Doctoral Dissertation

Doctoral Program in Electrical, Electronics and Communications Engineering (XXXVIII cycle)

Innovative Control Algorithms for Grid-Tied Inverters

By

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Abstract

Recent international reports indicate that the accelerating energy transition, driven by the increasing electrification of end users and the growth of renewable generation, is resulting in a substantial rise in grid-connected power electronic converters. This proliferation of power electronics–interfaced loads and generators challenges the reliable operation of power systems, due both to higher and often unpredictable peak power demands and to the increased risk of instabilities caused by the reduction of total inertia.

To ensure the stability of future power systems and avoid frequent grid disruptions, renewable energy source (RES) plants must be able to provide ancillary services analogous to those traditionally delivered by synchronous generators (SGs). Moreover, high-power loads equipped with local energy storage can also enhance grid stability by making part of the stored energy available to the power system, thus mitigating peak power flows and contributing to power system resilience by providing ancillary services, similarly to RES plants.

In this context, two established approaches for enabling static converters to provide ancillary services and improve power quality are the virtual synchronous machine (VSM) control algorithms and the active power filters (APFs). The VSM concept implements an algorithm within the control unit of a grid-tied inverter to emulate the behavior of a SG, thus providing the full spectrum of ancillary services, including frequency and voltage regulation, inertial support, fault current injection and harmonic compensation. APFs, on the other hand, are effective in canceling the distorted currents injected into the grid by non-linear loads, thus ensuring power system compliance with international power quality standards.

The goal of this PhD thesis is thus to design control strategies for grid-tied inverters that enable the proper provision of grid ancillary services, making them more grid-friendly rather than potential sources of instability. Accordingly, innovative control algorithms for both VSM and APF applications have been developed, along with systematic design

procedures addressing key hardware aspects of grid-tied converters. This thesis is structured into two main parts.

The first part focuses on the VSM concept, describing and classifying existing VSM models and introducing a conventional one that highlights their key features. The power coupling phenomenon in VSMs is analyzed and a feedforward-based decoupling method is proposed to limit current stress on hardware components and prevent power fluctuations from propagating to the DC-connected storage during grid support. A dedicated grid impedance estimator for VSM-driven inverters is proposed, which is noise-immune, fully tunable and easily integrable into any VSM model, overcoming existing methods in the literature that rely on the adaptation of algorithms originally designed for grid-following converters.

The second part addresses innovative control and hardware solutions for APFs. It first presents the industrial case study considered in this thesis, which involves APFs installed in a production facility and operating in parallel with regenerative systems for AC–AC converter testing. Then, a dedicated discontinuous pulse-width modulation (DPWM) technique for APFs is proposed, which is insensitive to power line noise and therefore particularly suitable for industrial environments. Compared to conventional space vector pulse-width modulation (SVPWM), it better exploits existing hardware, minimizes losses and allows a doubled switching frequency, reducing the APF high-frequency current ripple injected into the grid. Finally, a dedicated design procedure for the differential-mode (DM) LCL filter interfacing the APF with the grid is proposed, accounting for both APF operating conditions and the compensated load characteristics, thus ensuring compliance with harmonic distortion standards while minimizing the filter volume, weight and cost.