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SPECIAL SECTION

Standardization tests for the industrialization of grid-friendly Virtual Synchronous Generators

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Abstract. Three synchronous machine models representing three precision levels (complete, reduced and static), implemented in a virtual synchronous generator (VSG)-based industrial inverter, are compared and discussed to propose a set of tests for a possible standardization of VSG-based inverters and to ensure their "grid-friendly" operation in the context of isolated microgrids. The models and their implementation in the microcontroller of an industrial inverter (with the local control) are discussed, including the usability of the implementation with large-scale developments constraints in mind. The comparison is conducted based on existing standards (for synchronous machines and diesel generators) in order to determine their needed evolution, to define the requirements for future grid-friendly inverter-based generators, notably implementing a VSG solution.

Key words: grid forming inverters, microgrids, inverter-based generation, renewable energies, standardisation, synchronous machine, synchronverter, virtual synchronous generator.

Table 1.
Nomenclature

Symbol	Definition
ψ_d, ψ_q	Stator flux linkages in the dq-frame (p.u.)
ψ_{fd}	Rotor flux linkages in the dq-frame (p.u.)
ω_r, ω_0	Rotor electrical angular velocity and its base value: $\omega_r = \omega_{rotor}/\omega_0$ (rad/s)
e_d, e_q	Output voltage at the stator side in dq-frame (p.u.)
E	Grid's voltage (p.u.)
V_c	Stator output voltage vector (p.u.) defined as $V_c^* = \begin{bmatrix} e_d \\ e_q \end{bmatrix}$
i_d, i_q	Stator output current in dq-frame (p.u.)
I^*	Stator output current vector (p.u.) defined as $I^* = \begin{bmatrix} i_d \\ i_q \end{bmatrix}$
e_{fd}	Excitation voltage (p.u.)
R_s	Stator line (armature) resistance (p.u.)
R_{fd}	Rotor field winding resistance (p.u.)
L_d, L_q	Mutual stator and rotor inductance in dq-frame (p.u.)
L'_d, L''_d	Transient and sub-transient reactance in the d-axis (p.u.)
T'_{do}, T''_{do}	Respectively the transient and sub-transient open-circuit time constants in the d-axis (s)
T'_d, T''_d	Respectively the transient and sub-transient short-circuit time constants in the d-axis (s)
T''_{qo}	Sub-transient open-circuit time constants in the q-axis (s)
T''_q	Sub-transient short-circuit time constants in the q-axis (s)

1. Introduction

Classical distributed energy resources (DER) supplying energy to microgrids (usually diesel generator-sets) are being gradually based on renewable energy sources (RES). However, the intermittency of RES leads to major stability issues, especially in the context of microgrids, notably because these sources usually decrease the available inertia of the grid [1]. The virtual synchronous generator (VSG) is one of the most popular solution that can participate in the microgrids inertia and thus increase the stability margins. Many projects have shown the advantages of VSG-based inverters for various configurations of microgrids [2], and work on demonstrating them [3, 4].

In this expansion context, the standardisation of VSGs should be discussed. The SM is an established solution, requirements and specifications are well developed regarding design and performances [5–8]. Nowadays, as there is no specification or standards yet for the VSG-based inverter, the generator and SM standards are considered as reference to determine the performances of the VSG as well as study the stability of a (micro-)grid incorporating one or many of them. In the microgrids'

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context, the VSG is generally not the only power supply solution. This is the reason why a parallelism study of the VSG with similar or different power sources must be considered to finalize the study. To conclude, the choice of the SM model for a VSG is based on the computational capacity of the industrial micro-controllers, to run it with its local control, and the compliance of its behavior with SM standards by default, within the limitations of the inverter, which should at one point evolve to actual VSG standards.

In the state of art, the VSG solutions do not usually consider the capability of the industrial inverter and computational limitations of its micro-controller. Indeed, in order to shift the VSG from research to development and then furthermore to industrialization, the scalability and the replicability of the models must be at the center of the preoccupations, as increasing the computational capabilities of the micro-controllers significantly impacts the economic viability of future VSG solutions.

For the controller of the VSG, multiple synchronous machine (SM) models exist. Initial works on VSG [9] used SM models constituted of all the dynamic electrical equations, including the flux linkages and the effects of the damper windings [10–13]. Another SM model possibility would be a simplification based on the emulation of a virtual impedance, similar to a real SM impedance while conserving a dynamic electric model [14–17]. It is also possible to consider the most basic SM model [18], the so-called "algebraic" model, based on the SM's steady state representation [19–21].

