees in electrical engineering from the University of Bristol, Bristol. From 1984 to 1990, he was a Research Assistant and Lecturer with the University of Bristol, where he was involved in teaching and research on power electronic systems. Since 1990, he has been with the Power Electronics, Machines and Control (PEMC) Group, University of Nottingham, Nottingham, U.K., where he is currently a Professor of Power Electronics and Head of Research Group. His research interests include power-electronic converter topologies and modulation strategies, variable-speed-drive systems and power conversion applications including HVDC-VSC and other high power/high voltage systems.