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A glance of the Dynamic Behaviour

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On Short Circuit of Grid-Forming Converters Controllers: A glance of the Dynamic Behaviour

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***Abstract*—Power electronic converter (PEC) is an enabling technology for the energy transition, but the massive integration of PEC raises several issues. The use of Voltage source converters (VSCs) enabled with grid forming control offer a long-term solution of PEC-dominated power systems. This paper shows a glance of the dynamic performance during short-circuit of three common grid forming controller types emulating synchronous generation are implemented: Virtual Synchronous Machine (VSM), the Synchronverter and grid forming droop control; and compared with a classic synchronous generator. Simulation results, considering a single generator contacted to an infinite bus, show the grid-forming converters' high-speed and different behaviour compared to the synchronous generator.**

Keywords—converter, fault, grid-forming, grid-following, short circuit

I. INTRODUCTION

Power systems are experiencing significant changes; those changes are related to all the activities, the way to produce electricity, the mechanism used to supply it, and how the final customer uses the electricity.

The power system is changing the way to produce electricity by a considerable increase of electricity generation coming from environmentally friendly technologies, but they are characterised by a power production that is intermittent/highly variable as the primary renewable resource is weather dependant [1]. The delivery system of electricity is changing; there is a tendency to increase stressing/narrowly conditions on the transmission system to maximise the use of the assets at the time distribution systems are being populated by increased volumes of small and distributed generation technologies as photovoltaic (PV) systems, microturbines, biomass, fuel cells, etc. In fact, emerging trends suggest that the interaction between transmission system operators (TSO) and distribution network operators (DSO) are evolving. The full interaction between TSO-DSO will unleash the potential of the existing and future resources the time bring benefits to all the parties in the power system. Finally, the customer is no longer a passive party in the power system, the integration of embedded generation (EG), the massive deployment of electric vehicles (EV) and electrical energy storage (EES), all those technologies and the changes in the customer behaviour make the costumer a prosumer, an entity who both consumers and produces electricity. There is a common element at the heart of these changes, and that is the massive deployment of power electronic converter interfaced technologies [2], [3]. Modern generation and storage technologies take advantages of the power electronic converter (PEC) to deliver more controllable electricity and the time to interface renewable resources and energy storage.

The PEC is an enabling technology, and it has been a critical element in the integration of new low-carbon technologies providing the needed interface between two or more energy systems [1], [4]. Nevertheless, *what is the issue arising from the massive integration of power converters?* The reality is that is a far-reaching question; the increasing penetration of PECs is causing a reduction of the number of synchronous generators available in the power system. Many research papers and projects have identified two crucial issues [5], [6]: (i) Low (to none) supply of total system rotational inertia and (ii) Reduced and limited fault levels affecting short circuit ratio.

Different entities have recognised these issues, e.g., system operators, academia, and manufacturers [7]. Many documents cite reoccurring themes associated with the typical features of the PES, the lack of robustness (especially during extremely high overcurrent event and massive voltage drops), failure of the Phase-locked loop (PLL) to follow very deep voltage sags [8], fault ride-through (FRT) failures, and adverse interactions. In April 2020, the Power System Dynamic Performance Committee of the IEEE recognised the need of including the new forms of dynamic behaviour of the electrical power systems with high penetration of power electronic interfaced technologies [9]; Therefore, the classification and definition power system stability phenomena was enhanced by including additional considerations due to the penetration of PEC-interfaced technologies into bulk power systems. Two new stability

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classes have been introduced [9]: (i) Converter-driven stability and (ii) Resonance stability.

The dynamic behaviour of PEC-interfaced technologies evidently different from conventional synchronous generators due to the predominant voltage-source converter (VSC) interface with the grid [9]. This unique behaviour has been de cause of reported local instabilities, now called converter-driven instabilities. Those forms of instability have been caused by incorrect control settings or inappropriately tuned controllers, which can be characterised independently from the power system. However, substituting conventional synchronous generators with PEC-interfaced technologies is a situation with two sides; incorrect control settings can cause instability problems. However, if appropriate control loops are enabled with adequate settings, PEC-interfaced technologies can be a solution to some problems in the power systems, e.g., low rotational inertia. The PEC-interfaced technologies that replace conventional synchronous generators can be enabled with controllers to very quickly respond to contingency events and system imbalances; PEC-interfaced technologies canto that much faster than mechanical synchronous machines. Enhancing the stability of a PEC dominated power system relies on short terms and long-term solutions. One of the potential solutions is related to controlling the grid side inverter based on Voltage source converters (VSCs) using grid forming control.