In this paper, standardization proposal tests are detailed, initially based on the generators sets and SM standards, to identify the minimum set of requirements that a grid-friendly VSG must validate to be integrated in an isolated microgrid (as most constrained environment). Three SM models, representing various precision levels (a complete, a reduced and a static model), are implemented in a digital signal processor of an industrial inverter (with its local controller). The three models are submitted to the standardization proposal tests to identify their relevance regarding the needed VSG performances in a constrained environment with limited computational power, as the work on standards is set to take place with an economic viability perspective in mind. The system sole stability under load impacts, short-circuit and harmonics production is presented and discussed. To complete the standardization proposal tests, the capacity of the three resulting VSG to operate in parallel with identical and different power sources in an isolated microgrid is assessed in this study. In addition to the set of standardization proposal tests, the paper concludes on the comparison of the SM models regarding their capacity to comply with the defined requirements and the associated technical and economic compromise to be made in the wake of a future industrial commercialization of an inverter-based generator implementing a VSG solution.

2. Models of synchronous machines

The studies are conducted in per-unit (p.u.) and in the rotating dq frame. Three models are considered, with an increasing level of complexity, described below.

2.1. Complete model. The so-called "complete" model is constituted of 5 equations for the fluxes and 2 equations for the output currents, requiring to characterize 13 parameters [4, 22]. The complete model is not described here due to pages limitation.

2.2. Reduced model. The "reduced" model is based on hypotheses allowing to simplify the complete model's equations while retaining the most interesting transient characteristics. The following hypotheses are considered:

- non-salient pole machine;
- no magnetic saturation;
- no magnetic hysteresis;
- no imperfection, all leak fluxes are equal to zero;
- no dampers.

The reduced model is given in (1) to (3) in a state space form, first proposed in [23].

$$\frac{\mathrm{d}\psi_d}{\mathrm{d}t} = \omega_0\left[-\frac{R_s}{L'_d}\psi_d + \omega_r\psi_q + R_s\left(\frac{1}{L'_d} - \frac{1}{L_d}\right)\psi_{fd} + e_d\right], \tag{1}$$

$$\frac{\mathrm{d}\psi_q}{\mathrm{d}t} = \omega_0\left[-\frac{R_s}{L_d}\psi_q - \omega_r\psi_d + e_q\right], \tag{2}$$

$$\frac{\mathrm{d}\psi_{fd}}{\mathrm{d}t} = \omega_0\left[\frac{L_d}{L'_d T'_{do}}\psi_d + \frac{L_d}{L'_d T'_{do}}\psi_{fd} + e_{dd}\right]. \tag{3}$$

The output variables of the model, the stator output currents, are given by:

$$i_d = -\frac{1}{L'_d}\psi_d + \left(\frac{1}{L'_d} - \frac{1}{L_d}\right)\psi_{fd}\,, \tag{4}$$

$$i_q = -\frac{1}{L_d}\psi_q\,. \tag{5}$$

Hence, the reduced model is characterized by 3 fluxes equations, 2 output currents equations and only requires 4 parameters to be determined.

2.3. Static model. The "static" model is based on the phasors' diagram representation of a generator and only retains steady states characteristics. For this model, two constraints are considered in addition to the hypothesis of the reduced model:

- no saturation;
- the inductances are independent of the time.

Comparing this model to the other dynamic ones highlights the need of standards dedicated for VSG. This is notable from a performance point of view but also considering that this model is easy to implement and does not necessitate a large computational capacity. Probably for those reasons, the static model is indeed used in various VSG projects [18, 21, 24].

Fig. 1 represents the voltage diagram based on the phasor representation. It can be noted that the dq-frame is not defined as in [18]. For the comparison with the other two SM models, the q-axis is defined based on the excitation voltage e_{fd}, as rep-

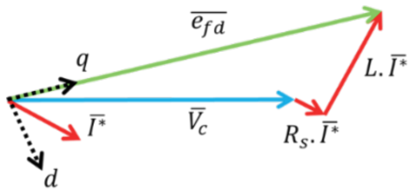

Fig. 1. Voltage diagram of the static SM model in dq-frame

resented in Fig. 1. Hence, the output currents are:

$$i_d = \frac{\omega_r L_d(e_{fd}-e_q)-R_s e_d}{(R_a^2+\omega_r^2 L_d^2)}, \tag{6}$$

$$i_q = \frac{-\omega_r L_d e_d + R_s(e_{fd}-e_q)}{(R_s^2+\omega_r^2 L_d^2)}. \tag{7}$$

The reactance L_d is generally greater than the resistance R_s. Hence, the reduced output currents are:

$$i_d = \frac{(e_{fs}-e_q)}{\omega_r L_d}, \tag{8}$$

$$i_q = -\frac{e_d}{\omega_r L_d}. \tag{9}$$

In the end, the static model is represented by two currents equations and is based on only one parameter: L_d.

