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Replicability and portability of an advanced grid-forming VSG control for electrical grid with high rate of renewable energies

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Abstract

The objective of his paper is to present a replicability and portability methodology of a virtual synchronous generator (VSG) to facilitate its development in an industrial context. This solution is designed to improve the electrical grid stability when facing a high penetration rate of renewable energies. In order to validate both the methodology and the portability of the proposed model, the VSG-based inverter is tested at different scales of inverters. The solutions are integrated in experimental grid for validation: at the Schneider Electric microgrid Lab facility as well in a simple microgrid, a laboratory-scale prototype system available at the G2ELab, France.

1 Introduction

Microgrids have received substantial attention as possible relevant solutions for the integration of renewable energy sources (RES), for allowing the energy access to remote locations and ensuring a potential increase of the system resiliency and reliability. Indeed, in recent years, the traditional distributed energy resources (DER) supplying energy to microgrids (usually diesel generator-sets) are supplanted by supplier based on RES. However, their intermittency leads to major stability issues, notably because these sources usually decrease the available inertia of already weak grids [5]. Hence, the traditional control strategies for inverters, interfacing the various DERs connected to the microgrid, needs adapting.

Hence, in order to increase the participation of renewable energy to the microgrid stability, the development of advanced inverter controller have been the centre of attention of recent research. The virtual synchronous generator (VSG) is a popular solution to increase the microgrid inertia, which is easily integrated thanks to its similarity with the well-known synchronous machines (SM) [13, 14]. Various projects have demonstrated and validated the advantages of VSG to better accept renewable DERs in microgrids [6, 15].

Different studies have been conducted to improve the performances of VSGs in microgrids. Those studies concerned the mode of reference of SM [16–18] or the controller, but few have tried improving the development of VSG considering an industrial context. Hence, to shift VSG from proof of concept to actual industrial inverter-based solution for microgrids,

it is necessary to simplify the integration of the controller in industrial inverters.

To that regard, a methodology is described in this paper to ease the development of VSG controller, under the technical constraints of the inverter characteristics. Indeed, two problems can be identified in this context: the reference SM model is not adapted and/or the entire VSG controller has to be redesign depending of the voltage or current nominal values. Based on the proposed controller in [7], built in p.u., a methodology is first developed to ensure the adaptation of the SM model to the inverter characteristics adapting its performances to the inverter's capability. Then, in a second part, the methodology is performed and integrated in an inverter and tested to ensure the reliability and the portability of the proposed method.

2 Methodology

The objective of the proposed methodology is to select the most adapted SM model to implement as a reference for the VSG solution in a controller [7], based on the inverter's characteristics, to ensure the replicability and portability of the VSG solution for different inverter characteristics. The generality of the implementation is one of its clear added values.

The second objective of this methodology is to ensure that the SM reference is still similar to a real SM, maintaining the principal characteristics of a VSG to operate as a SM solution. Hence, when possible, the designed SM model is based on real SM characteristics and only adapted to the inverter characteristics.

Different SM models were studied to be considered as reference, a complete [19], a reduced [22] or a static/simple one [8]. To ensure that the methodology can be applied to any VSG solution, we have chosen the most complete SM model with the highest number of parameters (worse case scenario).

2.1 Inverter characteristics

The inverter's characteristics used in the proposed methodology to determine the SM reference are:

- The maximal inverter currents, I_{ond}^{max} (A);
- The PWM switching frequency, f_{IGBT} (Hz);
- The inverter output nominal phase-phase voltage, E_n (V);
- The inverter output nominal current, I_n (A).

The following SM parameters must be determined to design the SM complete model:

- *Reactances:* $X_d, X'_d, X''_d, X_q, X'_q, X''_q$;
- *Stator resistor:* R_s ;
- *Time constants:* $T'_d, T''_d, T'_{d0}, T''_{d0}, T'_q, T''_q, T_a$.

The SM model should be based on the equations extracted from [23, 24]:

$$\text{d-axis: } \frac{T'_{d0}}{T'_d} = \frac{X_d}{X'_d} \text{ and } \frac{T''_{d0}}{T''_d} = \frac{X'_d}{X''_d} \quad (1)$$

$$\text{q-axis: } \frac{T'_{q0}}{T'_q} = \frac{X'_q}{X''_q} = \frac{X_q}{X''_q} \quad (2)$$

2.2 Methodology

The frequency, f_{IGBT} , permits to determine the time responses of the SM complete model. The maximal inverter currents and the nominal voltage and current help determining the reactances and the resistors of the SM reference.