This research paper shows a glance of the dynamic performance during short-circuit of three common grid forming controller types emulating synchronous generation are implemented: Virtual Synchronous Machine (VSM), the Synchronverter and grid forming droop control; comparing their behaviour against a classic synchronous generator during faulted conditions. Section II shows the main concepts and modelling aspects of grid supporting and grid following converters. Section III is dedicated to synchronous generation emulation control and presents details of the three grid forming controllers implemented in this paper. Section IV shows the simulation results and discussion rising of analysing the faulted conditions of the technologies. Section V contain the main conclusions in this paper.

II. Grid Forming and Grid Following

VSC-based grid-connected power converters provide a flexible interface between the generation/storage technologies and the grid to harvest energy from the technologies and feed the grid (see Fig. 1).

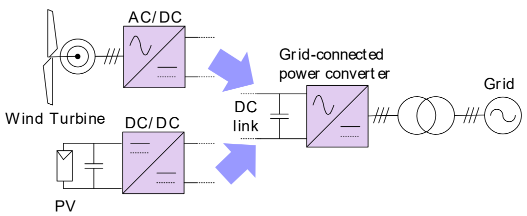
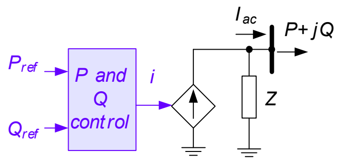


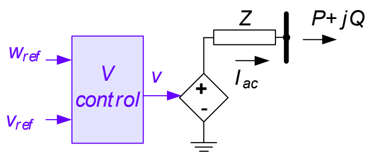
Fig. 1. PECs used in the integration of renewable energy sources into power systems.

The VSC is assumed to be a controlled voltage source behind a filter inductor, and very versatile and valuable control loops can be applied to this converter type. Considering the operational control model, two main groups of converters can be defined: (i) grid-forming and (ii) grid-following (also known as grid-feeding).

Grid following converters are the most used control philosophy found in commercial PEC; they typically behave as a current source that is controlled to fed active are reactive power to the grid (*PQ* bus) to do they require to be connected to an energised grid (no black start possibilities). Grid following converters are typically represented as an ideal current source (I_{ref}) connected to the grid in parallel with high impedance (*Z*) [10] -see Fig. 2a. A grid-following VSC works as a current source (*i*) which inject active (*P*) and reactive power (*Q*) to the grid according to defined power (P_{ref}, Q_{ref}), -or current setpoint. This control strategy is known as a grid-following converter as it requires a synchronisation mechanism with an energised grid in order to inject power into the grid. The synchronisation mechanism is typically based on a PLL that measures the angle of the grid voltage (θ). The grid-following converter technologies, like HVDC converters, rely on PLL loop in converters to see and react to the electricity network. PLL devices have been identified to have difficulty finding a reference from the system when retained voltages are low; this issue is known as "phase jumping", and it can lead to a delayed response to new conditions or a failure to respond adequately [8], leading to instabilities.



(a) Simplified representation of a grid following converter (based on current source model).



(b) Simplified representation of a grid forming converter (based on voltage source model).

Fig. 2. Equivalent model of grid-forming converter implementations.

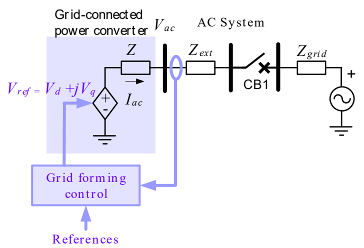


Fig. 3. Equivalent model of grid-forming converter using VSC.

A grid forming converter is a converter enabled with functionalities that support the grid operation. They typically behave like a voltage source that is controlled to fed is the time that controls the grid side voltage (V_{ac}) and frequency (*f*). They are typically represented as an ideal AC voltage source behind low-output impedance (*Z*), similar to the classic synchronous generator. A VSC operating with grid-forming control sets the voltage amplitude ($|V_{ref}|$) and frequency (f_{ref}) of the local grid by using a proper control loop -details will be discussed in the next section (see Fig. 2.a and Fig. 3). An enormous difference between a grid-forming and a grid-following control is the synchronisation mechanism that provides the correct rotation in the *abc*/*dq*-transformation. As explained before, the grid following converter relies in PLL devices, but the grid the following control this synchronisation considering the alternative mechanism described in the next section.

