



AALBORG UNIVERSITY
DENMARK

Aalborg Universitet

Modelling, Implementation, and Assessment of Virtual Synchronous Generator in Power Systems

Chen, Meng; Zhou, Dao; Blaabjerg, Frede

Published in:
Journal of Modern Power Systems and Clean Energy

DOI (link to publication from Publisher):
[10.35833/MPCE.2019.000592](https://doi.org/10.35833/MPCE.2019.000592)

Creative Commons License
CC BY 4.0

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Chen, M., Zhou, D., & Blaabjerg, F. (2020). Modelling, Implementation, and Assessment of Virtual Synchronous Generator in Power Systems. *Journal of Modern Power Systems and Clean Energy*, 8(3), 399-411. Article 9082071. <https://doi.org/10.35833/MPCE.2019.000592>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Modelling, Implementation, and Assessment of Virtual Synchronous Generator in Power Systems

Meng Chen, Dao Zhou, and Frede Blaabjerg

Abstract—As more and more power electronic based generation units are integrated into power systems, the stable operation of power systems has been challenged due to the lack of system inertia. In order to solve this issue, the virtual synchronous generator (VSG), in which the power electronic inverter is controlled to mimic the characteristics of traditional synchronous generators, is a promising strategy. In this paper, the representation of the synchronous generator in power systems is firstly presented as the basis for the VSG. Then the modelling methods of VSG are comprehensively reviewed and compared. Applications of the VSG in power systems are summarized as well. Finally, the challenges and future trends of the VSG implementation are discussed.

Index Terms—Inertia, virtual synchronous generator (VSG), frequency control, renewable energy source (RES), inverter.

I. INTRODUCTION

THE traditional power systems are dominated by synchronous generators (SGs), which are proved to have many inherent favorable features such as large inertia and damping that are beneficial for the stable operation of power systems. Meanwhile, the frequency and voltage regulation can easily be achieved by SGs with the governor and automatic voltage regulator (AVR). The inertia can be generally defined as the resistance of an object to the change in its state of motion. In terms of power system stability, the inertia implies the ability to maintain the rotor speed, and the frequency under disturbances, e. g., short circuits [1]. This function is determined by the swing equation of the SGs, which describes the power unbalance between the generation and load. When any disturbances lead to power unbalance, the rotor will release or store the kinetic energy proportional to the inertia to resist the frequency change [2]. This effect helps to decrease both the frequency nadir and the rate of change of frequency (RoCoF) [3], [4].

In the past decade, due to the potential shortage of fossil energy, the increase of energy consumption, and pollution of the environment, the renewable energy sources (RESs) such as solar and wind have drawn great attention worldwide. By

the end of 2018, 17.6% of the power supply is provided by RESs in USA, in which the capacities of solar and wind are 51 GW and 94 GW, respectively [5]. In EU, 115 GW and 178.8 GW of solar and wind power have been installed, accounting for 12.1% and 18.8% of the total installed power supply, respectively [6]. In this context, the characteristics of traditional power systems will change because most of the RESs are based on power electronics, which have neither mechanical rotors nor inertia. Therefore, since more power electronic based generation units are gradually connected to power systems, the total inertia of the system will decrease, which could influence the frequency response during certain events [7].

In general, the low inertia of power systems will have impact on two key aspects. Firstly, a lower inertia introduces a poorer frequency nadir during the disturbances. There is not sufficient kinetic energy to keep the frequency at a specified level, which causes large frequency deviations and might be harmful to both generation and consumers. Besides, a lower inertia will lead to a large RoCoF, which triggers the active protection system to trip the generators [8]-[10]. Some challenges and solutions of the low-inertia power systems are reviewed in detail in [11]. It has been concluded that the low inertia caused by the power electronic based generation units may deteriorate the frequency stability and the potential reliability of the modern power electronic based system.

One of the most promising solution is the virtual synchronous generator (VSG). Although different implementations have been proposed in the literature such as synchronverter [12] and virtual synchronous machine (VISMA) [13], they adopt the idea of controlling the inverter to mimic an actual SG by using its corresponding models. In this way, an inverter performs equivalent to an SG when neglecting the switching operation, especially in terms of inertia response [14]-[16]. Therefore, the VSG can play an important role in more power electronic based power systems in the future. Recently, some papers have tried to review the inertia emulation and the VSG from different perspectives. Inertia response techniques for RESs are reviewed in [17], which focuses on how to introduce the inertia response into the control strategies of the RESs. In [18], different ways to provide inertia such as DC-link capacitors and other energy storage systems (ESSs) are summarized. For the VSG, different topologies are proposed by some leading research groups and are reviewed in [19], [20]. Further, in [21], a number of VSG models are united into the Phillips-Heffron model represent-

Manuscript received: August 30, 2019; accepted: December 10, 2019. Date of CrossCheck: December 10, 2019. Date of online publication: April 29, 2020.

This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>).

M. Chen (corresponding author), D. Zhou, and F. Blaabjerg are with the Department of Energy Technology, Aalborg University, Aalborg 9220, Denmark (e-mail: mche@et.aau.dk; zda@et.aau.dk; fbl@et.aau.dk).

DOI: 10.35833/MPCE.2019.000592



ed by small-signals.

This paper will give a comprehensive review of VSG including modelling, new developments and application in power systems, and will also discuss the future challenges. The remaining part of this paper begins with a review of both the SG and VSG models as well as their comparison and assessment given in Section II. New development of VSG corresponding to different models is also included in this part. The application of VSG in power systems is described in Section III. Afterwards, the challenges and future trends of VSG are presented in Section IV. Finally, the conclusions are drawn in Section V.

II. PRINCIPLES OF VSG

The VSG introduces the models of SG into the control system of the inverters, and then the static power electronic converter is able to operate like a rotating electrical machine. In addition, by emulating the governor and AVR, the VSG can easily achieve the functions of quick damping of voltage and frequency oscillations, sharing the power automatically, and synchronizing to the grid.

The basic principle diagram of the VSG is shown in Fig. 1, where L_s and R_s are the line inductance and resistance, respectively. The common power stage of the VSG is a three-phase inverter with a filter, where L_f , R_f and C_f are the inductance, resistance, and capacitance of the filter, respectively; u_{abc} is the three-phase voltage of the inverter; v_{abc} is the voltage of the capacitor; i_{abc} is the three-phase current of the inductor; and i_{oabc} is the three-phase output current.

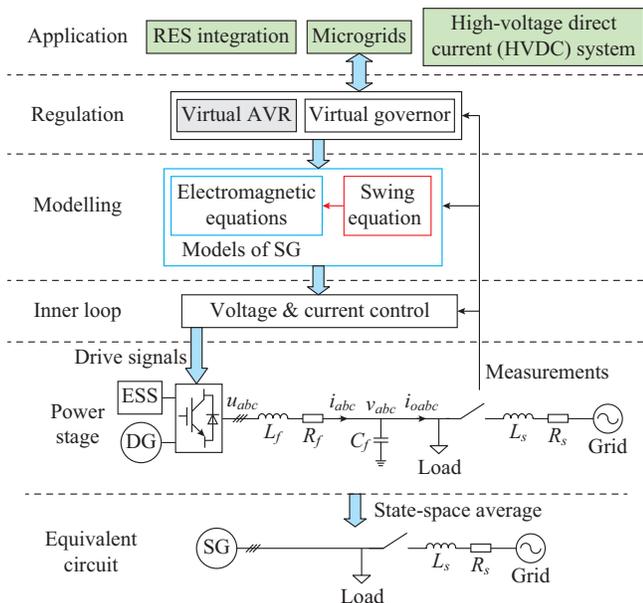


Fig. 1. Diagram of basic principle of VSG.

By introducing the models of SG into the control of the inverter, the VSG can make the power exchange between the DC source and the power system with the same characteristics as the SG. An inverter can be equivalent to an SG when the switching of power semiconductors is neglected. In the SG, the mechanical rotor and windings can provide the nec-

essary inertia and damping for a stable operation, while in the VSG, the virtual inertia and damping should be provided by the ESS, which can be an additional battery, super-capacitor, or DC-link capacitor itself, etc.

The control system of the VSG consists of three levels, i.e., the inner control loop, SG modelling, and the frequency and voltage regulation. The inner loop is identical to other control structures such as droop control [22], and they are not necessary in some implementations. Therefore, it will not be discussed in this paper in details. Models of the SG represent the mechanical and electromagnetic characteristics including the inertia and damping, which are the core of the VSG. Finally, the regulation of VSG using virtual governor and AVR enables the frequency and voltage within the specified levels, and achieves the interaction between the VSG and the power system. As a result, there are important applications of VSG in different areas of the power systems such as RES integration, microgrids, and HVDC system.

Generally, the VSG has the following features:

- 1) Enable the inverter to mimic the SG, especially its inertia and damping characteristics.
- 2) Enable the energy source to provide virtual inertia if necessary.
- 3) Enable to participate in frequency and voltage regulation via virtual governor and AVR.
- 4) Enable to feature “plug and play” in power systems.
- 5) Enable to operate in islanded mode for the grid-supporting VSG.
- 6) Select parameters flexibly without considering the physical constraints of the real SG.
- 7) Introduce problems of both SG such as power oscillation and inverter such as harmonics.