In case none of the inverter characteristics or the SM intrinsic equations permit to select parameter values, datasheets of real SM are used as support for hypothesis.

2.2.1 Determination of the reactances: To design the reactances of the d-axis (X_d, X'_d, X''_d), the maximal current admissible by the inverter I_{ond}^{max} and the nominal parameters of the inverter are used. The inverter's characteristics are linked to the d-axis reactance of the SM model (X_d, X'_d, X''_d). The SM short-circuit currents are considered, and defined in (3), where ψ is the phase angle (rad), and ω the angular velocity (rad/s).

$$\begin{aligned} I_{sc}(t) = E_n & \left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d} \right) \times \exp^{-t/T'_d} \right. \\ & + \left. \left(\frac{1}{X''_d} - \frac{1}{X'_d} \right) \times \exp^{-t/T''_d} \right] \cos(\omega t + \psi) \\ & + \frac{E_n}{2} \left(\frac{1}{X''_d} - \frac{1}{X'_d} \right) \times \exp^{-t/T_a} \left] \cos(\psi) \right. \\ & + \left. \frac{E_n}{2} \left(\frac{1}{X''_d} - \frac{1}{X'_d} \right) \times \exp^{-t/T_a} \right] \cos(2\omega t + \psi) \quad (3) \end{aligned}$$

Contrary to a traditional SM, the maximal/short-circuit inverter's current is usually limited to 1.5 or 2 times the nominal one. Therefore, the proposed methodology for the sizing of the X_d parameter is based on the permanent short-circuit current, to simplify the short-circuit detection by the inverter's protection. We have:

$$I_{sc}(t = \infty) = I_{ond}^{max} = \frac{E_n}{X_d} \quad (4)$$

Hence, the reactance X_d is defined by:

$$X_d = \frac{E_n}{I_{ond}^{max}} \quad (5)$$

The maximal and sub-transient SM current during a short-circuit could reach up to 10 to 20 times the nominal current. For the proposed methodology, the short-circuit current is fixed to 15 times the maximal inverter's current:

$$I_{sc}(t = 0) = \frac{2E_n}{X''_d} \quad (6)$$

The inverter cannot reach the same current. It is dealt with the saturation of the current's reference. Hence, the reactance X''_d is based on the equation:

$$X''_d = \frac{2E_n}{15 \times I_{ond}^{max}} \quad (7)$$

In order to determine the value of X'_d based on the inverter's characteristics, the relationship between the reactances X'_d and X''_d is used [23]. Traditionally, the value of the reactance X''_d is slightly superior to the reactance X'_d . So, based on different datasheets, the relation $X'_d = 2X''_d$ is used.

With the same idea as using the most complete SM model to validate the replicability of the proposed methodology, a salient-pole SM is used, where the reactance X_d is from 2 to 10 times superior to the reactance X_q . In order to avoid an over-salient machines, which have no impact on the VSG performances, the parameters X_q with the relation $2X_q = X_d$.

The value of the sub-transient reactance X''_q is similar to the sub-transient reactance X''_d . In addition, the value of the reactance X''_q is selected in order to minimize the value of the output harmonics following the relation $X''_q = 1.5 \times X''_d$ [23].

Based on the model of a SM, the stator winding resistor R_s is defined by (8).

$$R_s = \frac{X''_d + X''_q}{2T_a} \quad (8)$$

Now that all the SM reactances are linked to the inverter characteristics, the time response of the SM model is designed.

2.2.2 Determination of the times constant: The PWM switching frequency is considered to design the sub-transient time responses T'_d and T''_d . To ensure that the model is stable, enough calculation points are necessary. Hence, the coefficient multiplying the PWM switching frequency to obtain the SM sub-transient time response needs to be sufficient to ensure the model stability [11, 12]. However, the ratio between the PWM

switching frequency and the time response should not be too important to ensure that the performances are not impacted, thus minimising the microgrid fast stability recovery after an impact. Hence, the times responses T_d'' and T_q'' are chosen as $T_d'' = T_q'' = 50/f_{IGBT}$.

Knowing X_q'' , X_d'' and T_q'' , the response time T_{q0}'' can be determined thanks to the SM characteristics in (2) [13].

Similarly, it is possible to determine the relationship between T_{d0}' and T_d' as using (1).