III. Synchronous Generation Emulation Control: Grid Forming Converter

Grid forming converter controllers are an up-and-coming solution to enhance the stability of power systems. The grid forming converter controller enables the PEC to behave like a controllable voltage source behind an impedance, and this approach allows the controller to emulate synchronous generators' behaviour. A little summary of the main control techniques used to emulate a synchronous generator's behaviour is shown in Fig. 4 (see more details at [11]).

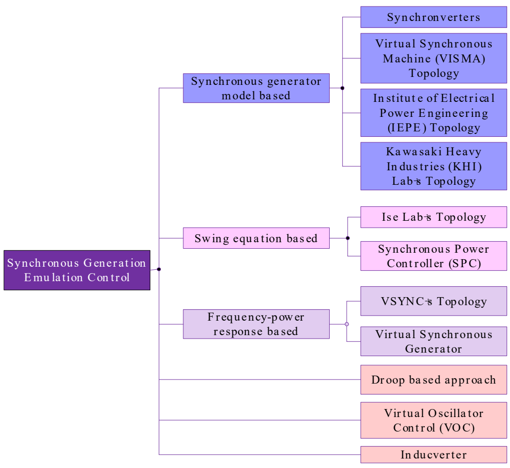


Fig. 4. Classification of different control strategies used for the implementation of synchronous generation emulation.

In this paper, the grid forming converter is based on a VSC that consists of a controllable AC voltage source behind low-output impedance (Z_{vi}) -see Fig. 5.

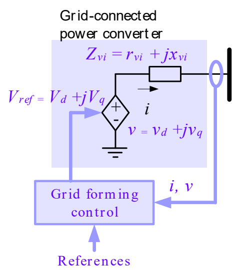


Fig. 5. Grid forming converter with virtual inertia (VI) concept.

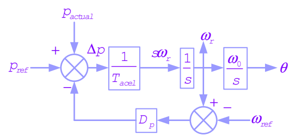
The virtual impedance (Z_{vi}) is modelled in the *dq*-axis as: $Z_{vi} = r_{vi} + jx_{vi}$. The *d*-axis and *q*-axis voltage drop over an algebraic type of virtual impedance are calculated as follows:

$$\begin{aligned} \Delta v_{vi,d} &= r_{vi} i_d - x_{vi} i_q \\ \Delta v_{vi,q} &= r_{vi} i_q + x_{vi} i_d \end{aligned} \tag{1}$$

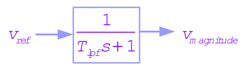
The virtual impedance controller provides flexibility to the converter to be adjusted to the grid conditions; it can be done by adjusting the virtual impedance parameters to the grid condition. This feature is attractive in an application where the short circuit would like to be reduced during a short circuit event, and it is done by artificially increasing the virtual impedance. The following subsections show a brief explanation about the modelling used in this paper; three common grid forming controller types emulating synchronous generation are implemented: Virtual Synchronous Machine (VSM), the Synchronverter and grid forming droop control.

A. Virtual Synchronous Machine (VSM)

The general model of the VSM is shown in Fig. 6.



(a) Electromechanical behaviour



(b) Voltage support control

Fig. 6. Classification of different control strategies used for the implementation of synchronous generation emulation.

The controller is built considering the control of the VSC using the *d-q* axis. The actual active (p_{actual}) and reactive (q_{actual}) power produced by the power converter is calculated from the voltage and current measurements ($v = v_d + jv_q$, $i = i_d + ji_q$):

$$\begin{cases} p_{actual} = v_d i_d + v_q i_q \\ q_{actual} = v_q i_d - v_d i_q \end{cases} \tag{2}$$

The VSM emulates the mechanical behaviour of the synchronous machine by using the swing equation:

$$\begin{cases} T_{acel} \dfrac{d\omega_r(t)}{dt} = p_{ref} - p_{actual} - D_p\left(\omega_r - \omega_{ref}\right) \\ \dfrac{d\theta}{dt} = \omega_r(t) - \omega_{ref} \end{cases} \tag{3}$$

where T_{acel} is the mechanical time constant, p_{ref} is the active power set point, and p_{actual} is the measured actual active power output. The rotating speed of the VSM is given by ω_r, ω_{ref} is the frequency setpoint, and D_p is the damping coefficient.

