Politecnico di Torino

Master's degree in Electrical Engineering – Thesis

String inverter control design for photovoltaic applications.

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In contemporary power systems, the electric power generation is provided by synchronous generators. Primary (SM1) and secondary (SM2) frequency regulations operate to restore the reference frequency in the power grid, i.e. $f_1 = 50\ Hz$, ensuring the active power balance.

Given the tendency to a larger penetration of converters connected to non-synchronous sources (e.g., solar PV), new control strategies are necessary.

This thesis is carried out at the at Huawei Nuremberg Research Center to develop a control model of a string inverter for the PV TRUST project, where it takes part in collaboration with ENEL to increase PV system reliability in large scale PV areas.

My personal contributions are:

- analysis of the state-of-the-art regulation system;
- understand what consequences arise in the future perspective of high-density non-synchronous generation grids and the functionalities of Grid following, Grid forming and Virtual Synchronous Machine control strategies;
- design a lumped average model of the string inverter using design for passivity methodology;
- design of current and square DC voltage control loop;
- design of the frequency control with virtual inertial energy;
- choose the kind of storage and design its activation/deactivation control;
- carry out PLECS simulations to show how the converter works cooperating with synchronous machines in frequency regulation and for several situation of power levels.

❖ State of the art

At first, the impact on the system of the various system parameters (e.g., inertia constant) of the state-of-the-art regulation system made by synchronous generators is studied using the simulation softwares MATLAB and PLECS. They demonstrate that having a sufficient amount of inertia in the system ensures grid stability because it makes the frequency variation response more linear limiting the synchronous machines deceleration

In addition to the higher risk of loss of stability, the exponential growth of static converter interconnected in the grid causes additional changes such as reduced amplitude of the short-circuit current and it tests the ability of the converter's PLL to resynchronize to the grid frequency, due to the very high frequency trend of voltage dynamics at the converter terminals during a fault.

In a future low-inertia power system, the functionalities of the frequency regulation must be provided by an appropriate control of the converters operation. To obtain the aim of the thesis, different control strategies are investigated and developed using simulation software solutions such as MATLAB and PLECS. Especially, control strategies for grid following converters (GFL), such as the ones interfacing PV arrays to the grid, which can adapt to the behaviour of the grid, and grid forming (GFM), which can generate an electric grid in islanded operation, are analyzed and developed. GFL control allowed to understand how to calculate the voltage references as a function of the frequency. The GFM control, especially the Virtual Synchronous Machine control introduces the typical frequency regulation dynamics of a synchronous machine to a static converter.

❖ Average model of string inverters

The realised string inverter is the result of 20 voltage source inverters (VSC) connected in parallel and interconnected to the grid with LCL filters. Because of the high computational power required and wanting to focus on the grid behaviour, a lumped model of the string converter is built to represent the behavior of all the inverters.

Inverter's PWM modulation technique and sampling non-linearities tend to compromise its passivity property and, as a consequence, the effectiveness of the control is increasingly reduced as the frequency increases. Design for passivity method includes the LCL filter as part of an external VSC admittance Y_c to assure the stability. Considering the rest of the grid consisting only of passive elements, the whole system is stable if Y_c is also passive. The following assumptions can be adopted:

- the non-linear effects depend on the references of the fundamental components;
- converter's reference current is zero for frequencies at which a passive behavior of the current controller is wanted;
- effect of anti-aliasing filters is negligible in the design region.

In this case, the Laplace equation of the converter's admittance $Y_c(s)$ is reduced to a first-order expression by choosing appropriate values for the proportional k_p and active-damping k_{ad} gains of the current control loop.

Thanks to a PLL, the inner current control loop operates in the rotating dq-axis reference frame directed as the measured output converter voltage. The controller is a proportional integral (PI) that from the current error generates the voltage reference. Saturation and anti-wind up technique are integrated calculating equivalent direct k_d and feedback k_{fdb} gains. Controller's gains are calculated according to the design for passivity method. The filter's output voltage feedforward v_{ff} considers the active-damping gain k_{ad}. Fig 1 shows the current control schematic block.

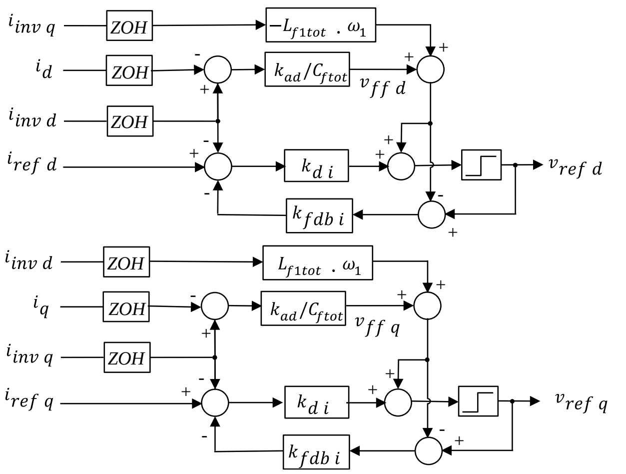

Fig. 1 Current control schematic block

The outer control loop is realised with a PI controller that controls the square value of the DC-link voltage v_{DC} to don't introduce non-linearity between DC and AC sides of the convert. It generates the active power reference P_{ref} for the current loop receiving energetic inputs. Fig. 2 shows the DC-link schematic block.

