UNIVERSITÀ DEGLI
STUDI DI SALERNO

Facoltà di Ingegneria

Dipartimento di Ingegneria dell'Informazione ed Elettrica e Matematica Applicata

Dottorato di Ricerca in Ingegneria dell'Informazione
XIV Ciclo – Nuova Serie

Tesi di Dottorato

Control Issues in Photovoltaic Power Converters

Candidato: **Massimiliano DE CRISTOFARO**

Coordinatore: **Prof. Maurizio LONGO**

Tutor: **Prof. Nicola FEMIA**

Co-Tutor: **Prof. Giovanni PETRONE**

Anno Accademico 2014 – 2015

The development of this work was born from cooperation between the *Power Electronics and Renewable Sources Laboratory* of the University of Salerno and the *ABB Solar Group* company (ex *Power-One*) of Terranuova Bracciolini (AR), Italy that is one of the most important manufactures of PV power converters. The aim of this thesis is to investigate control issues in photovoltaic system as the design of PV plants, in the present-day evolving scenario, is not completely defined. This company has pointed out a great interest to explore new control techniques that can have static and dynamic performance better than the existing techniques implemented in its systems, to analyze new scenarios due to the insertion of the Distributed Power Generating Systems (DPGSs) into the grid and to optimize the current methods to extract power from the PV source with the final goal to increase the performance of the PV systems at any level, system, grid and circuit. Hence, the starting points have been highlighted from the industry but they have also a great impact on the scientific and technologic fields. At system level, an improved Dead Beat (DB) control based on an Observe&Perturb (O&P) algorithm is developed with the aim to have static and dynamic performance better than the widely used, also by *ABB Solar Group*, Proportional Integral (PI) control. The O&P idea is to perturb the system control laws of values ΔV_d and ΔV_q, at a fixed time step T_a, to get zero average tracking errors keeping the fast dynamic of the Dead Beat (DB) control. Bigger are the average errors and bigger are the perturbations ΔV_d and ΔV_q. The conditions for the selection of the parameters, Ta, ΔV_d and ΔV_q, are provided making sure that they do not affect the system stability. As case study, a Neutral Point Clamped (NPC) inverter in the *dq* frame, based on the *ABB AURORA ULTRA* inverter is considered. A comparison between the PI, the DB, the Integral+DB (I+DB) and the O&P DB controls is done through simulations performed by a dedicated C++ language tool. The simulation results, taking the inputs from a real case of the Indian grid, highlight that the O&P DB has the same fast dynamic of the standard DB, faster than the PI and presents zero average tracking errors while the PI has zero average tracking errors, as expected, but slow dynamic. The DB and I+DB controls have dynamic faster than the PI but no zero average tracking errors. Hence the O&P DB control showed the best performance both static and dynamic. In presence of model mismatch, the O&P DB control still keeps zero average tracking errors but the dynamic start becoming slower. However, as shown in the simulation results, this mismatch has to be consistent, like no grid feedforward, to actually impact the dynamic. Both O&P method and simulation tool are not only for NPC inverters but they are very general being able to be applied to all the converters. The O&P control is also implemented on the F28379D Texas Instruments Microcontroller (µc) to test the feasibility of all its components, i.e. O&P algorithm, control and modulation, on a single embedded system and the results from the previous simulations and the µc are the same making the O&P DB control suitable for digital systems. This µc implementation has been performed at the Texas Instrument of Freising, Germany.

At grid level, a critical scenario composed by a Smart Transformer (ST), some loads and some Distributed Power Generating Systems (DPGSs) directly connected to the low voltage side of the ST is investigated. The correct analysis of the system requires that the loads and the DPGSs are properly modeled and the most used, for steady state power system studies, is a constant power load (CPL) model as power converters and motor drives, when well regulated, behave as constant power loads. The main characteristic of a CPL is to present negative impedance for the small signal analysis that can impact the system stability. The worst case for the stability is when the load presents only a CPL. Hence, a three-phase system with a Voltage Source Inverter (VSI), a LC filter representing the output stage of the ST, a DC-source representing the DC bulk of the ST, the CPL, the controller and the Pulse Width Modulator (PWM) is analyzed. The aim has been to verify if it is possible to use controllers usually designed for stable systems, proportional and P+Resonant, even when the system is unstable or if it is necessary to have a stable system to use them. This is very interesting for companies like *ABB Solar Group* as they widely implement these controllers on their systems. This investigation put the basis for all the future works for DPGSs with CPLs because it is proved that it is not possible to use a double loop control, as the closed-loop system is always unstable, and that the system should be stable with the action of the LC filter, for a single loop control, to use these controllers as it is not possible to stabilize the system with them. The stability conditions are provided and they mainly depend by the ratio L_f/C_fR_c where L_f is the filter inductor, C_f the filter capacitor and R_C the damping resistor. This ratio should be less than the equivalent CPL resistance to have a stable system. The analysis of a system with a CPL has been developed also in cooperation with the *Chair of Power Electronics* of the Albrechts-Universität zu Kiel, Germany.

At circuit level, a method to determine the sampling period T_{MPPT} and the duty-cycle step perturbation magnitude ΔD is presented to optimize the existing methods to extract power from the PV source. This method realizes the real time adaptation of a photovoltaic P&O MPPT control with minimum computing effort to maximize the PV energy harvesting against changes of sun irradiation, the temperature, the characteristics of the PV source and by the overall system the PV source is part of. It is exploited the correlation existing among the MPPT efficiency and the onset of a permanent 3 levels quantized oscillation around the MPP. Such universal property of P&O MPPT technique allows achieving optimum setup in microcontroller P&O MPPT implementation just by means of two counters, thus avoiding computations on measured quantities and the use of sophisticated models and algorithms. A comparison between an existing adaptive MPPT algorithm and the proposed one is highlighted that they have the same results in term of energy harvesting but the proposed one presents a slightly simpler implementation as the existing method uses a vector while the proposed one only 2 counters with the possibility to relax the ΔD adaptation through the 2 values N_n and N_p. A multi-function control application is discussed as a case study implementing the proposed adaptive PV MPPT control algorithm, including the LED driver dimming control and the bulk voltage control of a 70W LED lighting system prototype fed by a photovoltaic panel with a capacitor as storage device. The experimental results show the good performance of the proposed fully integrated control architecture, suitable for implementation with low cost microcontrollers. The proposed method can be applied to all the digital systems as it is not related to the specific implementation.