

# Ph.D. Thesis Abstract

## Operation of grid-connected photovoltaic power plants during voltage sags

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Renewable energy sources are occupying an increasing share in the global power generation market. Among various renewable energy sources, photovoltaic (PV) technology has been in the focus of many governments and, supported substantial subsidies has resulted a steep increase in the installed capacity. Moreover, with the decreasing trend in the PV panel costs from \$4.90/W in 1998 to \$0.3/W<sub>pk</sub> in 2015, the rate of growth of new PV installations is expected to remain on a high level. With high penetration of installed distributed generation (DG) units, power system operators (PSOs) are facing new challenges such as reliability, availability and power quality. In order to maintain the power quality and reliability of the power system, medium- and large-scale grid-connected photovoltaic power plants (GCPVPPs) should possess low-voltage ride-through (LVRT) capability, as regulated by new standards and grid codes. Therefore, improved GCPVPP structures with LVRT capabilities in combination with efficient control strategies are necessary. Subsequently, the operation of medium- and large-scale GCPVPPs during voltage sags is studied in this thesis.

A typical two-stage multi-string GCPVPP consists of a dc/dc converter in each PV string and one central inverter. It is commonly recognized as one of state of the art configurations for medium- and large-scale GCPVPPs, due to its inherent advantages. Multilevel converters have emerged as the most viable solutions for high power energy conversion applications due to their capability of delivering excellent power quality with low harmonic contents and better efficiency, compared to the two-level converters. Therefore, multilevel converters have been proposed and discussed for multi-string GCPVPPs in this thesis.

In this thesis, firstly, the operation of the GCPVPP with three-level neutral-point-clamped (3L-NPC) inverter with balanced current injection to the grid during voltage sags is investigated. An algorithm for the calculation of current references, in the dq-frame, during voltage sags is introduced, which considers the inverter current limitation, grid code requirements and the amount of extracted power from photovoltaic strings. The proposed algorithm uses the full current capacity of the inverter in injecting active or reactive powers to the grid during voltage sags, which leads in a higher grid voltage

enhancement. The performance of proposed control strategy is investigated on a 150-kVA GCPVPP connected to the 12.47-kV medium-voltage test-case system simulation model during different voltage sag conditions. An experimental setup of the 3.3-kVA grid-connected three-level neutral-point-clamped inverter with a dc/dc converter illustrates and validates the performance of the controller in injecting required active/reactive power and supporting the network voltage.

Secondly, the operation of GCPVPPs during unbalanced voltage sags with the injection of unbalanced currents to the grid is studied. This control strategy results into the zero active power oscillation during unbalanced voltage sags. An analytical expression for the calculation of active and reactive power references of a grid-tied inverter is proposed, which limits the peak current of the inverter during voltage sags. The key novelty is that the active/reactive power references are analytically calculated based on the dc-link voltage and grid codes, while they do not depend on the implemented current reference calculation algorithm and, as a general formulation, can be implemented in combination with various current reference calculation algorithms. Furthermore, based on the inverter nominal current and the injected reactive power to the grid during voltage sags, an analytical algorithm is introduced for the calculation of the active power reference, which can be extracted from PV strings. The proposed algorithm ensures that the maximum current capability of the inverter is used for the enhancement of the grid voltages during voltage sags, while it always complies with the reactive power injection requirement of grid codes and avoids increasing the dc-link voltage excessively. Experimental results of a grid-connected 3.3-kVA, 3L-NPC inverter laboratory prototype under several voltage sag conditions are presented to demonstrate the effectiveness of the proposed controller.