2.4. Frequency response of the three SM models. The study of the three models' frequency response characteristics provides an insight on the dynamic performances of each model, thus their relevance in the standardization proposal set of the following sections. This study is based on the fluxes equations, as detailed in [22]. The symbol Δ represents an elementary increment of the fluxes.

$$\Delta\psi_d(s) = \mathfrak{F}\Delta e_{fd}(s) - \mathfrak{L}_d(s)\Delta i_d(s), \tag{10}$$

$$\Delta\psi_q(s) = -\mathfrak{L}_q(s)\Delta i_q(s). \tag{11}$$

- $\mathfrak{L}_d(s)$ is the d-axis inductance transfer function;
- $\mathfrak{F}(s)$ is the stator to field transfer function;
- $\mathfrak{L}_q(s)$ is the q-axis inductance transfer function.

For the complete model, the transfer function parameters $\mathfrak{L}_d(s)$, $\mathfrak{F}(s)$, $\mathfrak{L}_q(s)$ can be found in [22]. For the reduced model, the parameters are defined below considering that $T'_{do} > T'_d$.

$$\mathfrak{L}_d^{reduced}(s) = L_d \frac{1+sT'_d}{1+sT'_{do}}, \tag{12}$$

$$\mathfrak{F}^{reduced}(s) = \frac{L_d}{R_{fd}} \frac{1}{1+sT'_{do}}, \tag{13}$$

$$\mathfrak{L}_q^{reduced}(s) = L_d, \tag{14}$$

$$\mathfrak{L}_d^{static}(s) = L_d, \tag{15}$$

$$\mathfrak{F}^{static}(s) = \frac{L_d}{R_{fd}}, \tag{16}$$

$$\mathfrak{L}_q^{static}(s) = L_d. \tag{17}$$

Fig. 2 highlights the three precision levels of the SM's models. The static model, due to its simplifications, only represents the steady-state and has no time-dependency. This also means that the response of the VSG is immediate after an impact.

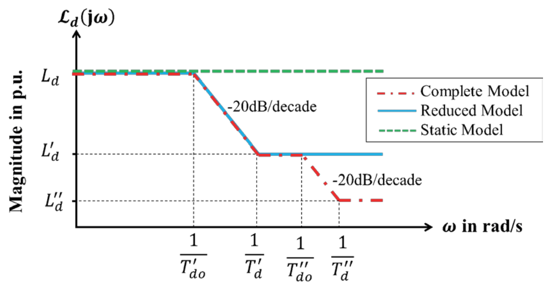

Fig. 2. $\mathfrak{L}_d(s)$ magnitude for the three SM models

For the reduced model, without the damper windings, only transient and steady-state's phenomena are reproduced, the system's response is linked to the short-circuit time response T'_d and the open-circuit time response T'_{do}. The complete model is the most precise one, as all phenomena of the SM are represented, from steady state to sub-transient variations. These phenomena are characterized by the short-circuit transient and sub-transient time responses T'_d and T''_d, the open-circuit transient and sub-transient time responses T'_{do} and T''_{do}.

Fig. 3 shows that the e_{fd} voltage presents similar impacts on the complete and reduced models at high frequencies (the effect of the e_{fd} voltage is minimized with the high frequencies). Concerning the static model, the impact of the e_{fd} voltage is identical for all frequencies which means that, during short-circuits, the value of e_{fd} will have a significant influence on the system's response when supplying loads with high frequencies characteristics. As highlighted in (14) and (17), the q-axis inductance transfer function has time dependency only in the case of the complete model, due to the implemented damper windings.

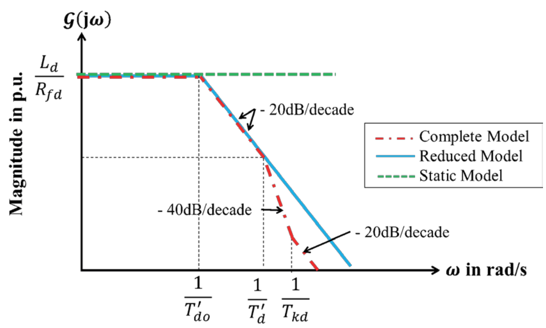

Fig. 3. $\mathfrak{F}(s)$ magnitude for the three SM models

The three SM models present different frequency responses. The static model only represents the steady-state, the reduced model represents in addition the d-axis transient phenomena and finally, the complete model details sub-transient, transient and steady states frequency responses. These three complementary models are chosen to practically illustrate the needs of standardization of the VSG-based inverters as well as the possible limitations such standard tests could emphasize.

3. Implementation in the digital controller of an industrial inverter

As the VSG must be a plug-and-play solution, the idea is ultimately to study the integration of the three SM models in a digital signal processor (DSP) of an industrial inverter, a SCHNEIDER ELECTRIC SOLAR grid tie inverter, a 25 kVA and 400 V phase-phase output voltage. Fig. 4 shows the control scheme of the VSG implemented in the control card of the industrial inverter. The controller represented in Fig. 4 is detailed in [4]. Only the SM model of the VSG control, emphasized in bold in Fig. 4, is modified for the comparison.

