Comparison of Models and Implementation of Virtual Synchronous Generators

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***Abstract*—To interface solar and wind power generators with the grid, power electronics converters are employed. Conventional control techniques are not suitable to provide ancillary services and support the grid. Therefore, the spread of renewable power generators is limited because it would lead the grid to become more and more unstable. Thanks to the Virtual Synchronous Generator (VSG) concept, it is possible to make static converters mimic synchronous generators or even outdo them, overcoming this issue. The goal of my master thesis is to implement and compare VSG models available in the literature, in order to demonstrate their capability to provide ancillary services.**

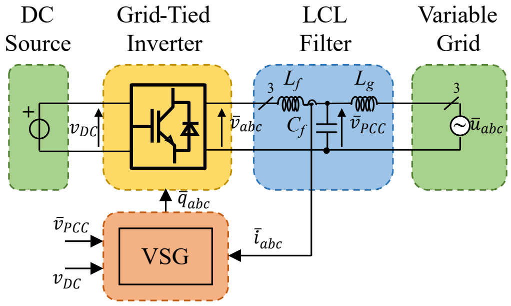


Figure 1: Hardware block diagram adopted for every VSG solution.

I. INTRODUCTION

In the last years, the issue of global warming and emission of greenhouse gases led to a major interest and exploitation of renewable energy sources (RESs). The most promising renewable power generators (RPGs) are based on solar and wind energy. To interface them with the grid, power electronics converters, in particular inverters, are needed. The grid stability is strictly linked with the presence of the synchronous generators (SGs) of hydro/thermal plants, because they can provide ancillary services and support the grid. Static converters do not embed such features and conventional control techniques are not suitable to solve this problem. Therefore, the spread of RPGs is limited because it would lead the grid to become more and more unstable.

To solve this issue, many solutions were proposed in literature, under the name of Virtual Synchronous Generator (VSG). With this different approach, it is possible to make static converters mimic synchronous generators or even outdo them, limiting the problem of grid instability.

II. GOAL OF THE MASTER THESIS

The **goal of this master thesis** is to study, implement and compare VSG models available in literature. The scheme adopted is proposed in Fig. 1.

The main activities are the following:

- Bibliography research and study of the following VSG solutions: Synchronverter, Osaka, VISMA, VISMA1, VISMA2, SPC, VSYNC, Kawasaki and CVSM;
- Realization of PLECS simulations for each VSG model;
- C-code implementation of the discrete-time version of each solution;
- Evaluation of each considered VSG model by means of the following experimental tests:
  - **Active and reactive power references variation**: this test is useful to observe the VSG power response in terms of damping and time to reach the set point as well as evaluate the effect of the reactive droop control;
  - **Frequency transient**: starting from the nominal value of 50 Hz, grid frequency varies reaching a nadir of 48.6 Hz and a steady state value of 49.58 Hz. The active droop control and the damping-droop coupling can be evaluated;
  - **Harmonic distortion**: 5% of fifth harmonic is added to the ideal three phase grid voltage. This test is useful to understand if VSG helps or not the grid in case of harmonic distortion, featuring an active filter behaviour;
  - **Short circuit fault**: the response to three types of symmetrical voltage dips is studied. In this way, the grid support of VSG during faults can be quantified.

III. EXPERIMENTAL RESULTS

The experimental tests have been performed on the setup shown in Fig. 5. The results have demonstrated the capability of many VSGs to provide ancillary services. An exemplary experimental outcome is shown in Fig. 2. The SPC model improves the power quality by compensating the voltage harmonic distortion. Moreover, the reactive support to the grid during faults can be performed by each VSG solution, as demonstrated for the Synchronverter model in Fig. 3a. Finally, some VSG models provide inertial support during grid frequency variations, without embedding any active droop action. In fact, the frequency regulation is performed independently of the inherent damping contribution of the model. An example is the result obtained with the Kawasaki model in Fig. 3b.

IV. Main Characteristics

VSG models can be divided into two categories: voltage-input current-output and current-input voltage-output. The former provides the current reference to perform a closed-loop current control. The output is the voltage reference for the PWM modulator. The latter directly produces the voltage reference. The connection with the grid can be represented with the equivalent circuits shown respectively in Fig. 4a and Fig. 4b. For the current-output models, the ideal current generator is equivalent to the series of a virtual electromotive force generator and a virtual impedance arbitrarily tunable. They define the virtual stator of the VSG. For the voltage-output models, instead, the virtual stator is constituted by the ideal voltage generator and the physical filter impedance.

