Doctoral Dissertation
Doctoral Program in Electrical, Electronics and Communications Engineering (36^{th}cycle)

Next Generation Grid-Tied Inverters with Virtual Synchronous Machine Features for Grid Services and Grid Support

By

Vincenzo Mallemaci

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Supervisor(s):
Prof. Radu Bojoi, Supervisor
Prof. Enrico Carpaneto, Co-Supervisor

Doctoral Examination Committee:
Prof. Paolo Mattavelli, Referee, Università di Padova
Prof. Giovanni De Carne, Referee, Karlsruhe Institute of Technology

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Abstract

Currently, synchronous machines (SMs) employed in thermoelectric and hydroelectric power plants ensure the stability of the grid frequency and voltage by providing ancillary services, such as inertial response, active and reactive power regulation, and fault support. However, with the ongoing decommissioning of thermoelectric power plants, particularly coal-based ones, the number of synchronous generators on the grid is decreasing. Additionally, renewable energy plants, such as those using solar and wind power, inherently lack inertial support because they connect to the grid through static power electronic converters. This reduction in total power system inertia poses a risk to grid frequency and voltage stability. Consequently, newest grid codes mandate that even power electronics-interfaced renewable energy sources provide grid services. For this purpose, control algorithms based on the Virtual Synchronous Machine (VSM) concept enable grid-connected converters to mimic conventional SMs and guarantee essential grid services. The goal of this PhD thesis is to develop control strategies that integrate the Virtual Synchronous Machine (VSM) control concept to provide grid services (such as virtual inertia) and grid support in compliance with the most recent grid codes. The thesis is divided into two main parts.

The first part provides a theoretical and experimental assessment for the main VSM topologies available in the literature. It begins by discussing the key aspects of grid-connected converters and defines the differences between grid-following, grid-forming and VSM, which are often sources of confusion in the literature. It then presents a literature review of the main VSM topologies. Each topology is implemented following a common tuning strategy. Their inertial behavior, frequency regulation and support capability during faults are compared using a common setup to highlight the differences and similarities between the various topologies. The beneficial effect of inertial response is then demonstrated using a dynamic network. The focus then shifts to the behavior of VSMs under non-ideal grid conditions. The thesis proposes a method to predict the response of the main VSM topologies to grid harmonics and imbalances. Some topologies can improve grid voltage quality by acting as harmonic/unbalance sinks, while

others may deteriorate it. The thesis also demonstrates how the harmonic/unbalance sink capability of grid-forming VSMs is limited by the effect of dead time, making the dead-time compensation essential to guarantee the correct sink performance.

The second part of the thesis focuses on the S-VSC, the VSM developed at the Politecnico di Torino. The peculiarity of this solution is its operation as a virtual compensator rather than as a virtual generator, like most VSMs from the literature. Its principle of operation as a grid-feeding VSM was demonstrated in previous works. This thesis extends the S-VSC algorithm to grid-forming operation, demonstrating its validity for the control of converters connected to microgrids that operate both in grid-connected and in island mode. The following chapter adopts the μ-analysis as a tool to evaluate the robust stability of the S-VSC against system uncertainties. The thesis also demonstrates that a converter functioning as a compensator is more robust than one functioning as a generator, both as a single grid-connected converter and in parallel with another. The final chapter shows that implementing the S-VSC algorithm into a battery charger control can enable battery chargers to provide ancillary services to the grid.