Table 2 defines the SM parameter considered for the implementation, the parameters that are not listed in Table 2 are determined thanks to the SM characteristics.

Table 2
Parameters definition for the SM models

Parameters	p.u.	Parameters	ms
X_d	1.93	T'_d	74
X'_d	0.154	T''_d	7
X''_d	0.077	T'_{do}	1006
X'_q	1.16		
X''_q	0.162		
R_s	0.0347		

For the discretization and implementation in the DSP, the Euler forward method is used, resolving the differential systems of equations of the SM defined by $\dot{y} = f(y)$ thanks to [4], considering T_s as the sampling time:

$$y(k) = y(k-1) + T_s f(y(k-1)). \tag{18}$$

The discrete model is implemented with MATLAB Simulink™ using the "Embedded Coder" toolbox of MATHWORKS™, and the "Code Composer Studio" toolkit. The DSP's central processing unit (CPU) load is reported in Table 3 for the three SM models.

Table 3
CPU load per SM model implemented in the DSP of the VSG

Model	CPU load in %
Complete model	76.61
Reduced model	69.42
Static model	62.60

All the CPU load cannot be used for the VSG model, in order to ensure a proper operation of the controller (maximum 75%, to avoid overloading and numerical errors that could destabilize the controller). Note that only the SM model changes in the comparison, not the rest of the controller including the direct and inverse Park transformations, the mechanical equations and the regulation. This explains why the CPU load is still high even with the static model as there is a mandatory minimum CPU load needed by the local controller, independently from the SM model itself.

Considering the industrial inverter computation capability, the complete model is not adapted, as the VSG could be unstable. The complete model can be implemented in this industrial inverter; however, no other feature can be added to the solution (ancillary systems). Hence, the advantage to have a virtual model that could be modified is lost due to its high CPU load. With the reduced model, the CPU load is still important, but far enough from 75% to ensure a proper operation of the controller in the industrial inverter. The CPU load of the static model is clearly reduced compared to the complete one. This model will have no implementation problem.

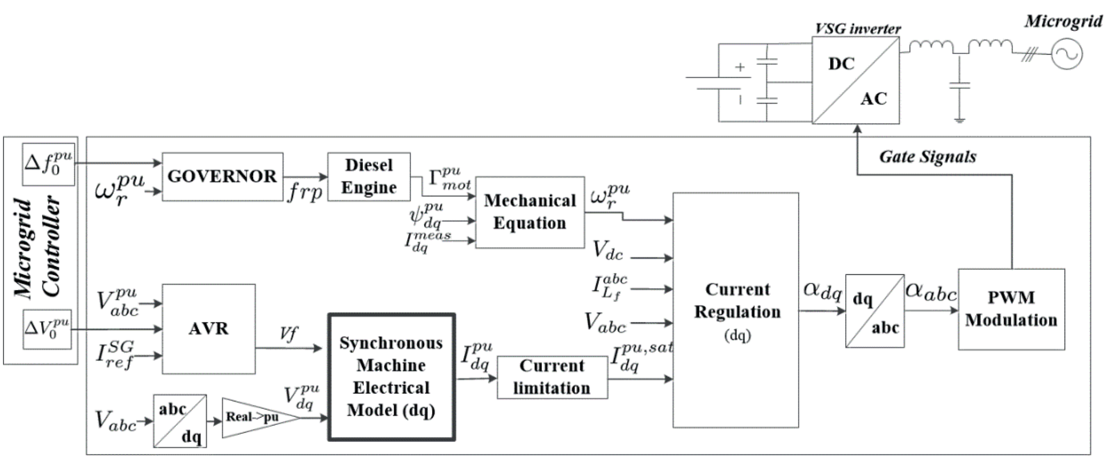

Fig. 4. Control scheme of the VSG

4. Proposed tests for the standardization of the VSG

Considering the generator sets and SM standards as a reference, an assessment of the stability of the VSG and an harmonics analysis are mandatory. Determining the impact of the SM model on the performances of the VSG-based inverter in that context is used to highlight the relevance of the proposed tests. Note that it is not necessary to study the small or large signals stability of the internal angle of the machine because it is possible to change the theoretical value of the mechanical torque at any time.

4.1. System stability. In order to validate the frequency and voltage stabilities, three test cases have been selected and chained in a complete scenario, described in Table 4. The load variation was chosen first to highlight the impact of the SM model on the performances of the VSG-based inverter and second to apply some tests from the SM standards like harsh load impact and shedding, overloading, the voltage harmonic distortion and short-circuit to a VSG [7].