A. Representation of SG in Power Systems

Before discussing the VSG, this part will firstly summarize the representation of SG in power systems. These SG models are the basis of the VSG.

According to different simplifications, the models of SG can be classified from the 9th-order to the 2nd-order, as illustrated in Fig. 2. An accurate model of an SG is the 9th-order or the 8th-order based on the type of the turbines. These models can hardly be used directly because of the time-varying inductances, where it is typical to transform the models into dq frame and into a p.u. system [23]. Nevertheless, the models can still be as high as the 8th-order or the 7th-order. Therefore, the standard representation of SG in power systems, especially in the stability studies, is from the 6th-order to the 2nd-order according to different accuracy requirements [23]. In addition, the 2nd-order model of the SG can be classified into a constant E'_q (the q -axis component of the voltage behind transient reactance X'_d) model, a constant flux model and a steady-state model [23].

For the state-of-art solutions, the 7th-order, 4th-order, and 2nd-order models of SG have been revised and applied into the implementation of VSG. As mentioned above, the most important part of SG models is the swing equation, which is given in (1).

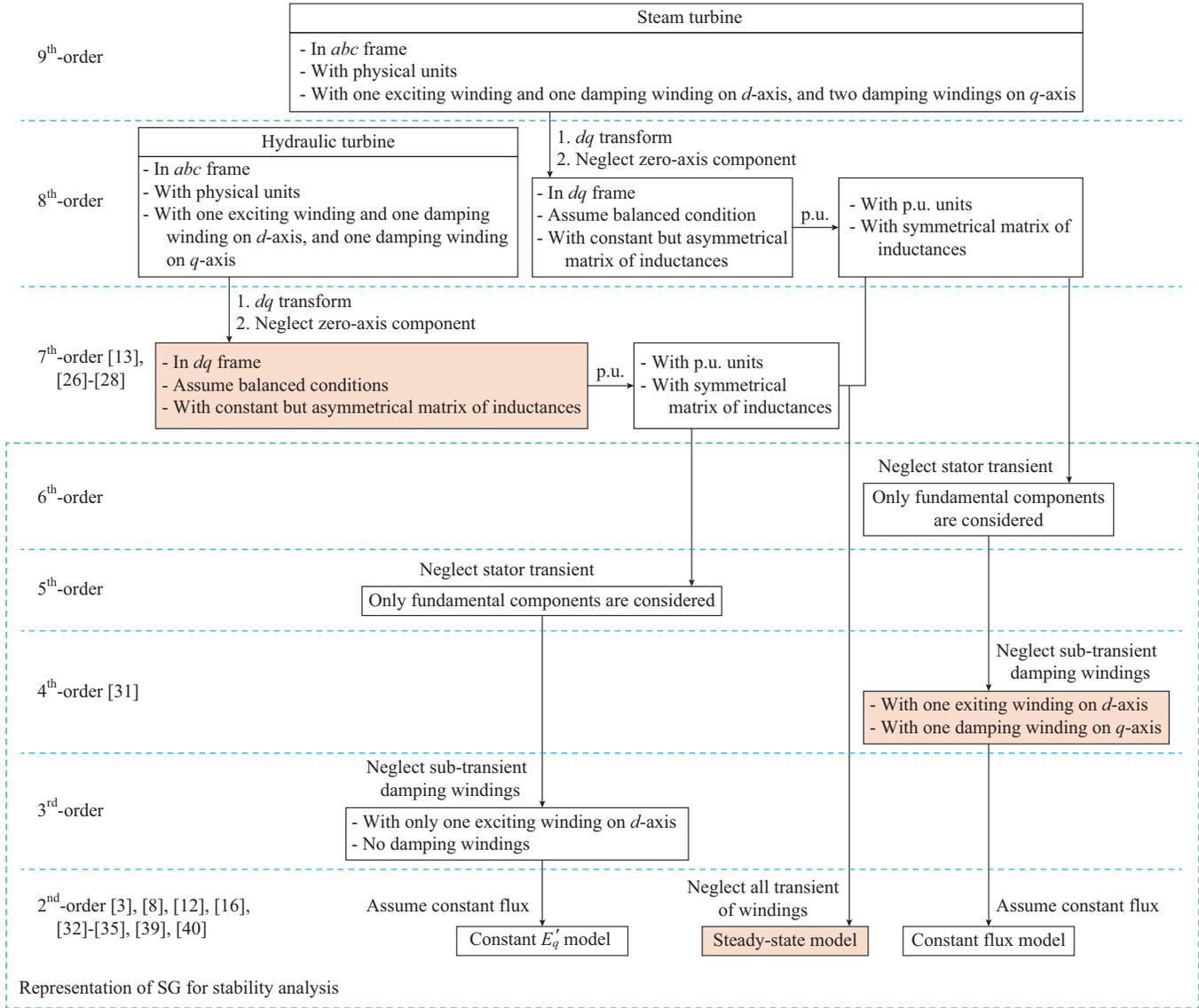


Fig. 2. Summary of eight different representation levels for SG in power systems.

As seen in the following, some literatures only use the swing equation to build the VSG model even without the electromagnetic part.

$$\begin{cases} T_m - T_e - K_d \Delta \omega = J \frac{d\omega}{dt} \\ \frac{d\theta}{dt} = \omega \end{cases} \quad (1)$$

where T_m and T_e are the mechanical and electromagnetic torques, respectively; K_d is the damping factor; ω is the angle frequency; θ is the angle of the rotor; and J is the moment of inertia, which will not influence the steady-state operation but have apparent impact on the dynamics. A large J implies more energy released or absorbed during the disturbance, and stronger ability for frequency support.

A converter can be controlled as a grid-feeding inverter, a grid-forming inverter, or a grid-supporting inverter [22]. Only a few literatures investigate the grid-feeding or current-controlled VSG, which usually adds virtual inertia terms in

the traditional PQ control strategy [24]-[27]. However, this strategy relies on the phase-locked loop (PLL) and cannot operate in islanded mode like an actual SG. The grid-forming behaves like the traditional Vf control strategy, and the power sharing cannot be achieved easily. Therefore, from the perspective of reliability and flexibility, it is controlled as a grid-supporting inverter, which is voltage-controlled and can mimic the model of SG directly. In this way, the inverter can emulate the benefits of an SG better such as frequency and voltage self-establishment ability, and flexible regulation of frequency and voltage.

B. Modelling of VSG

1) 7th-order Model

As mentioned before, not all the models of SG have been used in the modelling of VSG. The highest order and most accurate model presented in the literature is the 7th-order model [13], [28], which is also called virtual synchronous machine (VISMA) model. Nevertheless, it has still made a

further simplification that the matrix of the inductances is symmetrical, which is not true for the SG as described in Fig. 2.

The VISMA strategy requires much calculation burden due to the complicated dynamic model. Together with the potential instability of the dq model in unbalanced conditions [29], two improved models, named VISMA Method-1 and VISMA Method-2, are proposed and compared in the abc frame, respectively [30]. It is shown that the VISMA Method-2 is a better strategy to implement the VSG due to the high voltage quality and the widely used pulse width modulation (PWM) technique. The control structure is shown in Fig. 3 [30], where R_v and L_v are the resistance and inductance of the virtual stator, respectively; and E is the magnitude of the voltage. However, the PWM technique is easily used in VISMA Method-1 when adding a proportional-integral (PI) controller instead of a hysteresis controller [31]. A novel VSG control with coupling compensation terms is proposed in [32], where the frequency and voltage deviations are introduced into the power control loop with the electromagnetic equations being the dynamic model like the VISMA. This new VISMA-based VSG has smaller power oscillations caused by power coupling.

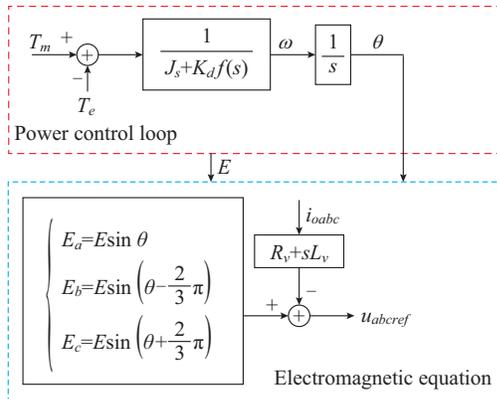


Fig. 3. Control structure of VISMA Method-2.

Compared with the 7th-order model of SG besides building in different modelling frames, the VISMA Method-1 and Method-2 neglect all the damper windings and the influence of flux coupling. The 7th-order model shows the most accurate emulation of the SG. However, it can hardly be used in stability analysis of power systems due to the complexity.

2) 4th-order Model

Neglecting the stator transient and sub-transient damping windings, the representation of SG can be simplified to a 4th-order model. Nevertheless, some transient dynamics are still considered in the model.