Almost every VSG solution belongs to the first category, because of the reliable current limitation capability. The main advantage of the second category is the better dynamic due to the lack of a closed-loop control. On the other hand, they do not guarantee current limitation. Therefore, additional strategies must be implemented to operate safely.

In Table I the main characteristics of the analysed VSG solutions are listed.

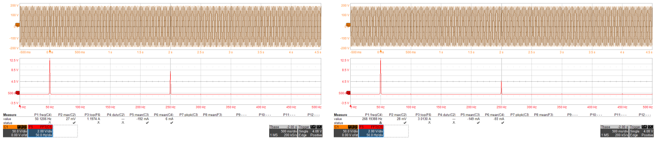
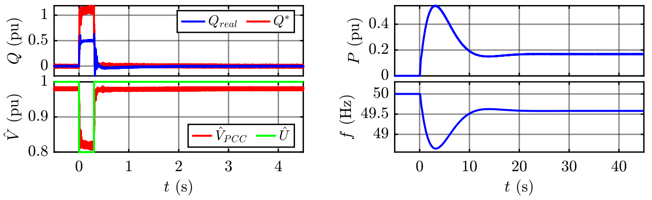
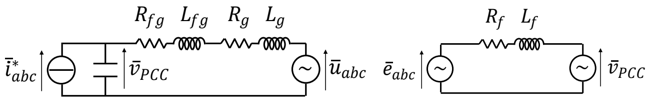

(a) (b)

Figure 2: PCC Phase Voltage with 5% of fifth harmonic (top) and its FFT (bottom) whe SPC PI's current references are: (a) disabled and (b) enabled.



(a) (b)

Figure 3: From left to right: (a) Synchronverter's response to voltage dip, from left to right: reactive power (top) and PCC voltage $\widehat{V}_{PCC}$ and grid voltage $\widehat{U}$ (bottom) with reactive droop control enabled; (b) Kawasaki's response to grid frequency variation of -0.42 Hz: active power (top) and frequency (bottom).



(a) (b)

Figure 4: Equivalent Circuit for: (a) current-output models; (b) voltage-output models.

Table I: Summary of the analysed VSG solutions.

Feature	**Models**
Current Output	Synchronverter, VISMA, VISMA1, SPC, VSYNC, Kawasaki, CVSM
Voltage Output	Osaka, VISMA2
PLL need	Osaka, VISMA, VISMA1, VISMA2, Kawasaki
Damping–droop decoupling	Osaka, SPC PI-LL, Kawasaki, CVSM
Harmonic Filtering Action	Synchronverter, Osaka, VISMA1, VISMA2, SPC
Grid supporting during faults	All solutions

V. Conclusions

In this master thesis, the theoretical description and the experimental validation of the VSG solutions available in the literature have been carried out. Moreover, the analogies and the differences among them have been highlighted, by means of a series of tests. It has been demonstrated that VSG control algorithms can provide ancillary services, representing a promising solution to facilitate the spread and the penetration of the renewable energy plants into the electric system.

During my master thesis, I carried out the following main activities, which can be considered **my personal contributions**:

- Bibliography research and study of VSG solutions available in literature;
- Implementation and tuning of each VSG control algorithm by means of PLECS simulations;
- Realisation of C-codes for the discrete-time version of each solution;
- Adaptation of C-codes for dSPACE environment and the real setup;
- Experimental testing of every VSG model by means of the setup.

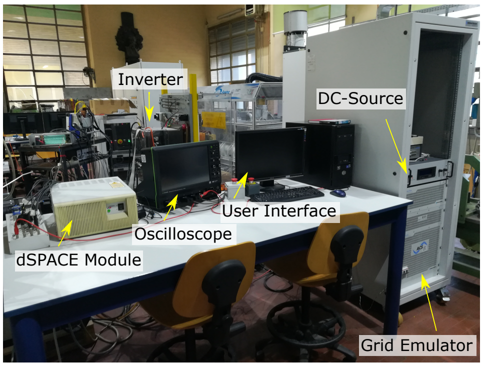


Figure 5: Laboratory setup at PEIC.