Table 4
Load variation scenario proposed for standardisation

Time (s)	Load impact
0	Off-loading
1	25% of active power (5 kW)
2	100% of active power (20 kW)
3	120% of active power (25 kW)
4	Off-loading (0 kVA)
5	Three-phases short-circuit of 50 ms in output of the inverter
6	30% of reactive power (6 kVAr)
7	30% of reactive and 30% of active power (16 kVA)
8	Off-loading (0 kVA)
9	Stop

4.1.1. Models stability with load variations. The VSG is developed to be a plug-and-play solution for microgrids with a high share of renewable energy production, having a positive impact on microgrids stability during large load and generation variations. The generality of the scenario presented in Table 4 is designed to validate the stability and performances of any implementation of VSG. For this paper, the three SM models are completed with frequency and voltage control, a governor, an automatic voltage regulator (AVR), and the mechanical equation of a SM [4] as depicted in Fig. 5 and Fig. 6. Those figures present the output currents of the VSG with the three SM models, based on the scenario presented in Table 4. The three models are stable during the load variations, overload and highly reactive power load that are necessary for the standards validation. As expected, the differences between the models are visible during the transient and sub-transient events.

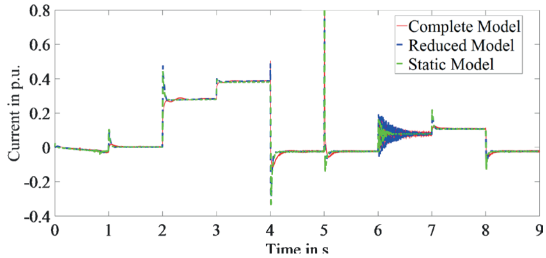

Fig. 5. Output current i_d for the three SM models

When initiating the transient responses, the models' differences reduce rapidly until the steady state is reached. All models present a similar behavior in steady state. The static model is subject to noticeable oscillation during load variations, while the other models, with the help of the transient and sub-transient characteristics, are less impacted.

Another notable difference between the three models is the output three-phases current in response to a highly inductive load, as it can be seen in Fig. 5 and Fig. 6 at $t = 6$ s. Due to the high inductance, an output DC-component appears in the current, both the reduced and the static models stabilize more rapidly than the complete one as the dampers of the complete model are opposed to the DC currents dissipation.

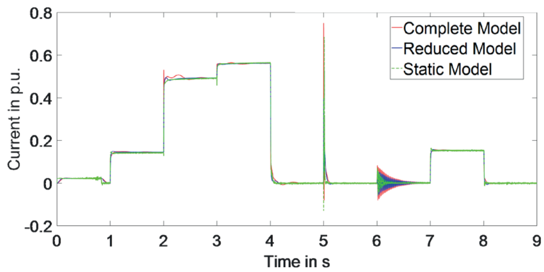

Fig. 6. Output current i_q for the three SM models

Fig. 7 details the mechanical frequency variation of the three models during the scenario described in Table 4. It can be noted that the frequency deviation is similar for the complete and the reduced models. The static model frequency deviations are more important. This high frequency deviations for the static model could be considered in the context of a grid's protection determination to avoid inopportune load-shedding due to the high frequency variations.

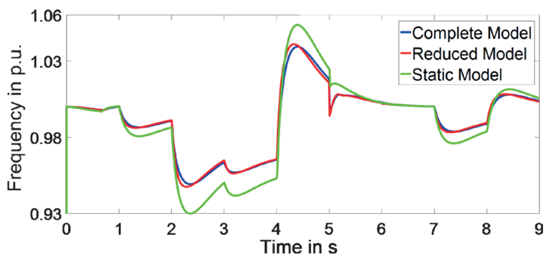

Fig. 7. Output frequency in Hz for the three SM models

Fig. 8 represents the root mean square (RMS) output voltage of the three models. The complete and reduced models have similar responses. The static model is different especially during highly inductive load variations and short-circuits. It can be noted that the RMS output voltage of the static model is less impacted by load variations than both the other models as it is opposed to the voltage variations. However, the transient voltage characteristics of the static model does not respect the standards described in [9] as this VSG is less subject to voltage variations.

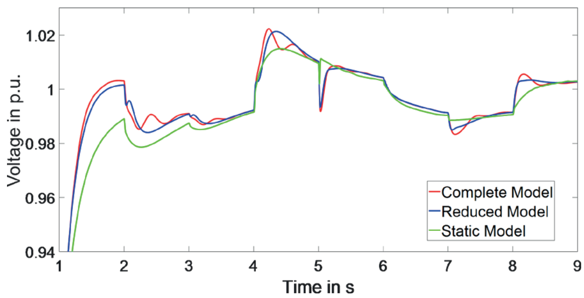

Fig. 8. RMS output voltage for the three SM models

To conclude, all the models are stable during the scenario described in Table 4. However, it has been noted that the performance of the static model is clearly worse than the one of the other two models in this context and does not respect the SM standards for industrial applications. In addition, the frequency deviation is important with the static model, which means that the microgrids over/under frequency protection devices must be configured adequately (with higher tolerances) to include these deviations and avoid inappropriate load-shedding.