The proposed unbalanced current injection algorithm is a general algorithm, which can be applied for different multilevel inverter topologies. However additional considerations on the operation of the inverter and voltage balancing of capacitors is required in various inverter topologies. Multilevel cascade H-bridge (CHB) converters are one of the promising solutions for medium- and large-scale GCPVPPs. However, there is a lack of a complete study about their operation during voltage sags in the literature. Accordingly, a flexible control strategy is introduced for the operation of photovoltaic grid-connected CHB inverters during unbalanced voltage sags. The key novelty is that the proposed strategy is able to inject both active and reactive powers to the grid with either balanced or unbalanced currents, while ensuring that all dc-link capacitor voltages remain balanced. A zero-sequence voltage injection algorithm is proposed for inter-phase balancing, which allows for energy exchange between various phases. For inter-bridge balancing, the extracted power from different bridges of one phase is changed by modifying bridge voltage references. A feedforward voltage control is also applied to

decrease the inverter transient current at the beginning of the voltage sag. The performance of the proposed control strategy is investigated on a 10-MVA photovoltaic power plant connected to a 6.6-kV medium-voltage test-case system simulation model. An experimental setup of a 9-kVA grid-connected seven-level CHB illustrates and validates the performance of the proposed strategy for the operation of the grid-connected CHB during different unbalanced voltage sags.

One of the issues of the operation of GCPVPPs during voltage sags, is the reduction of the extracted power from PV strings to a certain power reference. During the voltage sag, both active and reactive powers are injected to the grid through the inverter, therefore the amount of the injected active power is reduced compared to the grid normal operation. In order to obtain a constant dc-link voltage in the GCPVPP, the extracted power from PV strings should be equal to the injected power to the grid in all operating conditions (excluding power losses). Consequently, a constant power generation (CPG) algorithm from PV strings is introduced in this thesis, which reduces the extracted power from the PV string to the required power reference. An algorithm for the calculation of the photovoltaic panel voltage reference, which generates a constant power from the GCPVPP is suggested. The key novelty of the proposed algorithm is its applicability for both single- and two-stage GCPVPPs and flexibility to move the operation point to the right- or left-side of maximum power point. Furthermore, the frequency of execution for the algorithm and voltage increments between consecutive operating points are modified based on a hysteresis band controller in order to obtain fast dynamic response under transients and low power oscillation during steady-state operation. The performance of the proposed algorithm for both single- and two-stage GCPVPPs is examined on a 50-kVA simulation setup of these topologies. Moreover, experimental results on a 1-kVA PV system validate the effectiveness of the proposed algorithm under various operating conditions, demonstrating the proposed CPG algorithm functionalities. The proposed control strategies in this thesis enable the operation of medium- and large-scale GCPVPPs during voltage sags, while they achieve LVRT capability and comply with grid codes and standards.

## List of Publications:

- [1] **H. Dehghani T.**, A. I. Maswood, G. Konstantinou, J. Pou, K. Kandasamy, Z. Lim and G. H. P. Ooi, "Study on the low-voltage ride-through capability of photovoltaic grid-connected neutral-point-clamped inverters with active/reactive power injection," *IET Gener. Transm. Distrib.*, Dec. 2016.  
(Accepted for publication)
- [2] **H. Dehghani T.**, A. I. Maswood, G. Konstantinou, J. Pou and F. Blaabjerg, "A general constant power generation algorithm in photovoltaic power plants," *IEEE Transaction of Power Electronics*.  
(Submitted for review)
- [3] **H. Dehghani T.**, A. I. Maswood, G. Konstantinou, Christopher D. Townsend, Pablo Acuna and J. Pou, "Operation of photovoltaic cascaded H-bridge converters during voltage sags," *IEEE Transactions on Industrial Electronics*.  
(Submitted for review)
- [4] **H. Dehghani T.**, A. I. Maswood, G. Konstantinou, J. Pou and P. Acuna, "Active/reactive power control of photovoltaic grid-tied inverters with peak current limitation and zero active power oscillation during unbalanced voltage sags," *Solar Energy (Elsevier)*.  
(Submitted for review)