However, to determine T_d' or T_{d0}' , another relationship is necessary to identify one of the two parameters. Based on different datasheet, the T_d' parameters is often included between $2T_d''$ and $10T_d''$. Similarly to the time responses T_d'' and T_q'' , the T_d' or T_{d0}' parameter affect both the stability of the model and the performance of the inverter. Hence, the time response T_d' is chosen as $T_d' = 4T_d''$. The entire methodology is summarized in Table 1.

Table 1 Recapitulation of parameters expressions.

Parameters (p.u.)	Time response (s)
$X_d = \frac{E_n}{I_{ond}^{max} \times Z_{base}}$	$T_d'' = T_q'' = \frac{50}{f_{IGBT}}$
$X_d'' = \frac{2E_n}{15I_{ond}^{max} \times Z_{base}}$	$T_{q0}'' = T_q'' \frac{X_q}{X_d''}$
$X_d' = 2X_d''$	$T_d' = 4T_d''$
$2X_q = X_d$	$T_{d0}' = 30T_d''$
$X_q'' = 1.5 \times X_d''$	
$R_s = \frac{(X_d'' + X_q'')}{2T_d''}$	$X_l = 0$
$X_0 = 0$	

The integration of the proposed methodology is experimented and validated in the following section.

3 Experimental validation

3.1 Experimental laboratory presentation

A power-in-the-loop (PHIL), with a real inverter, has been used to validate the proposed methodology, to transfer the VSG-based control to another inverter with different characteristics that have been used in [7].

To that purpose, in the facilities of the G2ELab, a laboratory-scale prototype has been built to develop and validate control strategies that enhance the capabilities of inverter-based generation systems, notably used for renewable energies such as photovoltaic [9, 20, 21], wind turbines [10], or microgrid controllers [25].

The test-bench is constituted of two main systems: the VSG inverter and the microgrid used to validate the replicability of the VSG controller. Each system can be divided in two layers: software and hardware. Both are controlled and represented by their associated real-time digital simulators, dSPACE and RT-LAB respectively.

3.2 Testbench characteristics

The local grid is connected to the test bench via a transformer imposing the nominal inverter voltage and frequency. Hence, in

order to benefit from that connexion, the inverter voltage reference is imposed at 240 V and the frequency at 50 Hz. Knowing the nominal voltage, it is possible to determine the DC voltage, input of the inverter.

To limit the risk of deterioration, the VSG inverter's maximal current is also limited, and so the admissible power of the inverter. Concerning the PWM switching frequency, the test-bench is limited to 10 kHz. Table 2 details the characteristics of the prototype that is considered to validate proposed methodology.

Experiments were validated for different PWM switching frequency, however, due to the page limitation, only a PWM switching frequency of 5 kHz is presented in this paper.

Table 2 Test-bench setup.

Inverter parameters	Value	
Maximal apparent Power	S_{max}	5 kVA
Maximal output 3-phase voltage	E_{max}	400 V
Maximal output current	I_{ond}^{max}	20 A
Maximal PWM frequency	f_{PWM}	5 kHz
Maximal DC voltage	V_{DC}	800 V

3.3 VSG model characteristics with the methodology

Following the proposed methodology and based on the test-bench characteristics, the adapted SM parameters established considering the SM characteristics are defined in Table 3 and Table 4.

Table 3 Synchronous machine reactance values.

Parameters	Value (p.u.)
X_d	3.7712
X_d''	0.1257
X_d'	0.2514
X_q	1.8856
$X_q'' = 1.5 \times X_d''$	
R_s	0.10

Table 4 Synchronous machine time constant values.

Parameters	Value (p.u.)
T_d''	10
X_{q0}''	100
T_d'	40
T_{d0}'	12,000

3.4 Experimental results

Now that the prototype system has been presented, the experimental results are studied to validate the replicability of the proposed controller and the methodology to determine the SM model reference of the VSG controller.

The experimental tests are separated in two parts: a stand-alone and a grid-connected mode. Due to the page limitation, one test for each mode is represented but more experiments have been conducted to ensure the replicability of the VSG control in industrial conditions.

3.4.1 Standalone operations: In this section, the implemented prototype VSG represents the unique power source connected to the microgrid. Fig. 1 shows the general schematic of the tests conducted in the stand-alone application with the test-bench.

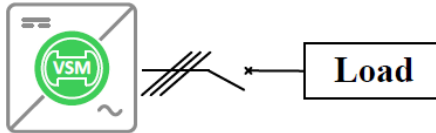


Fig. 1 Schematic representation for the stand-alone test-bench.

Fig. 2 shows the transient dynamic behaviour of the VSG under a 4 kW load impact (i.e., 100 % of its power) realised with the real loads. The voltages and currents waveforms are similar to the one of a real SM.