In [33], the 4th-order model of the SG is completely implemented in the VSG control without any changes. Simulation results imply that the VSG based on the 4th-order model can mimic the response of the SG with the same parameters in different conditions. The control structure is shown in Fig. 4 [33], where P_{set} , f_{set} , and V_{set} are the set-points of active power, frequency, and voltage, respectively; X_{dq} and X'_{dq} are the

virtual synchronous and transient reactances of d -axis or q -axis, respectively; v_{dq} and i_{odq} are the output voltage and current of d -axis or q -axis, respectively; T'_{dq0} is the virtual transient open-circuit time constant of d -axis or q -axis; E'_{dq} is the d -axis or q -axis voltage behind the virtual transient reactances; and u_{dqref} is the d -axis or q -axis voltage reference of the inverter.

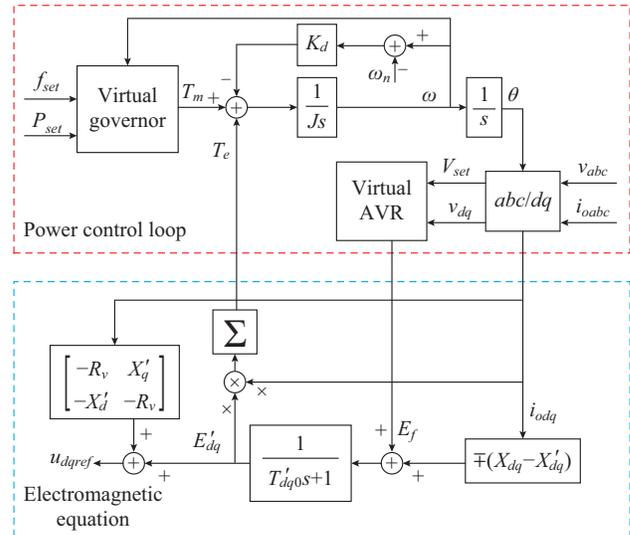


Fig. 4. Control structure of 4th-order model based VSG.

Although the 4th-order based VSG is much simpler than that based on the 7th-order model, there are still many parameters to be designed corresponding to the transient windings. Meanwhile, there is still no literature discussing the necessity of such parameters in the modelling of VSG.

3) 2nd-order Model

A simpler modelling of VSG is based on the 2nd-order model of SG. As seen in Fig. 2, the constant E'_q model is not applied in the VSG, and the other two models have the similar equivalent circuit as shown in Fig. 5 [23], where the internal voltage and the impedance used in the models are different.

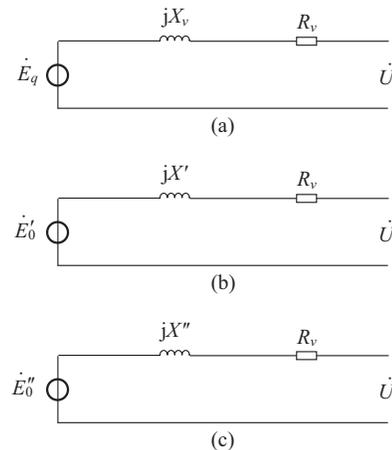


Fig. 5. Equivalent circuit of 2nd-order model of SG. (a) Steady-state model. (b) Classical model (constant flux model). (c) Subtransient model (constant flux model).

In Fig. 5(c), X'' is the subtransient impedance. In the literatures of VSG, the virtual impedance is usually seen as the synchronous impedance. Therefore, the steady-state model is used, where all the winding transients are neglected and only the steady-state influence is considered without changing the inertia characteristic [34]. The dynamics of the voltage source converter (VSC) are neglected as well due to the fast response of the voltage control loop and the filter [35]. The control structure is shown in Fig. 6 [34], where X_v is the virtual reactance. In this method, the virtual torque is evaluated by the output power of VSG, which implies that, compared to the SG, the virtual power consumed by the virtual stator resistances does not appear in the calculation of the electromagnetic power.

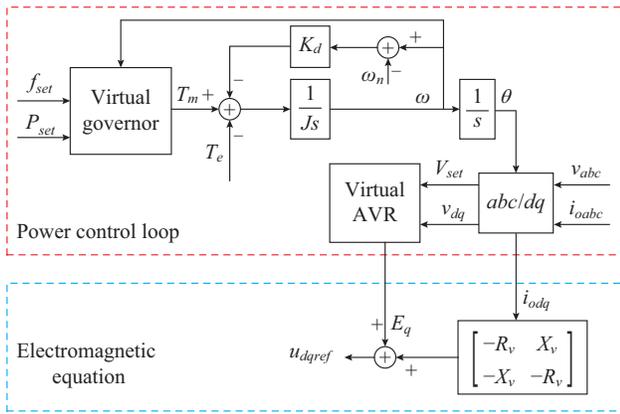


Fig. 6. Control structure of steady-state model based VSG.

It is worth mentioning that the stator parameters should be designed carefully without leading to synchronous resonance [36]. In [37], only the virtual resistance is added to limit the current. It shows the flexibility of VSG, which can design the parameters according to the requirement without considering the physical constraints of the real SG.

As mentioned before, the swing equation represents the important inertia characteristics. Therefore, there are a lot of literatures implementing the VSG by just using the swing equation and focusing on the most important feature. One of the famous implementations is called synchronverter, as shown in Fig. 7 [38], where i_f is the virtual excitation current, and Q is the output reactive power.

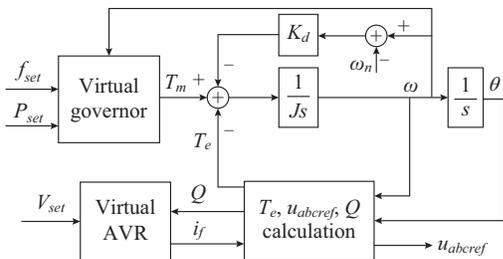


Fig. 7. Control structure of synchronverter.

The synchronverter can take the filter inductance as the stator windings. However, in terms of the control system, it is a 2nd-order system based on the swing equation. It is

worth mentioning that the power calculation of the synchronverter is still based on the electromagnetic relationship of SG rather than the output power of VSG. Reference [39] introduces a damping correction loop into the synchronverter to decouple the active power control and the frequency regulation. Furthermore, a parameter design criterion is proposed directly based on the required steady-state and transient responses. In [40], a Lyapunov function based synchronverter is presented by changing the active power control loop, which implies a better performance for frequency and voltage. In contrast, an improved synchronverter from the perspective of virtual excitation and virtual elements is proposed in [41]. These modifications make the inverter more stable even in asymmetrical grid operation.

A simpler implementation of VSG is shown in Fig. 8 [42]. In this strategy, only the electromechanical characteristics represented by the swing equation are emulated without modelling the electromagnetic characteristics of the SG. In some cases, it is enough to obtain the favorable inertia dynamics [43]. This control structure is much like the traditional droop control, which can also provide the frequency support. Some literatures have compared these two control strategies from different aspects. In [3] and [16], it is proved that the droop control and the VSG are equivalent to small-signals under certain conditions. In [44], the droop control is combined with the DC-link capacitor in order to provide the inertia to some extents like the VSG. Further, a VSG control is proposed in [45], which has better performance compared with the droop control. Although the swing equation based VSG is simple, the parameters such as the virtual inertia can be flexibly implemented to be variable or even negative in order to achieve good performance [8], [46]. In [9], the reactive power is also added into the swing equation to decouple the active and reactive power, and then the output power oscillation is easy to be damped. An improved damping strategy for the swing equation based VSG is shown in [47]. By introducing the damping effect in the voltage control, the proposed method gives more freedom to regulate the damping without influencing the inertia characteristics. The swing equation based VSG focuses only on the inertia and damping characteristics of SG. As mentioned before, the VSG is more flexible than an actual SG since its parameters are not constrained by physical limitations. Therefore, a VSG can be built with inertia and damping in a general way, where different forms lead to different required dynamics [48].

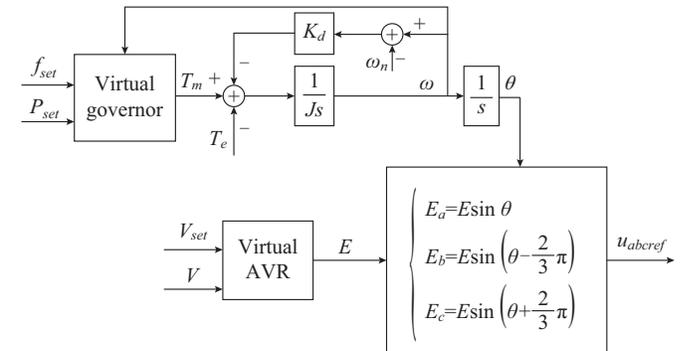


Fig. 8. Control structure of VSG based on swing equation [42].

It should be mentioned that, in the above figures of the control structure, it is assumed that the damping is included in the virtual governor or the droop characteristics, whose equation can be expressed as:

$$P_m - P_{set} = K_d(\omega_{set} - \omega) \quad (2)$$

where P_m is the mechanical power. This is because the damping provided by the rotor, which is much smaller than that provided by the governor, can usually be neglected due to an actual SG [23]. In some literatures, an additional damping term which can improve the performance of VSG is as follows [3], [34], [49]:

$$P_D = K_d(\omega - \omega_g) \quad (3)$$

where P_D is the damping power; and ω_g is the frequency of the grid derived by a PLL. This can be seen as an independent loop, which means that it can be added into different VSG models. A detailed discussion on different damping terms can be found in [50].