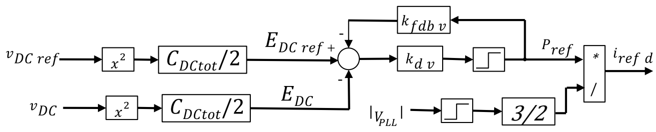

Fig. 2 DC-link square-voltage control schematic block.

❖ **Frequency control with power electronic converter**

In order to provide inertial support to the power system, the inverter must be sensitive to frequency variation. For this reason, the virtual inertia energy E_w of the converter is calculated from the current speed variation $\Delta\omega$ of synchronous machines, choosing a value for the inertia constant J and the starting time of the converter $T_{a\,c}$. It enters in the input energy balance of the DC-link voltage control modifying the reference power generation. E_w The schematic block of the inertial energy calculation is in Fig. 3.

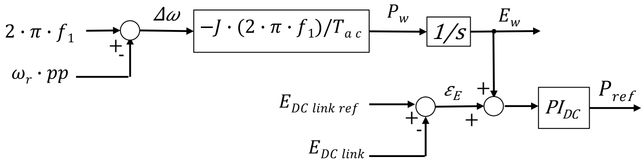

Fig. 3 Virtual inertial energy schematic block.

Finally, an energy storage (SMES) connected to the DC-link is introduced in the power configuration. In the control it's added an activation/deactivation logic that considers the power difference between PV's generation P_{PV} and AC power request P_{AC} and the current DC-link voltage value. A range between a minimum $V_{DC\,min}$ and maximum $V_{DC\,max}$ values that the capacitor must maintain is chosen. An emergency condition is entered, to store or deliver power from the storage to the converter, respectively, if:

- Storage: $v_{DC} = V_{DC\,max}$ and $P_{PV} > P_{AC}$
- Supply: $v_{DC} = V_{DC\,min}$ and $P_{PV} < P_{AC}$

In this way, when in emergency the power demand at the DC-link $P_{DC-link}$ is allocated to the storage and the DC voltage remains constant. Fig. 4 shows the schematic block of the storage activation control.

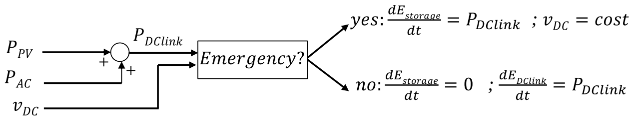

Fig. 4 Schematic block of the storage activation control.

The full schematic block of the string inverter control designed in the thesis is in Fig. 5.

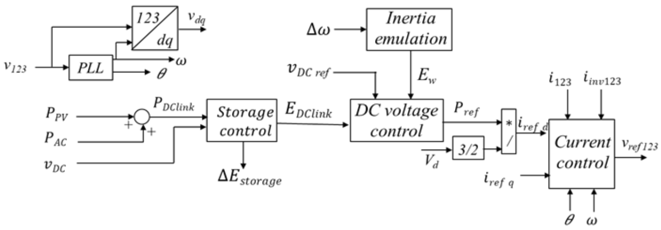

Fig. 5 Full schematic block of the string inverter control.

PLECS simulations are carried out to test the converter's response to variations in reference DC voltage, power supplied by the PVs and load request. They reveal that the introduction of the storage solves the problems due to the insufficient size of the DC-link capacitance:

- overvoltage of the capacitor beyond the maximum permissible value at the variation of the PV's power
- unacceptable voltage drops when a load request occurs;
- it helps the converter's insertion into the system.

Given the discontinuous functionality of renewable energy sources, the situation in which there is a PV power overproduction compared to the load's demand is simulated in PLECS. Also in this case, the introduction of the storage reveals the advantages of delivering an average value equal only to the power load request and avoiding the synchronous machine acceleration. In this way, the excessive power is stored and the transitory frequency deviation is reduced. Fig. 6 shows the measured speed of machines in this latter described situation.

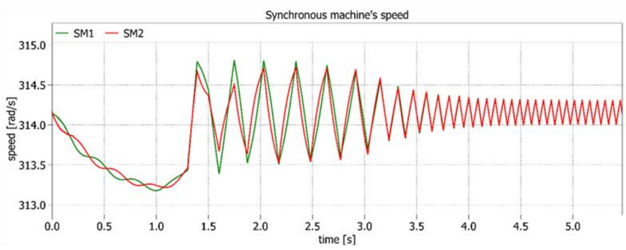

Fig. 6 measured speed of SM at high PV production.

In conclusion, the converter can satisfy the load power demand by working stably with the alternators. The control exploits the maximum converter's power and delivers it in short time respect the synchronous machines. This avoids the speed variation of machines in frequency regulation and grid frequency remains as closer to the reference value.

The designed model satisfies all the requirements of the PV TRUST project and it should be tested in the next points of the project.