B. Synchronverter

The original concept of the synchronverter was introduced by Q. Zhong and G. Weiss in a scientific paper titled '. *Synchronverters: Inverters that mimic synchronous generators*' in 2011 [12]. In this paper, the synchronverter is modelled based on that paper [12]. The main difference between the synchronverter and the VSM is the implementation of the electromechanics dynamic. In the syncrhonverter mechanical part of the machine is governed by:

$$\begin{cases} T_{acel} \dfrac{d\theta^2(t)}{dt^2} = T_{ref} - T_{actual} - D_p \dfrac{d\theta(t)}{dt} \\ \dfrac{d\theta(t)}{dt} = \left(\omega_r - \omega_{ref}\right) \end{cases} \tag{4}$$

where the electrical toque (T_{actual}) is calculated as:

$$T_{actual} = M_f i_f \sin\theta \tag{5}$$

where i_f is the imaginary field (rotor) winding of the synchronverter fed by an adjustable dc current source and M_f is the mutual inductance between the field coil and each of the three stator coils. The internal voltage (v) is defined as:

$$v = \frac{d\theta}{dt} M_f i_f \sin\theta \tag{6}$$

The active (p_{calc}) are reactive power (q_{calc}) are calculated as:

$$\begin{cases} p_{calc} = \dfrac{d\theta}{dt} M_f i_f i \sin\theta \\ q_{calc} = -\dfrac{d\theta}{dt} M_f i_f i \cos\theta \end{cases} \tag{7}$$

The reactive power production can also be calculated by using a voltage-droop control; the reactive power error (Δq) is calculated as

$$\Delta q = q_{ref} - q_{calc} - D_q \left(v - v_{ref} \right) \tag{8}$$

where q_{ref} is the reference of reactive power, q_{calc} is the calculated reactive power, v is the measured voltage, v_{ref} is the reference voltage, and D_q is the voltage droop coefficient.

C. Grid Forming Droop Control

The grid-forming droop control uses a droop approach to calculate frequency (Δf_{droop}) and voltage (Δv_{droop}) deviation from the steady-state operation point [13]:

$$\begin{aligned} \Delta f_{droop} &= m_p \Delta p \\ \Delta v_{droop} &= m_q \Delta q \end{aligned} \tag{9}$$

where m_p and m_q are the active and reactive power droop coefficients and Δp and Δq are the low-pass filtered active and reactive power deviations from the steady-state operating point, respectively; It has been shown in [14] that the frequency calculation of the droop control and VSM are similar when parameters are tuned accordingly [15].

IV. Experiments

This paper investigates the performance of three common grid forming controller types emulating synchronous generation during faults conditions. Specifically, three types of grid forming controllers are implemented in this paper: Synchronverter (SynC), grid forming droop control (simply called Droop from here onwards) and Virtual Synchronous Machine (VSM). The test system is a classical single machine corrected to an infinite bus through a step-up transformer (T) and two transmission lines (see Fig. 7).

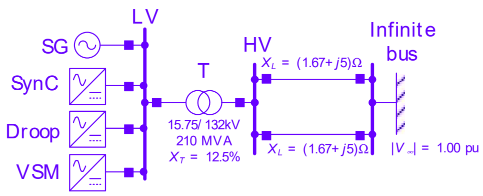


Fig. 7. *Test System*: A single generation technology connected to an infinite bus.

The test system is configured to assess the dynamic performance during faulted conditions of one of the generation technologies at the time. The performance of three types of grid forming controllers and a synchronous generator during fault conditions are compared in this paper. The synchronous generator *(SG)* is a 210 MVA, 15.47 kV, $fp = 0.8$ is modelled considering the simplest model, a constant voltage source behind the reactance with following parameters T_{acel} = 18.36 sec, x_{str} = 0.2 pu. Table I to IV show the model parameters used for the grid forming controllers; it must be noticed that the electromechanical related parameter has been updated to be equal to SG.