C. Comparison of VSGs

To evaluate different implementations of VSG, some comparison results are given in this part, and the response of the SG is also investigated. The models of SG and their frequency characteristics are in focus, and therefore the inner loop and virtual AVR are not included in the control system as discussed in [3]. Actually, the inner loop and AVR have a standalone structure, which means that the VSG with different SG models can have the same AVR and inner loop control strategy. Besides, the DC source is assumed to be ideal as well. A VSG system as shown in Fig. 1 is used as an example. The system has a power rating of 20 kW with the parameters shown in Table I.

TABLE I
SPECIFICATIONS OF TEST VSG SYSTEM

Parameter	Value	Parameter	Value
P_{set}	5 kW	f_{grid}	50 Hz
V_d	800 V	D_p	3×10^{-4} rad/(Ws)
L_f	1.5 mH	J	0.8 kg·m ²
R_f	0.1 Ω	R_v	0.0015 p.u.
C_f	10 μ F	X_v	0.3 p.u.
R_s	0.64 Ω	X'_d	0.15 p.u.
L_s	0.26 mH	X'_q	0.15 p.u.
V_{grid}	380 V	T'_{d0}	1.5 s
f_{set}	50 Hz	T'_{q0}	1.5 s
V_{set}	380 V	L_v	0.3 p.u.

Figure 9 shows a general diagram of the power control loop of the VSGs. The Bode plots of the open-loop transfer functions of the power control loop for different VSGs shown in Fig. 9 are compared in Fig. 10. The swing equation based model and the synchronverter have similar frequency characteristics. When the synchronous impedance is introduced in the VSG, the system becomes more stable with a larger stability margin. In terms of the 4th-order model, the transient impedance is in action in the high-frequency domain, which leads to a smaller stability margin than that

of the VSG of the 2nd-order with synchronous impedance. The model of VISMA Method-2 has the same characteristics as that of the VSG of the 2nd-order with synchronous impedance in the low-frequency domain. However, it introduces a resonance at the synchronous frequency due to the differential term. A 180° phase lag is also induced at the resonant peak.

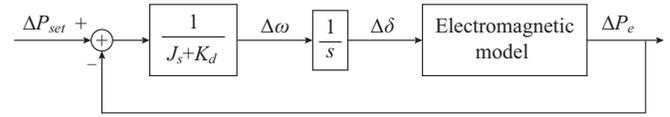


Fig. 9. Block diagram of power control loop of VSGs.

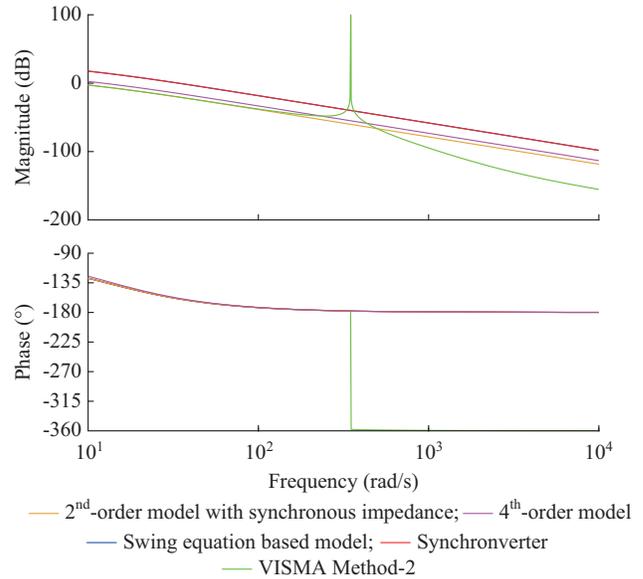


Fig. 10. Comparison of frequency characteristics of open-loop transfer functions for different VSG implementations.

After the system is in the steady state, a load step from 10 kW (14.44 Ω) to 20 kW (7.22 Ω) occurs at $t=2$ s. Then at $t=3.5$ s, the power set increases to 10 kW. Furthermore, a 0.5 Hz frequency decrease in the system is implemented at $t=5$ s. Finally, the VSG turns into islanded mode at $t=6.5$ s.

Figure 11 shows the frequency measured at the load bus. The control strategies without the impedances, which imply the swing equation based model and the synchronverter, have larger oscillations and longer settling times in response to the load and power steps as well as the grid frequency. In comparison, the other models have lower oscillations and/or less settling times, which prove that the impedances of SG contribute to the oscillation damping. Specifically, when there is a load step, the swing equation based VSG causes the largest frequency deviation, i.e., 0.104 Hz. The models of VISMA Method-2 and the 2nd-order model with synchronous impedance have lower frequency deviations, i.e., less than 0.06 Hz. However, the VISMA Method-2 leads to synchronous oscillations because it includes the dynamics of the stator windings. When the power increases to 10 kW, the maximum frequency deviation, i.e., 0.094 Hz, still appears in the swing equation based method, while the 2nd-order

model with synchronous impedance has the minimum frequency deviation, i.e., 0.016 Hz. When the frequency of the system decreases, all the control strategies lead to similar frequency nadir, where both the synchronverter and SG have the maximum and minimum values of the frequency deviation, i.e., 0.720 Hz and 0.640 Hz, respectively. After $t=6.5$ s, it can be observed that all the control strategies operate in the islanded mode due to their grid-supporting characteristics. However, the dynamics and steady-state performances are quite different. The virtual impedance of SG leads to a voltage decrease on the load bus, which implies that the actual active power consumed by the resistive load is smaller than the rated value. Therefore, the frequency of the islanded system is higher than that of the swing equation based model and the synchronverter. In terms of dynamics, the 2nd-order model with synchronous impedance and the VISMA Method-2 have large frequency oscillations, while the swing equation based model and the synchronverter have much smoother dynamics. This is because the virtual synchronous impedance increases the equivalent electrical distance between the power supply and the load [3]. In contrast, the 4th-order model and the SG have smaller frequency oscillations as well due to the transient and/or sub-transient damping windings.

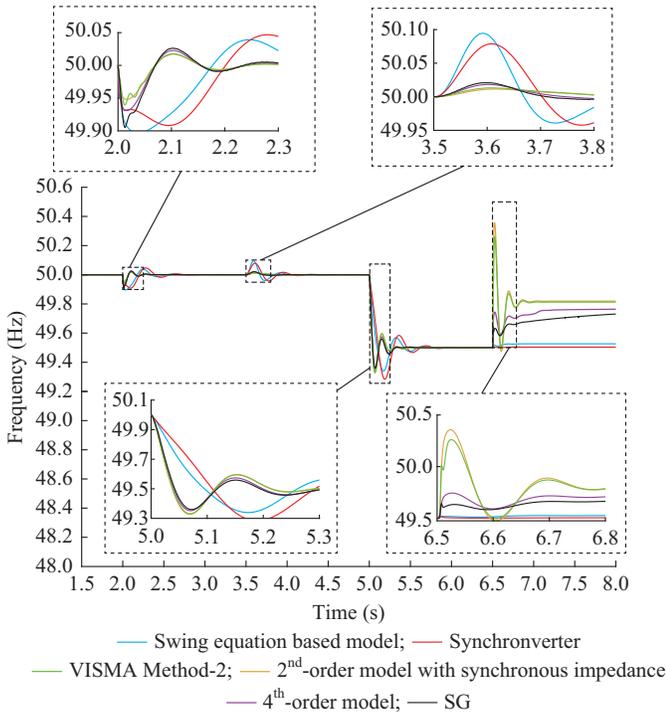


Fig. 11. Comparison results of frequency on load bus under different VSG implementations using data from Table I.

Figure 12 shows the RoCoF of the system, which is measured on the load bus as well. It is noted that the VISMA Method-2 has the best performance under a load step, where the RoCoF can be as small as 42.4% compared to the 4th-order model. At the moment of power and frequency steps, although the swing equation based model and the synchronverter have much longer settling time than other strategies,

the RoCoFs are quite different. When there is a power step, both the swing equation based model and the synchronverter lead to larger RoCoF, while it is just opposite under the change of system frequency. Finally, when turning to the islanded mode, the larger frequency deviations always appear with bigger RoCoFs.