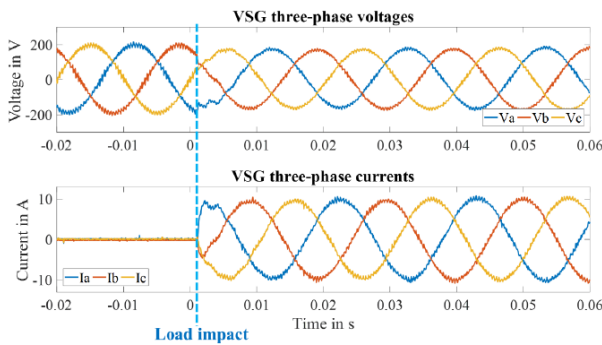


Fig. 2. VSG behaviour during a 4 kW load impact (100 %).

During the load impact, the three-phase voltage decreases immediately and then stabilizing at its nominal value. Similarly, during the load impact, the current rapidly increases before stabilizing. To conclude, the VSG based on the proposed methodology is able to cope with a significant load impact, equal to its maximal power.

3.4.2 Parallel operations: In this section, the VSG is integrated in a microgrid to validate its parallel operation. Fig. 3 represents the VSG integration in the microgrid. Each element of the microgrid, real or emulated, can be connected or disconnected depending on the desired configuration, thanks to controllable interrupters. The two emulated power sources connected to the microgrid can be both a generator set and another VSG, each of 4 kVA, as the prototype VSG.

For the test presented in Fig. 4, a 12 kW load (i.e., 100 % of the power sources in the microgrid) is connected (a) and disconnected (b) to/from the microgrid constituted of the three power sources: a real and an emulated VSG and a generator.

The three-phase voltage of the microgrid are shown in Fig. 4 during the load impact and the load shedding (100 % of the

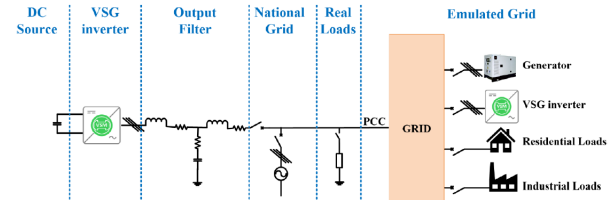


Fig. 3 Schematic representation for the VSG in a microgrid test-bench.

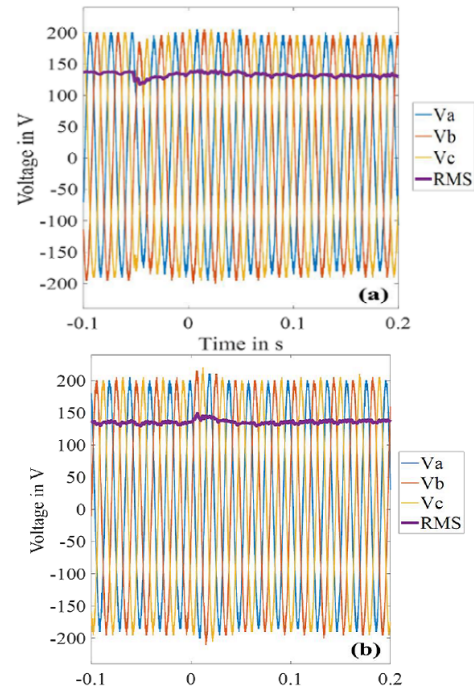


Fig. 4 Three-phase voltages behaviour of the microgrid after a 12 kW (a) load impact and (b) load shedding.

load). The voltage rapidly returns to its nominal value after the load impact and shedding without creation of oscillation between the three power sources, as shown by the RMS voltage value in violet on Fig. 4 (a) and (b).

4 Conclusion

In the first part of the paper, a methodology is detailed in order to ensure the design of a SM model for a virtual synchronous generator specified for the integration of the controller considering the inverter characteristics .

In order to validate the proposed methodology, the VSG inverter is tested in both stand-alone and parallel operations. In the stand-alone operation, the VSG control is stable for step-like load impact, unbalanced and non-linear loads connection (the first experiment only being presented in the paper due to page limitations). For the parallel operation, the VSG-based inverter is integrated in a basic microgrid connecting multiple power sources to a load where different use-cases have been tested, such as load impacts.

As presented in this paper, the proposed model of VSG is stable through 100 % loads impacts in various configuration of

grids as well as multiple integration in industrial inverters. This proves its replicability and portability in such contexts.

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