TABLE I. Main Parameters of the SynC Control Model

Description	Variable	Value
Acceleration time	T_{acel}	18.36 sec
Damping coefficient	D_p	100.00pu
Voltage control gain	K_p	1000 pu
Reactive power drop coefficient	D_q	20.00 pu
Damping filter cut-off frequency	ω_r	0.00 rad/sec

TABLE II. Main Parameters of the VI used in SynC Control Model

Description	Variable	Value
Basic virtual resistance	r	0.006 pu
Basic virtual reactance	x	0.006 pu
Limit of overcurrent	I_{lim}	1.01 pu
Proportional factor of additional resistance	k_{pr}	8.00 pu
Proportional factor of additional reactance	k_{px}	8.00 pu
Time constant of low pass filter	T_{lpf}	0.0001 sec

TABLE III. Main Parameters of the VSM Control Model

Description	Variable	Value
Acceleration time	T_{acel}	18.36 sec
Damping coefficient	D_p	100.00pu
Damping filter cut-off frequency	ω_r	0.00 rad/sec
Voltage setpoint low-pass filter time constant	T_{lpf}	0.003 sec

TABLE IV. Main Parameters of the VI used in VSM Control Model

Description	Variable	Value
Basic virtual resistance	r	0.006 pu
Basic virtual reactance	x	0.006 pu
Limit of overcurrent	I_{lim}	1.01 pu
Proportional factor of additional resistance	k_{pr}	8.00 pu
Proportional factor of additional reactance	k_{px}	8.00 pu
Time constant of low pass filter	T_{lpf}	0.0001 sec

TABLE V. Main Parameters of the Droop Grid Forming Control Model

Description	Variable	Value
Active power droop coefficient	m_p	0.01 pu
Reactive power droop coefficient	m_q	0.05 pu
Low-pass filter cut-off frequency	ω_r	60 rad/sec

TABLE VI. Main Parameters of the Virtual Inertia used in Droop Grid Forming Model

Description	Variable	Value
Basic virtual resistance	r	0.006 pu
Basic virtual reactance	x	0.006 pu
Limit of overcurrent	I_{lim}	1.01 pu
Proportional factor of additional resistance	k_{pr}	8.00 pu
Proportional factor of additional reactance	k_{px}	8.00 pu
Time constant of low pass filter	T_{lpf}	0.0001 sec

DIgSILENT PowerFactory is used to perform time-domain analysis of the test system subject to a bolted three-phase short circuit at bus HV. Initially, a preliminary assessment of the transient rotor angle stability is performed considering only the SG technology; the critical fault clearing time (CFCT) was found to be t_{clear} = 0.3508 sec. As a consequence, the comparison between technologies is performed considering a fault direction of t_{clear} = 0.3500 sec.

For comparative purposes, the time series of the dynamic behaviour of the technologies are capture considering: the angle (θ) and the rotational speed (ω_r); those electrical quantities are taken from the voltage signal at bus LV (see Fig. 7). Fig. 8 shows the performance of θ and ω_r during the fault condition. As expected, the rotational speed tends to increase during the fault, the SG exit the classical straight line caused by accelerating power created by the mechanical power applied in the shaft. However, the behaviour of rotational speed of the SynC and VSM tends to follow the SG but it slower than that one. The Droop controller is not following the swing equation of a synchronous generator; as a consequence, the response follows the behaviour of a first-order transfer function as included in the controller. Post disturbance behaviour of the rotational speed is oscillatory in the SG, but the grid forming controllers exhibit a non-oscillatory behaviour due to the avoidance created by the fast controllers. A summary of the oscillatory behaviour of the SG against a damped and fast response of the grid forming controller is demonstrated in the loci of the state variables shown in Fig. 9.

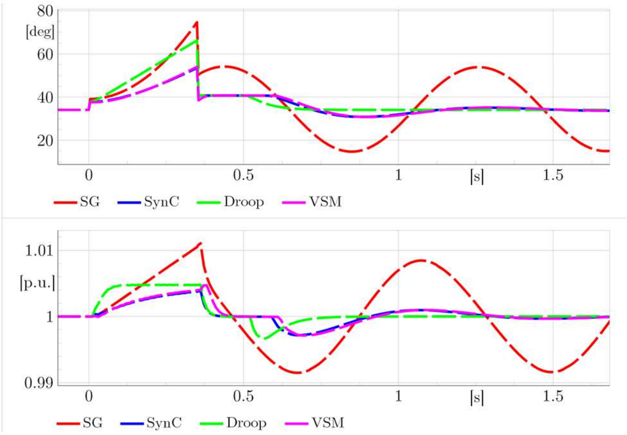


Fig. 8. Time-domain repose of the state variables (ω_r bottom, θ up) during fault condition of the three technologies.