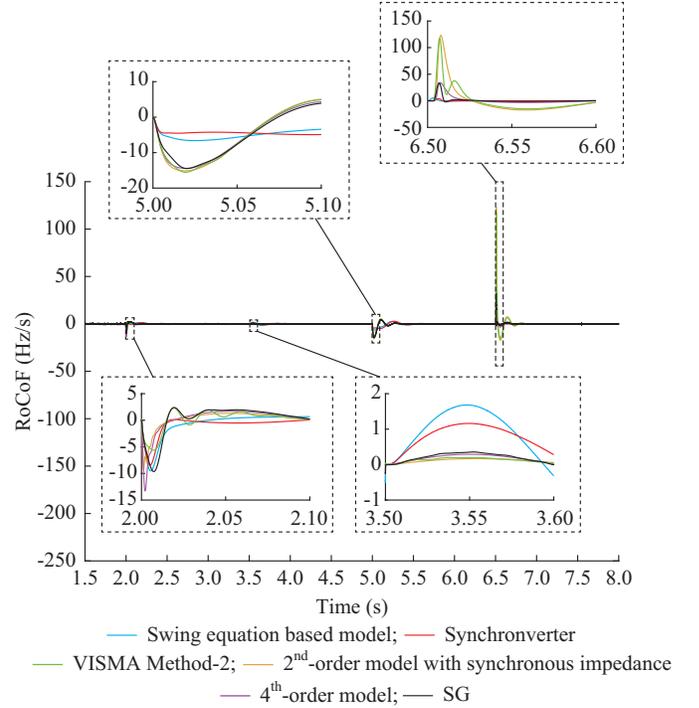


Fig. 12. Comparison results of RoCoF at load bus with different VSG implementations using data from Table I.

Based on the introduction and comparisons above, the different VSG emulation methods are summarized in detail in Table II.

III. APPLICATIONS OF VSG IN POWER SYSTEMS

A. Application of VSG in RES Integration

As an increasing number of RESs are connected to power systems and the number of conventional generators are decreasing, the total system inertia decreases, which may lead to the increasing risk of unstable operation of the system during transient events. The VSG is a promising solution to the problem, and much research efforts have been devoted to this area.

Figure 13 shows a schematic diagram of permanent magnet synchronous generator (PMSG) based wind power system as an example, which also can operate as a VSG. Usually, P_{set} is determined by maximum power point tracking (MPPT), while during the implementation of the VSG, P_{set} will deviate from the MPPT value. In terms of virtual inertia, it can come from different sources such as additional ESS (battery, super-capacitor), DC-link capacitor, the use of operating rotor of the turbine, and power curtailing from the MPPT.

TABLE II
IMPLEMENTATION OF VSG BASED ON SG MODELS

Model of SG	VSG implementation	Difference in modelling between VSG and SG	Advantage	Disadvantage
9 th - and 8 th -order	No	-	-	-
	VISMA [13], [28]	Neglect asymmetry of inductances	Inheriting all good characteristics of SG	- Complicated - Unexpected characteristics of SG can also be introduced
7 th -order	VISMA Method-1 and 2 [29], [30]	- Neglect coupling of windings - Neglect damping windings	- Simpler than the original VISMA - Small frequency deviation and RoCoF response to load disturbance - Good dynamics response to power step	- Synchronous resonance - May need current derivation - Poor dynamics when changing to islanded mode - Large RoCoF response to change of system frequency
6 th - and 5 th -order	No	-	-	-
4 th -order	[33]	Exactly the same in modelling	- Simpler than detailed model - All important characteristics are included - Good dynamic response to power step	- Many parameters to be designed - Large RoCoF under load disturbance and change of system frequency
3 rd -order	No	-	-	-
	Synchronverter [12], [38]	Neglect synchronous impedance	- Simple - Good dynamics when changes to islanded mode	- Dynamics is hard to regulate due to low control freedom - Large frequency deviation response to change in system frequency - Poor dynamic response to load disturbance and power step
2 nd -order (steady-state)	With synchronous impedance [34], [36], [37]	Neglect virtual loss of synchronous impedance	- Simple - More stable due to synchronous impedance - Small frequency deviation response to load disturbance - Good dynamic response to power step	- Poor dynamics when changing to islanded mode - Large RoCoF response to change of system frequency
	Swing equation based [3], [8], [16], [42], [43]	Neglect synchronous impedance	- Simplest - Good dynamics when changing to islanded mode - Small RoCoF response to change of system frequency	- Dynamics is hard to regulate due to low control freedom - Poor dynamic response to load disturbance and power step
2 nd -order (constant flux/constant)	No	-	-	-

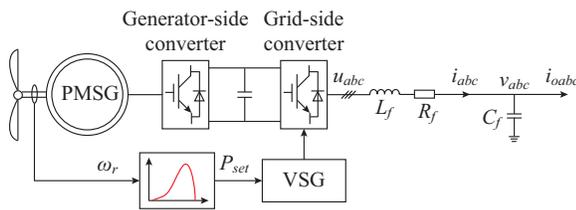


Fig. 13. Simplified diagram of PMSG-based wind power system controlled as VSG.

In [51], the power oscillation of a PMSG-based VSG is used as a study case. A “generator-motor-generator” system is proposed in [52], where both the machine-side and the grid-side converters of the PMSG are controlled as a VSG. This system can improve not only the dynamics but also the ride-through capability. To further enable the wind power system to regulate the output power, a short-term energy storage is added to the system in [53], which enhances the dynamics of the wind turbine system in the power system. In terms of a DFIG-based VSG, it can support the system frequency as well, even for a weak power grid [54]. In [37],

the inertia of DFIG-based VSG is investigated in detail, where the equivalent inertia constant is derived and the impacts on the different parameters are investigated as well.

In addition, photovoltaic [55], controllable loads [56], ESSs, etc., can also be controlled as a VSG. In this way, more power electronic based systems in the future can still have a stable operation like in the traditional SG dominated power systems.

B. Application of VSG in Microgrids

Microgrid is a promising solution to integrate, manage, and optimize the distributed generation (DG) units, which can operate either in grid-connected mode or in islanded mode. An islanded microgrid should build the voltage and frequency by itself. However, as a power electronic dominated system without SGs, the islanded microgrid comes across many problems such as lack of inertia, low power quality and robustness.

Figure 14 shows a schematic diagram of a microgrid with the VSG as an example, where the ESS-based VSG can be responsible for voltage and frequency regulation, inertia support, etc.

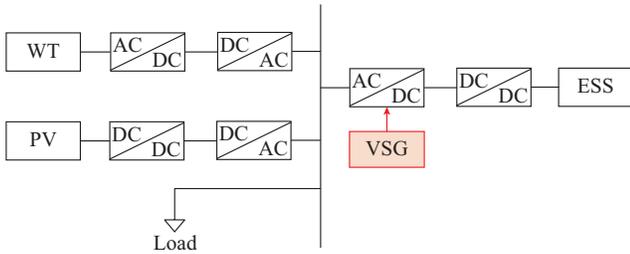


Fig. 14. Schematic diagram of AC microgrid using a VSG in connection with an ESS.

In [57], a microgrid control structure is proposed based on the VSG. The structure includes a grid-forming inverter operating as a VSG to provide virtual inertia during the transient, which may improve the dynamic response of the traditional microgrids. An H_∞ based robust control design method of the VSG is proposed in [58] to achieve better frequency performance in the microgrid. Secondary control similar to the traditional power system is also included in this paper. A more specific microgrid structure is proposed in [59] for the residential microgrid. In this microgrid, a VSG-controlled battery storage system, which behaves as a grid-supporting inverter, is the main power supply and energy buffer with virtual inertia, while a current-controlled fuel cell system behaves as a grid-feeding inverter with constant power supply. In [60], a combined VSG and digital frequency protection system is proposed. During the abnormal operation, the VSG can provide virtual inertia for the microgrid, and then with a large disturbance, the digital protection system is activated to keep security of the system.

As more and more DGs are connected into the distribution grid, microgrids are necessarily required to provide variable auxiliary services. The VSG can help DGs participate in the management of microgrids and improve the stability and economy of the system, which should be investigated further.

C. Application of VSG in VSC-HVDC

As an advanced power transmission technology, voltage source converter based HVDC (VSC-HVDC) transmission has many applications in system interconnection, wind power integration, and powering of islands, etc. However, traditional control strategies of HVDC cannot provide frequency support to a weak grid, where large frequency deviations appear when there is power unbalance, and a stable operation of the system is violated. Figure 15 shows a schematic diagram of the VSC-HVDC controlled by VSG as an example, where the DC-link capacitor C_{dc} might be used to provide the virtual inertia.

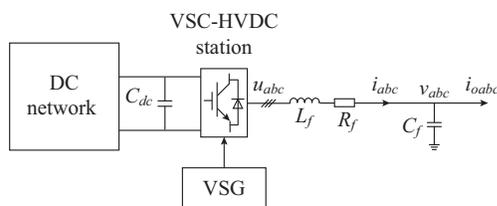


Fig. 15. Schematic diagram of VSC-HVDC controlled as VSG.