From the standard point of view, the definition of ranges of deviations in frequency and voltage must be set and adapted to the characteristics of VSGs, similarly to what has been done for the SM in order to ensure a proper integration in grids without destabilizing the system stability. The proposed set of tests is well calibrated to automatically validate an industrial solution regarding those requirements and would in addition be useful to discriminate the precision of the models and the reactivness of the controls.

4.1.2. Short-circuit. Short-circuit is a needed feature for a VSG-based inverter when targeting its industrialization in current isolated microgrids. That is why we tested a three-phase short-circuit with the three VSG implementations to discriminate their capacity to that regard.

One major difference appears between models during a short-circuit fault as it can be seen Fig. 5 and Fig. 6. Indeed, the maximal short-circuit current I_{cc} for the complete model is:

$$I_{cc}^{complete}(max) = \frac{\|V_c\|}{\sqrt{2}L_d''\omega_r}. \tag{19}$$

For the reduced model, the short-circuit current depends only on the transient inductance. Hence, the maximal short-circuit current is defined by:

$$I_{cc}^{reduced}(max) = \frac{\|V_c\|}{\sqrt{2}L_d'\omega_r}. \tag{20}$$

Similarly, as the static model only has steady-states components, the maximum short-circuits current is:

$$I_{cc}^{static}(max) = \frac{\|V_c\|}{\sqrt{2}L_d\omega_r}. \tag{21}$$

Based on the SM characteristics, the d-frame sub-transient, transient and steady-state inductances are taken as $L_d'' \leq L_d' \ll L_d$. Hence, $I_{cc}^{static} \ll I_{cc}^{reduced} \leq I_{cc}^{complete}$ as it can be seen in Fig. 9, presenting the SM model output current magnitude during a three-phases short-circuit of 50 ms applied directly at the output of the inverter. The short-circuit output current magnitude of the complete and reduced models are similar, as the sub-transient inductance L_d'' and transient inductance L_d' are similar and negligible compared to L_d. In this context, the current magnitude during the short-circuit is reduced as expected.

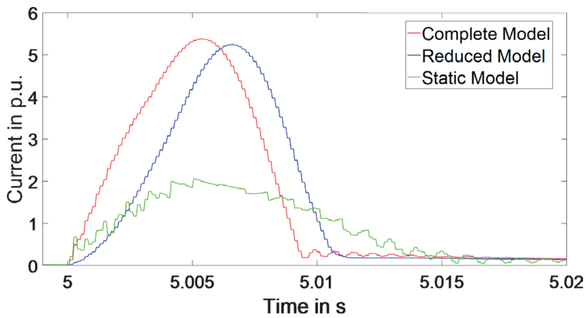

Fig. 9. Output current magnitude defined as $|i| = \sqrt{i_d^2 + i_q^2}$ for the SM models during a three-phases short-circuit of 5 ms

Note that the VSG-based controller is able to sustain the short-circuit for (theoretically) an infinite duration, contrary to a real SM. The model should remain stable except (possibly) for a too short duration (experimentally in the order of magnitude of the ms or less) where the saturation of the inverter could destabilize its operation.

However, the three models are implemented in an inverter, whose output current is limited between 1.5 to 2.5 times the nominal output current, and cannot reproduce the short-circuit current of an actual SM (up to more than 10 times the nominal current). It is an advantage for the static model, regarding the implementation in the controller of the inverter. From a standardization point of view, either there is a limit on the current and then the only choice for the utility is to select the appropriate model based on an entire new set of standard tests, and there is a need to develop new protections, or there is no limit and then the question is the technical and economic compromise between the maximum current of the inverter and its capacity in time to survive a short-circuit, and help detect it.

The voltage dynamic during the short-circuit complies with the to fault ride through requirements defined in the standards of SM [7]. A standard short-circuit test is a necessity in order to both conclude on the VSG stability during short-circuit but also help define adapted protections. Knowing how the VSG reacts during a short-circuit is a necessity to define the microgrids' protection scheme and the VSG viability in an industrial context. However, short-circuits are usually not considered during the traditional study on VSG-based inverters. It is mandatory in the SM standardization and should be as well for the VSG in the future.

4.2. Harmonics analysis. Finally, a harmonics analysis is conducted as it is linked to the SM standards validation tests, whose protocols are defined in [5] and [7].

4.2.1. Voltage harmonics at off-load condition. The total harmonic distortion of voltage (THD_V) is calculated based on [5]:

$$THD_V = \frac{\sqrt{V_0^2 + V_2^2 + V_3^2 + \ldots + V_{n-1}^2 + V_n^2}}{V_1}. \tag{22}$$

With V_k the RMS voltage of k^{th} harmonic of the main frequency and $n = 100$ as defined by the standards [5, 7].