## Conferences:

- [5] **H. Dehghani T.**, A. I. Maswood, J. Pou, G. Konstantinou and V. G. Agelidis, "An algorithm for reduction of extracted power from photovoltaic strings in grid-tied photovoltaic power plants during voltage sags," in *proc. IEEE Industrial Electronics Conference (IECON)*, Oct. 2016, pp. 3018-3023.
- [6] **H. Dehghani T.**, Ali I. Maswood, G. Konstantinou, J. Pou, K. Kandasamy, Z. Lim and G. Ooi H. P., "Unbalanced current injection of the PV grid-tied three-leg four-wire NPC Inverter Using 3-D Space Vector Modulation in abc Frame," in *proc. IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2016, pp. 1-6.
- [7] **H. Dehghani T.**, Ali I. Maswood, G. Konstantinou and J. Pou, "Low-voltage ride-through capability of cascaded H-bridge multilevel converters for large-scale photovoltaic power plants," in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Nov. 2016, pp. 52 - 57.
- [8] **H. Dehghani T.**, Ali I. Maswood, G. Konstantinou, C. D. Townsend and J. Pou, "Low-voltage ride-through capability of full-row connected cascaded H-bridge converters," in *proc. IEEE Region 10 Conference TENCN*, Nov. 2016, pp. 984-987.
- [9] **H. Dehghani T.**, A. I. Maswood, Z. Lim, G. H. P. Ooi and P. H. Raj, "A review of active/reactive power control strategies for PV power plants under unbalanced grid faults," in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Nov. 2015, pp. 1-6.

- [10] **H. Dehghani T.**, A. I. Maswood, Z. Lim, G. H. P. Ooi and P. H. Raj, "NPC photovoltaic grid-connected inverter with ride-through capability under grid faults," in *proc. IEEE 11th International Conference on Power Electronics and Drive Systems*, Jun. 2015, pp. 518-523.
- [11] **H. Dehghani T.**, A. I. Maswood, A. Ukil, O. H. P. Gabriel and L. Ziyou, "NPC photovoltaic grid-connected inverter using proportional-resonant controller," in *proc. IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Dec. 2014, pp. 1-6.

***Other publications, which are not included in the thesis; but have been prepared during the Ph.D. candidature:***

- [12] M. Roomi, A. I. Maswood, **H. Dehghani T.**, P. H. Raj, "A novel modulation method for non-ideal dual z-source neutral point clamped inverter," *IET Power Electronics*, vol. 10, no. 2, pp. 222-231, 2016.
- [13] **H. Dehghani T.**, A. I. Maswood and M. M. Roomi, "Active/reactive power control of PV grid-tied NPC inverter using 3-D space vector modulation in abc coordinate," in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Nov. 2015, pp. 1-6.
- [14] **H. Dehghani T.**, A. I. Maswood, Z. Lim, G. H. P. Ooi and P. H. Raj, "Proportional-resonant controlled NPC converter for more-electric-aircraft starter-generator," in *proc. IEEE 11th International Conference on Power Electronics and Drive Systems*, Jun. 2015, pp. 41-46.
- [15] M. S. U. Khan, A. I. Maswood, **H. Dehaghani T.**, M. M. Roomi and M. Tariq, "Control of bidirectional DC/DC converter for back to back NPC-based wind turbine system under grid faults," in *proc. IEEE 4th International Conference on the Development in the in Renewable Energy Technology (ICDRET)*, Jan. 2016, pp. 1-6.
- [16] P. H. Raj, A. I. Maswood, G. H. P. Ooi and **H. Dehghani T.**, "Five-level multiple-pole multilevel diode-clamped inverter scheme for reactive power compensation," in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Nov. 2015, pp. 1-6.
- [17] M. M. Roomi, A. I. Maswood and **H. Dehghani T.**, "Performance evaluation of boost and Z-source converters for fuel cell application," in *proc. IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, Nov. 2015, pp. 1-7.
- [18] P. H. Raj, A. I. Maswood, G. H. P. Ooi and **H. Dehghani T.**, "Multiple-pole multilevel diode clamped inverter for permanent magnet synchronous motor drive," in *proc. IEEE 11th International Conference on Power Electronics and Drive Systems*, Jun. 2015, pp. 862-866.