To solve the problem above, the swing equation can be introduced into the control strategy of the inverter station. It has been proved under different conditions that the VSG-based HVDC can help to improve the frequency stability of the low-inertia AC grid [42]. On the other hand, like the SG, the VSG can also introduce problems such as low-frequency oscillations due to the large capacity, especially in the VSC-HVDC system. The problem is studied in [49] by virtual torque analysis. A lead-lag compensator is introduced in the swing equation to eliminate the negative damping effect of PLL. In [45], the VSG is adopted to damp the low frequency oscillations in multi-terminal VSC-HVDC systems. The governor emulation and design of parameters are also dealt with in this paper. When the multi-terminal VSC-HVDC system is interconnected to a very weak AC grid, the VSG control can provide good grid synchronization ability, which solves the problem induced by the PLL and, thereby, a more stable system dynamics can be obtained [61]. Similar problem of weak AC grid is investigated in [26]. Impedance analysis shows that the proper design of parameters is sufficient for the stable operation of VSG-based VSC-HVDC system integrated into a weak AC grid. As an important issue, the DC voltage control is studied in [62], where the receiving end converter is controlled to provide virtual inertia from the DC-link capacitor and the sending end converter is controlled to regulate the frequency taking advantages of the interaction between the frequency and the DC voltage. In [63], the DC-side resonance of multi-terminal VSC-HVDC is analyzed, and it is solved by three different models of VSG. It reveals the benefits of VSG in order to obtain the stable operation of multi-terminal VSC-HVDC. In [64], the dynamics of the DC voltage is considered as well. The interaction between the VSG and the DC voltage is investigated by a low-order response model of the wind farm multi-terminal VSC-HVDC based on the equivalent inertia and damping of DC-link capacitor.

IV. CHALLENGES AND FUTURE TRENDS OF VSG SYSTEMS

A. Stability Analysis

The VSG has its own special dynamics compared to the traditional grid-connected inverters, and changes the stability of traditional power systems [65]. Stability analysis is important in order to study the system operation characteristics and the design of VSG.

Investigations in [66] show the possibility of small-signal angular instability of power systems caused by VSG. In [34], [67], both small-signal models of the grid-connected and islanded modes are given to achieve eigenvalues and parametric sensitivity analysis for a 2nd-order model with synchronous impedance. Similar work is done for the model using VISMA Method-1 in [68]. These studies are all done in the time domain. Recently, the sequence impedance based stability method in the frequency domain is also investigated [27], but further research is important to carry on.

Transient stability is another important aspect of VSG. With a large disturbance, the power system with VSG is no longer a linear system, and the results from small-signal

analysis are not available. To evaluate the transient stability, the classic Lyapunov method can be applied [8], [69]. In [8], a convenient energy function is designed to study the transient stability of VSG, and then a “bang-bang” control strategy is proposed using the power-angle relationship to improve the transient stability. An effective virtual inertia constant is proposed in [70] including both SG and ESS for transient stability control. It helps to understand how the VSG influences the transient stability. As the nonlinear characteristics are enhanced due to the nonlinear components and nonlinear control strategy, a comprehensive method using nonlinear transient test and analysis is of high importance to investigate. In particular, the ability to manage high short-circuit current of the SG is still not an available feature for the VSG due to the current capacity of VSC.

B. ESS

The VSG relies on the ESS to provide inertial energy no matter whether it is from additional sources or from the capacitors in the VSC. It has been proved that the ESS can effectively support the system frequency with different kinds of disturbances [2].

In practice, the ESS is limited by its power and energy density, and the actual state of charge, etc. A self-tuning VSG is proposed in [71] to change the inertia and damping online. Then the required energy can be as small as 58% of a regular VSG, which can extraordinarily decrease the cost of the system. In [72], a combined battery and ultra-capacitor hybrid ESS is used for VSG implementation. Therefore, both power and energy requirements for VSG can be met. Similar idea is discussed in [73] by using a solid oxide fuel cell super-capacitor ESS. If only focusing on the short-term energy buffer, the DC-link capacitor of the inverter can be used to provide virtual inertia by a proper control strategy as well, which will not require any additional hardware and will be more economical [74]. An improved VSG is proposed in [75].

It can be seen that there is still no effective method to determine the optimal size and type of ESS by considering the economy, stability and reliability in a complete context, which is important for practical implementation of VSG. In addition, a power curtailment strategy deviating the operation power away from the maximum power point of RES during the transient state, which can use the power reserve to provide virtual inertia, may also be an interesting direction for further investigation.

C. Multiple VSG Systems

Like traditional power systems with multiple SGs, the coordination of multi-VSG in one system is of vital importance for the stable and reliable operation of power systems. A consensus-based control of VSG is proposed in [43], which focuses on the secondary control level of microgrid control. In [76], a small-signal model is built to investigate the dynamics of paralleled VSG. By proper regulation of the synchronous impedances, the stable operation and proper power sharing can be achieved. The transient stability of multi-VSG system is investigated in [77]. After that, a “bang-bang” controller is tuned by particle swarm optimization

to determine the inertia among different VSGs. In [78], frequency and voltage fluctuations in the microgrid with both SGs and VSGs are studied. It verifies the benefits of the VSG on damping oscillations. Another way to improve the stability of multi-VSG system is using a higher control level. The center of inertia is used in [79] to derive an additional power input in VSG control. In this strategy, a centralized controller and communication network are necessary. In [80], an optimization method is proposed to investigate the power sharing between different VSGs not only in the steady state but also under dynamic conditions. In addition, for multi-VSG systems, the inertia match between different VSGs is important. Proper inertia design gives a better frequency response [81]. A similar problem is the placement of VSGs. In [82], an H_2 optimization based method is used to determine the parameters and placement of virtual inertia provided by both grid-forming and grid-feeding VSGs.

It is evident that some literatures have started to investigate multi-VSGs rather than single VSG. As in a power supply case, multi-VSG system has the same problems such as power sharing and power oscillation as the traditional paralleled inverters. Moreover, due to its special functions of inertia and damping provision, the size, placement, and design of parameters of multi-VSGs need to be further evaluated in order to achieve stable, reliable, and optimal operation.

V. CONCLUSION

This paper has presented a comprehensive review of VSG emulation including the modelling development and the important application in power systems such as RES integration, microgrids, and VSC-HVDC. As a promising technology for more power electronic based power systems in the future, the basic modelling, analysis, and design methods of VSGs have been studied in the literature. However, to achieve a practical application, further investigations on the stability analysis and ESS controlling, sizing, and optimization are still necessary. In particular, in terms of a system with high penetration of RES, multi-VSGs system has drawn more attention in recent years, which can be one of the most important issues for future power systems.

REFERENCES

- [1] S. Eftekharijrad, V. Vittal, G. T. Heydt *et al.*, “Impact of increased penetration of photovoltaic generation on power systems,” *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 893-901, May 2013.
- [2] G. Delille, B. François, and G. Malarange, “Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system’s inertia,” *IEEE Transactions on Sustainable Energy*, vol. 3, no. 4, pp. 931-939, Oct. 2012.
- [3] J. Liu, Y. Miura, and T. Ise, “Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators,” *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3600-3611, May 2016.
- [4] D. Gautam, L. Goel, R. Ayyanar *et al.*, “Control strategy to mitigate the impact of reduced inertia due to doubly fed induction generators on large power systems,” *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 214-224, Feb. 2011.
- [5] C. Marcy. (2019, Mar.). U.S. renewable electricity generation has doubled since 2008. U.S. Energy Information Administration, U.S. [Online]. Available: <https://www.eia.gov/todayinenergy/detail.php?id=38752#>
- [6] I. Komusanac, D. Fraile, and G. Brindley. (2019, Feb.). Wind energy