Table 5 details the harmonics value of the three SM models. Both the complete and the reduced models have similar harmonics content and respect the standards. The static model still respects the standards but produces much more harmonics than the other two models. This is due to the influence of L_d in the high frequencies, as L_d is big compared to L'_d and L''_d.

Table 5
THD_V and individual harmonics results at off-load condition

	THD_V in % of rated voltage $< 5\%$		
	Complete model	Reduced model	Static model
THD_V	0.41	0.26	3.24

Individual Harmonic value in % of rated voltage $< 3\%$

Harmonic value	3	5	7	11
Complete Model	0.10	0.11	0.13	0.08
Reduced Model	0.20	0.12	0.10	0.09
Static Model	2.28	0.82	0.79	0.41

4.2.2. Voltage harmonics on non-linear load. For this test, a non-linear load represented by a three-phase diode bridge rectifier and a three-phase resistor is connected to the VSG (one test per SM model). The value of the resistor for this normalized test is defined following the SM standards [5], with E the grid voltage, S the apparent power of the system and $\cos\phi$ the power factor, equal to 0.8 in this paper.

$$R_{THD} = 1.872 \frac{E^2}{S\cos\phi}. \tag{23}$$

Table 6 shows the harmonics analyses of the three models connected to a non-linear load. The complete and the reduced model both respect the standards. The static model does not respect the standards anymore as the total harmonic distortion of voltage exceeds 5%. In addition, the static model individual voltage harmonics for the 3rd harmonic exceeds 3%.

Table 6
THD_V and individual harmonics results with nonlinear load

	THD_V in % of rated voltage $< 5\%$		
	Complete model	Reduced model	Static model
THD_V	3.81	3.92	7.92

Individual Harmonic value in % of rated voltage $< 3\%$

Harmonic value	3	5	7	11
Complete Model	2.37	1.31	0.59	0.33
Reduced Model	2.75	1.53	0.86	0.42
Static Model	3.64	1.15	0.73	0.45

To conclude on the harmonics production of the VSG, both the complete and reduced models respect the SM standards. However, the static model produces a high quantity of harmonics, which does not respect the SM standards.

As the production of harmonics could impact the supplied load depending on the loads' characteristics and sensibility, it is a necessity to define harmonics thresholds that are adapted to the inverters' characteristics. If the same standards as the SM are kept for the VSG-based inverters, the solution based on the static model is not acceptable. On the contrary, for the other two models, the VSG satisfies easily the voltage harmonic requirements, thus allowing to imagine more severe standards, or simply removing filtering devices and decreasing the manufacturing costs. Hence, based on the proposed tests, it is possible to develop specific harmonics standards, better considering the inverters' intrinsic properties but still ensuring that the loads are not impacted by the harmonics production of the inverter.

4.3. Interoperability: parallel operation. The VSG should be a plug-and-play solution. It must be able to operate correctly in parallel with other power sources in any configuration of (micro-)grid. As shown in [24], the microgrid instabilities can be exacerbated by the resonance between generators and VSG. Hence, the capacity of the VSG to operate properly in parallelism with a various set of power sources (independently from the SM model) is mandatory.

As the complete model is the most accurate one compared to a real generator set, a VSG based on the complete model can be put without any problem in parallel with similar or other power sources [26]. However, this is not the case of the reduced or the static model-based VSG. For the parallelism study of the three models, the encountered problems have been divided in two categories, depending on the power sources put in parallel with the VSG.

4.3.1. With an identical VSG. For the static and the reduced models, as there is no damper windings, to avoid any risk of oscillation between multiple identical power sources, some modifications are necessary. The governor's time-response must be adapted with regards to the oscillating time between the SM models. This modification concerns the time response of the voltage and frequency controllers, and only impacts the VSG solution before integration in a microgrid [23]. The oscillation period of the solution without damper must be considered for the frequency controller of the VSG, the governor, to avoid the creation of oscillation. The considered oscillation period is defined by the equation extracted from [25]:

$$T = \frac{2\pi}{p}\sqrt{\frac{10J\omega_0}{I_{cc}E}}\,. \tag{24}$$

With ω_0 the base angular velocity (rad/s), p the number of poles of the SM, E the grid voltage (V), J the moment of inertia (kg.m^2), I_{cc} the short-circuit current (A). The maximum short circuit current I_{cc} is defined depending on the SM model.

4.3.2. With other power sources. As the static model does not have transient characteristics, during a load variation, the voltage is instantly modified and imposed by the static VSG. In addition, as showed in Fig. 8, the voltage variations of the static model are completely different from what can be expected from a SM. Indeed, the voltage produced by the diesel generator present sub-transient and transient characteristics which are opposed to the instantly modified voltage of the static VSG. Hence, voltage oscillations appear in the microgrid as each power source tries to impose the voltage after a load impact, as it can be seen in Fig. 10.