- in Europe in 2018: trends and statistics. WindEurope, Brussels, Belgium. [Online]. Available: https://www.researchgate.net/profile/Ivan_Komusanac2/publication/333641792_Wind_energy_in_Europe_in_2018/links/5cf8d4b0299bf1fb185bc642/Wind-energy-in-Europe-in-2018.pdf
- [7] Z.-S. Zhang, Y.-Z. Sun, J. Lin *et al.*, "Coordinated frequency regulation by doubly fed induction generator-based wind power plants," *IET Renewable Power Generation*, vol. 6, no. 1, pp. 38-47, Jan. 2012.
- [8] J. Alipoor, Y. Miura, and T. Ise, "Power system stabilization using virtual synchronous generator with alternating moment of inertia," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 2, pp. 451-458, Jun. 2015.
- [9] T. Shintai, Y. Miura, and T. Ise, "Oscillation damping of a distributed generator using a virtual synchronous generator," *IEEE Transactions on Power Delivery*, vol. 29, no. 2, pp. 668-676, Apr. 2014.
- [10] M. F. M. Arani and E. F. El-Saadany, "Implementing virtual inertia in DFIG-based wind power generation," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1373-1384, May 2013.
- [11] P. Tielens and D. Van Hertem, "The relevance of inertia in power systems," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 999-1009, Mar. 2016.
- [12] Q.-C. Zhong and G. Weiss, "Synchronverters: inverters that mimic synchronous generators," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1259-1267, Apr. 2011.
- [13] H.-P. Beck and R. Hesse, "Virtual synchronous machine," in *Proceedings of 9th International Conference on Electrical Power Quality and Utilisation*, Barcelona, Spain, Oct. 2007, pp. 1-6.
- [14] N. Soni, S. Doolla, and M. C. Chandorkar, "Improvement of transient response in microgrids using virtual inertia," *IEEE Transactions on Power Delivery*, vol. 28, no. 3, pp. 1830-1838, Jul. 2013.
- [15] J. Zhu, C. D. Booth, G. P. Adam *et al.*, "Inertia emulation control strategy for VSC-HVDC transmission systems," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1277-1287, May 2013.
- [16] S. D'Arco and J. A. Suul, "Equivalence of virtual synchronous machines and frequency-droops for converter-based microgrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 394-395, Jan. 2014.
- [17] M. Dreidy, H. Mokhlis, and S. Mekhilef, "Inertia response and frequency control techniques for renewable energy sources: a review," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 144-155, Mar. 2017.
- [18] J. Fang, H. Li, Y. Tang *et al.*, "On the inertia of future more-electronics power systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 7, no. 4, pp. 2130-2146, Dec. 2019.
- [19] H. A. Alsiraji and R. El-Shatshat, "Comprehensive assessment of virtual synchronous machine based voltage source converter controllers," *IET Generation, Transmission & Distribution*, vol. 11, no. 7, pp. 1762-1769, May 2017.
- [20] U. Tamrakar, D. Shrestha, M. Maharjan *et al.*, "Virtual inertia: current trends and future directions," *Applied Sciences*, vol. 7, pp. 1-29, Jun. 2017.
- [21] S. Tan, H. Geng, G. Yang *et al.*, "Modeling framework of voltage-source converters based on equivalence with synchronous generator," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 6, pp. 1291-1305, Nov. 2018.
- [22] J. Rocabert, A. Luna, F. Blaabjerg *et al.*, "Control of power converters in AC microgrids," *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4734-4749, Nov. 2012.
- [23] P. Kundur, *Power System Stability and Control*. New York: McGraw-Hill, 1993.
- [24] I. Serban and C. Marinescu, "Control strategy of three-phase battery energy storage systems for frequency support in microgrids and with uninterrupted supply of local loads," *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 5010-5020, Sept. 2014.
- [25] S. Alepuz, A. Calle, S. Busquets-Monge *et al.*, "Use of stored energy in PMSG rotor inertia for low-voltage ride-through in back-to-back NPC converter-based wind power systems," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 5, pp. 1787-1796, May 2013.
- [26] A. Asrari, M. Mustafa, M. Ansari *et al.*, "Impedance analysis of virtual synchronous generator-based vector controlled converters for weak AC grid integration," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 3, pp. 1481-1490, Jul. 2019.
- [27] W. Wu, Y. Chen, L. Zhou *et al.*, "Sequence impedance modeling and stability comparative analysis of voltage-controlled VSGs and current-controlled VSGs," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 6460-6472, Aug. 2019.
- [28] R. Hesse, D. Turschner, and H.-P. Beck, "Micro grid stabilization using the virtual synchronous machine (VISMA)," *Renewable Energy and Power Quality Journal*, vol. 1, no. 7, pp. 676-681, Apr. 2009.
- [29] Y. Chen, R. Hesse, D. Turschner *et al.*, "Dynamic properties of the virtual synchronous machine (VISMA)," *Renewable Energy and Power Quality Journal*, vol. 1, no. 9, pp. 755-759, May 2011.
- [30] Y. Chen, R. Hesse, D. Turschner *et al.*, "Comparison of methods for implementing virtual synchronous machine on inverters," *Renewable Energy and Power Quality Journal*, vol. 1, no. 10, pp. 734-739, Apr. 2012.
- [31] W. Zhang, D. Remon, and P. Rodriguez, "Frequency support characteristics of grid-interactive power converters based on the synchronous power controller," *IET Renewable Power Generation*, vol. 11, no. 4, pp. 470-479, Mar. 2017.
- [32] Z. Peng, J. Wang, D. Bi *et al.*, "The application of microgrids based on droop control with coupling compensation and inertia," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 3, pp. 1157-1168, 2018.
- [33] C.-H. Zhang, Q.-C. Zhong, and J.-S. Meng *et al.*, "An improved synchronverter model and its dynamic behaviour comparison with synchronous generator," in *Proceedings of 2nd IET Renewable Power Generation Conference (RPG 2013)*, Beijing, China, Sept. 2013, pp. 1-4.
- [34] S. D'Arco, J. A. Suul, and O. B. Fosso, "A virtual synchronous machine implementation for distributed control of power converters in smartgrids," *Electric Power Systems Research*, vol. 122, pp. 180-197, May 2015.
- [35] J. Chen and T. O'Donnell, "Analysis of virtual synchronous generator control and its response based on transfer functions," *IET Power Electronics*, vol. 12, no. 11, pp. 2965-2977, Sept. 2019.
- [36] J. Chen and T. O'Donnell, "Parameter constraints for virtual synchronous generator considering stability," *IEEE Transactions on Power Systems*, vol. 34, no. 3, pp. 2479-2481, May 2019.
- [37] S. Wang, J. Hu, X. Yuan *et al.*, "On inertial dynamics of virtual-synchronous-controlled DFIG-based wind turbines," *IEEE Transactions on Energy Conversion*, vol. 30, no. 4, pp. 1691-1702, Dec. 2015.
- [38] Q.-C. Zhong, P.-L. Nguyen, Z. Ma *et al.*, "Self-synchronized synchronverters: inverters without a dedicated synchronization unit," *IEEE Transactions on Power Electronics*, vol. 29, no. 2, pp. 617-630, Feb. 2014.
- [39] S. Dong and Y. C. Chen, "A method to directly compute synchronverter parameters for desired dynamic response," *IEEE Transactions on Energy Conversion*, vol. 33, no. 2, pp. 814-825, Jun. 2018.
- [40] Q.-C. Zhong, G. C. Konstantopoulos, B. Ren *et al.*, "Improved synchronverters with bounded frequency and voltage for smart grid integration," *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 786-796, Mar. 2018.
- [41] V. Natarajan and G. Weiss, "Synchronverters with better stability due to virtual inductors, virtual capacitors, and anti-windup," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 7, pp. 5994-6004, Jul. 2017.
- [42] M. Guan, W. Pan, J. Zhang *et al.*, "Synchronous generator emulation control strategy for voltage source converter (VSC) stations," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3093-3101, Nov. 2015.
- [43] L.-Y. Lu and C.-C. Chu, "Consensus-based secondary frequency and voltage droop control of virtual synchronous generators for isolated AC micro-grids," *IEEE Journal of Emerging and Selected Topics in Circuits and Systems*, vol. 5, no. 3, pp. 443-455, Sept. 2015.
- [44] W. Wang, Y. Li, Y. Cao *et al.*, "Adaptive droop control of VSC-MTDC system for frequency support and power sharing," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1264-1274, Mar. 2018.
- [45] Y. Cao, W. Wang, Y. Li *et al.*, "A virtual synchronous generator control strategy for VSC-MTDC systems," *IEEE Transactions on Energy Conversion*, vol. 33, no. 2, pp. 750-761, Jun. 2018.
- [46] R. Shi, X. Zhang, C. Hu *et al.*, "Self-tuning virtual synchronous generator control for improving frequency stability in autonomous photovoltaic-diesel microgrids," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 3, pp. 482-494, May 2018.
- [47] M. Ebrahimi, S. A. Khajehoddin, and M. Karimi-Ghartemani, "An improved damping method for virtual synchronous machines," *IEEE Transactions on Sustainable Energy*, vol. 10, no. 3, pp. 1491-1500, Jul. 2019.
- [48] X. Meng, J. Liu, and Z. Liu, "A generalized droop control for grid-supporting inverter based on comparison between traditional droop control and virtual synchronous generator control," *IEEE Transactions on Power Electronics*, vol. 34, no. 6, pp. 5416-5438, Jun. 2019.
- [49] L. Huang, H. Xin, and Z. Wang, "Damping low-frequency oscillations through VSC-HVDC stations operated as virtual synchronous ma-

- chines,” *IEEE Transactions on Power Electronics*, vol. 34, no. 6, pp. 5803-5818, Jun. 2019.
- [50] X. Meng, Z. Liu, J. Liu *et al.*, “Comparison between inverters based on virtual synchronous generator and droop control,” in *Proceedings of 2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Cincinnati, USA, Oct. 2017, pp. 4077-4084.
- [51] Y. Wang, J. Meng, X. Zhang *et al.*, “Control of PMSG-based wind turbines for system inertial response and power oscillation damping,” *IEEE Transactions on Sustainable Energy*, vol. 6, no. 2, pp. 565-574, Apr. 2015.
- [52] Q.-C. Zhong, Z. Ma, W.-L. Ming *et al.*, “Grid-friendly wind power systems based on the synchronverter technology,” *Energy Conversion and Management*, vol. 89, pp. 719-726, Jan. 2015.
- [53] Y. Ma, W. Cao, L. Yang *et al.*, “Virtual synchronous generator control of full converter wind turbines with short-term energy storage,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 11, pp. 8821-8831, Nov. 2017.
- [54] S. Wang, J. Hu, and X. Yuan, “Virtual synchronous control for grid-connected DFIG-based wind turbines,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 4, pp. 932-944, Dec. 2015.
- [55] H. Alatrash, A. Mensah, E. Mark *et al.*, “Generator emulation controls for photovoltaic inverters,” *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp. 996-1011, Jun. 2012.
- [56] H. E. Brown and C. L. DeMarco, “Risk of cyber-physical attack via load with emulated inertia control,” *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 5854-5866, Nov. 2018.
- [57] I. Serban and C. P. Ion, “Microgrid control based on a grid-forming inverter operating as virtual synchronous generator with enhanced dynamic response capability,” *International Journal of Electrical Power & Energy Systems*, vol. 89, pp. 94-105, Jul. 2017.
- [58] A. Fathi, Q. Shafee, and H. Bevrani, “Robust frequency control of microgrids using an extended virtual synchronous generator,” *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6289-6297, Nov. 2018.
- [59] Y. Hirase, O. Noro, H. Nakagawa *et al.*, “Decentralised and interlinkless power interchange among residences in microgrids using virtual synchronous generator control,” *Applied Energy*, vol. 228, pp. 2437-2447, Oct. 2018.
- [60] G. Magdy, G. Shabib, A. A. Elbaset *et al.*, “Renewable power systems dynamic security using a new coordination of frequency control strategy based on virtual synchronous generator and digital frequency protection,” *International Journal of Electrical Power & Energy Systems*, vol. 109, pp. 351-368, 2019.
- [61] L. Huang, H. Xin, H. Yang *et al.*, “Interconnecting very weak AC systems by multiterminal VSC-HVDC links with a unified virtual synchronous control,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 3, pp. 1041-1053, Sept. 2018.
- [62] R. Yang, C. Zhang, X. Cai *et al.*, “Autonomous grid-synchronising control of VSC-HVDC with real-time frequency mirroring capability for wind farm integration,” *IET Renewable Power Generation*, vol. 12, no. 13, pp. 1572-1580, Oct. 2018.
- [63] C. Li, Y. Li, Y. Cao *et al.*, “Virtual synchronous generator control for damping DC-side resonance of VSC-MTDC system,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, no. 3, pp. 1054-1064, Sept. 2018.
- [64] H. Ye, W. Pei, L. Kong *et al.*, “Low-order response modeling for wind farm-MTDC participating in primary frequency controls,” *IEEE Transactions on Power Systems*, vol. 34, no. 2, pp. 942-952, Mar. 2019.
- [65] W. Wu, L. Zhou, Y. Chen *et al.*, “Sequence-impedance-based stability comparison between VSGs and traditional grid-connected inverters,” *IEEE Transactions on Power Electronics*, vol. 34, no. 1, pp. 46-52, Jan. 2019.
- [66] W. Du, Q. Fu, and H. F. Wang, “Power system small-signal angular stability affected by virtual synchronous generators,” *IEEE Transactions on Power Systems*, vol. 34, no. 4, pp. 3209-3219, Jul. 2019.
- [67] S. D’Arco, J. A. Suul, and O. B. Fosso, “Small-signal modeling and parametric sensitivity of a virtual synchronous machine in islanded operation,” *International Journal of Electrical Power & Energy Systems*, vol. 72, pp. 3-15, Nov. 2015.
- [68] O. Mo, S. D’Arco, and J. A. Suul, “Evaluation of virtual synchronous machines with dynamic or quasi-stationary machine models,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 7, pp. 5952-5962, Jul. 2017.
- [69] Z. Shuai, C. Shen, X. Liu *et al.*, “Transient angle stability of virtual synchronous generators using Lyapunov’s direct method,” *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 4648-4661, Jul. 2019.
- [70] E. Hammad, A. Farraj, and D. Kundur, “On effective virtual inertia of storage-based distributed control for transient stability,” *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 327-336, Jan. 2019.
- [71] M. A. Torres, L. A. C. Lopes, L. A. Morán *et al.*, “Self-tuning virtual synchronous machine: a control strategy for energy storage systems to support dynamic frequency control,” *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp. 833-840, Dec. 2014.
- [72] J. Fang, Y. Tang, H. Li *et al.*, “A battery/ultracapacitor hybrid energy storage system for implementing the power management of virtual synchronous generators,” *IEEE Transactions on Power Electronics*, vol. 33, no. 4, pp. 2820-2824, Apr. 2018.
- [73] P. F. Frack, P. E. Mercado, M. G. Molina *et al.*, “Control strategy for frequency control in autonomous microgrids,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 4, pp. 1046-1055, Dec. 2015.
- [74] J. Fang, H. Li, Y. Tang *et al.*, “Distributed power system virtual inertia implemented by grid-connected power converters,” *IEEE Transactions on Power Electronics*, vol. 33, no. 10, pp. 8488-8499, Oct. 2018.
- [75] S. A. Khajehoddin, M. Karimi-Ghartemani, and M. Ebrahimi, “Grid-supporting inverters with improved dynamics,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 3655-3667, May 2019.
- [76] J. Liu, Y. Miura, H. Bevrani *et al.*, “Enhanced virtual synchronous generator control for parallel inverters in microgrids,” *IEEE Transactions on Smart Grid*, vol. 8, no. 5, pp. 2268-2277, Sept. 2017.
- [77] J. Alipoor, Y. Miura, and T. Ise, “Stability assessment and optimization methods for microgrid with multiple VSG units,” *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 1462-1471, Mar. 2018.
- [78] Y. Hirase, K. Abe, K. Sugimoto *et al.*, “A novel control approach for virtual synchronous generators to suppress frequency and voltage fluctuations in microgrids,” *Applied Energy*, vol. 210, pp. 699-710, Jan. 2018.
- [79] M. Choopani, S. H. Hosseinain, and B. Vahidi, “A novel comprehensive method to enhance stability of multi-VSG grids,” *International Journal of Electrical Power & Energy Systems*, vol. 104, pp. 502-514, Jan. 2019.
- [80] S. S. Guggilam, C. Zhao, E. Dall’Anese *et al.*, “Optimizing DER participation in inertial and primary-frequency response,” *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5194-5205, Sept. 2018.
- [81] U. Markovic, Z. Chu, P. Aristidou *et al.*, “LQR-based adaptive virtual synchronous machine for power systems with high inverter penetration,” *IEEE Transactions on Sustainable Energy*, vol. 10, no. 3, pp. 1501-1512, Jul. 2019.
- [82] B. K. Poolla, D. Groß, and F. Dörfler, “Placement and implementation of grid-forming and grid-following virtual inertia and fast frequency response,” *IEEE Transactions on Power Systems*, vol. 34, no. 4, pp. 3035-3046, Jul. 2019.

Meng Chen received the B.S. degree in electrical engineering from Qingdao University of Science and Technology, Qingdao, China, in 2013. Since 2013, he was enrolled in a master-doctoral program in electrical engineering at North China Electric Power University, Beijing, China. Currently, he is pursuing the Ph.D. degree in power electronics at Aalborg University, Aalborg, Denmark. His research interests include power grid with new energy resources.

Dao Zhou received the B.S. degree from Beijing Jiaotong University, Beijing, China, in 2007, the M.S. from Zhejiang University, Hangzhou, China, in 2010, and the Ph.D. from Aalborg University, Aalborg, Denmark, in 2014, all in electrical engineering. Since 2014, he has been with Department of Energy Technology, Aalborg University, where currently he is an Assistant Professor. Dr. Zhou received the Renewable and Sustainable Energy Conversion Systems of the IEEE Industry Applications Society First Prize Paper Award in 2015, and Best Session Paper at Annual Conference of the IEEE Industrial Electronics Society (IECON) in Austria in 2013. His research interests include modelling, control, and reliability of power electronics in renewable energy application.

Frede Blaabjerg was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. He received the Ph.D. degree in electrical engineering at Aalborg University, Aalborg, Denmark in 1995. He became an Assistant Professor in 1992, an Associate Professor in 1996, and a Full Professor of power electronics and drives in 1998. From 2017, he became a Villum Investigator. He is honoris causa at University Politehnica Timisoara (UPT), Timisoara, Romania and Tallinn Technical University (TTU), Tallinn, Estonia. He has received 32 IEEE Prize Paper Awards, the IEEE PELS Distinguished Service

Award in 2009, the EPE-PEMC Council Award in 2010, the IEEE William E. Newell Power Electronics Award 2014, the Villum Kann Rasmussen Research Award 2014, the Global Energy Prize in 2019 and the 2020 IEEE Edison Medal. He was the Editor-in-Chief of the IEEE Transactions on Power Electronics from 2006 to 2012. He has been Distinguished Lecturer for the IEEE Power Electronics Society from 2005 to 2007 and for the IEEE Industry Applications Society from 2010 to 2011 as well as 2017 to 2018. In 2019-2020, he serves as President of IEEE Power Electronics Society. He is

Vice-President of the Danish Academy of Technical Sciences too. He is nominated in 2014-2019 by Thomson Reuters to be between the most 250 cited researchers in Engineering in the world. He has published more than 600 journal papers in the fields of power electronics and its applications. He is the co-author of four monographs and editor of ten books in power electronics and its applications. His current research interests include power electronics and its applications such as in wind turbines, PV systems, reliability, harmonics and adjustable speed drives.