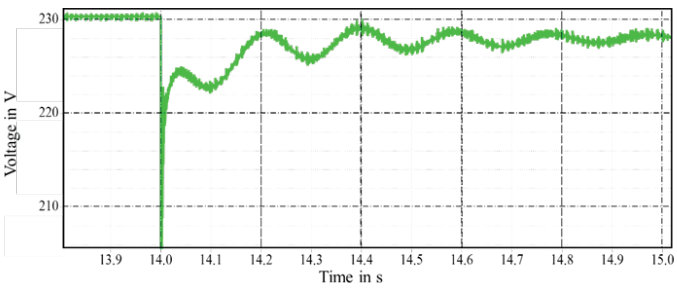

Fig. 10. Grid RMS voltage after a load impact of 25% with the static model VSG and a generator set in parallel

To conclude, for a diesel generator in parallel with a VSG based on the static model, the droop control must be adapted because the voltage is imposed by the model of the VSG as it was identified in [18]. If not solved, this problem could generate voltage instability and reduce the operational performances of the considered microgrid with high frequency oscillation.

In addition to the problem of voltage oscillations, the frequency deviation is noticeable with the static model compared to the other SM models as identified in Fig. 7. During a load impact, the VSG with the static model will have a frequency deviation largely different from the other power sources connected to the microgrid which could result in high frequency and powers variations, protections triggering, etc.

However, the solution proposed in [18] to avoid voltage oscillations requires major modifications to all the other power sources connected to the microgrid. An advanced solution of AVR and governor are proposed in [21] in order to minimize the oscillation in voltage and frequency. The solution was validated in simulation and in experimentation but without considering the computation limitations of the industrial inverter, thus its economic viability once in production.

Finally, with the parallel operation, it can be concluded that the ranges of performances and the class definitions are becoming a necessity to ensure the stability of the microgrid when integrating VSG-based inverters as power sources. Indeed, the parallel operation shows that the frequency and voltage deviations of the VSG-based inverter, especially when considering a static model, impacts the microgrid stability. Hence, such studies should be part of future standards of inverter-based generators, and notably those implementing a VSG controller.

5. Conclusion

In this paper, three SM models implementing a VSG in an industrial inverter are detailed, characterized, and compared with respect to various test cases (load variations, short-circuit events). The tests relate to the context of real SM and generators sets standards and parallel operation with other power sources as in a real microgrid. The three SM models are a "complete" one, constituted of the all dynamic electrical equations, a "reduced" model constituted of a virtual impedance, and a "static" model based on the SM's steady state, whose objective is to discuss the elaboration of a set of standardization proposal tests for grid-friendly VSG-based inverters.

The standardization proposal tests are constituted of active and reactive power load impacts, short-circuit in standalone or parallel configurations and total harmonics distortions. The tests are designed to ensure that any VSG solution (independently from the implemented SM model) can be integrated in a microgrid, once respecting the proposed standards.

The standardization proposal shows that the static SM model is too limited for the industrial context. Indeed, this model presents multiple disadvantages: high frequencies variations that could create inappropriate load-shedding if the protections of the grid are not adapted, no respect of the voltage standards which increases the difficulty of parallelism with other power sources and high productions of harmonics which can be destructive for sensible loads. In addition, the static model has the disadvantage to encounter difficulties to be operated with other power sources, trying to impose instantly a new voltage after a load impact as the model does not have time dependency. The model still presents some advantages: the output short-circuit current is lower than with a real SM and the computational burden for its implementation is low on a DSP. So, for this model, some improvements are necessary to ensure a VSG that respects future standards for the integration in (micro-)grids without destabilizing the existing system or needing alternative protections.

The complete model is the most realistic one. It respects the SM and generator standards and has a limited production of harmonics when supplying load. However, a first problem is the output currents during a short-circuit that must be saturated, otherwise the inverter could be damaged. A second problem is the difficulty to be implemented in a current industrial inverters' DSP without considering extra costs that could be justified by the definition of a more restrictive standard.

Finally, the reduced SM model is the most adapted to a VSG implementation in an industrial inverter as it respects the standardization proposal and can operate in parallel with other power sources while being "light" enough for the inverter's DSP not to necessitate extra investments. The parallel operation has been resolved easily in just choosing adapted voltage and frequency controllers to avoid the risk of oscillations between this VSG and other power sources.

The set of tests proposed in this paper for the standardization of grid-friendly VSG is a first step that would necessitate to more precisely define thresholds regarding for example harmonics analysis (maybe allowing to consider a basic model in some configurations) as well as requirements for additional modification of power sources that are integrated in parallel with VSG solutions. To conclude, as highlighted in the text, a much needed work would be to determine jointly the requirements for both the VSG solution and its protection, including the protection scheme of the concerned (micro-)grid.

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