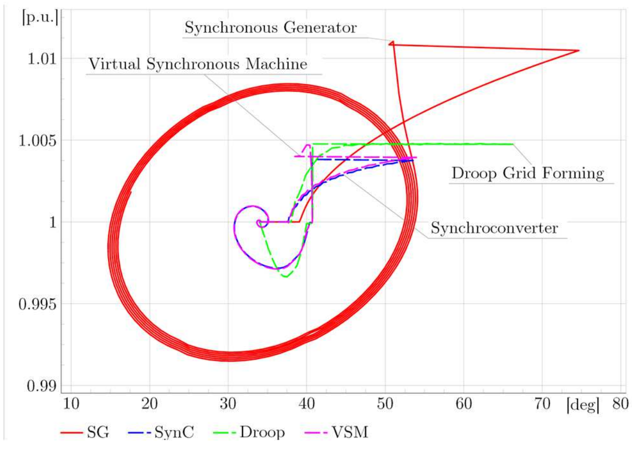


Fig. 9. Loci of the state variables (ω_r vertical axis and θ horizontal axis) during fault condition of the three technologies.

V. Conclusions

Several transmission system operators worldwide are concerned about the massive integration of Power electronic converter (PEC) based technologies. However, the appropriate use of voltage source converters (VSCs) enabled with grid forming control offer a long-term solution of PEC-dominated power systems beyond the simple inertia emulation. This paper presented a single glance of the dynamic performance during short-circuit of three common grid forming controller types emulating synchronous generation are implemented: Virtual Synchronous Machine (VSM), the Synchronverter and grid forming droop control; and compared with a classic synchronous generator. This paper is just a starting point in characterising the performance of the grid forming controller during fault conditions to create an efficient protection mechanism ageing short circuit in power converted dominated power systems. Simulations presented in this paper are plain and simple but offer a glance at the future scene of power converter dominated systems. Power converter-based technologies enabled with grid forming controllers have high speed and behaviour compared to the synchronous generator.

References

[1] F. Gonzalez-Longatt, M. N. Acosta, H. R. Chamorro, and Jose Luis Rueda, "Power Converters Dominated Power Systems," in *Modelling and Simulation of Power Electronic Converter controlled Power Systems in PowerFactory*, First Edit., F. Gonzalez-Longatt and Jose Luis Rueda, Eds. Switzerland: Springer Nature Switzerland AG, 2021.

[2] H. R. Chamorro *et al.*, "Data-Driven Trajectory Prediction of Grid Power Frequency Based on Neural Models," *Electronics*, vol. 10, no. 2, p. 151, Jan. 2021, doi: 10.3390/electronics10020151.

[3] M. N. Acosta, F. Gonzalez-Longatt, D. Topić, and M. A. Andrade, "Optimal Microgrid–Interactive Reactive Power Management for Day–Ahead Operation," *Energies*, vol. 14, no. 5, p. 1275, Feb. 2021, doi: 10.3390/en14051275.

[4] F. S. Gorostiza and F. Gonzalez-Longatt, "Deep Reinforcement Learning-Based Controller for SOC Management of Multi-Electrical Energy Storage System," *IEEE Trans. Smart Grid*, pp. 1–1, 2020, doi: 10.1109/TSG.2020.2996274.

[5] "High Penetration of Power Electronic Interfaced Power Sources and the Potential Contribution of Grid Forming Converters European Network of Transmission System Operators for Electricity ENTSO-E Technical Group on High Penetration of Power Electronic Interfaced Power Sources." Accessed: Mar. 30, 2021. [Online]. Available: www.entsoe.eu.

[6] Australian Energey Market Operator, "Black System South Australia 28 September 2016," 2017. Accessed: Mar. 30, 2021. [Online]. Available: www.aemo.com.au.

[7] IEEFA, "Australia's Opportunity To Plan Ahead for a Secure Zero-Emissions Electricity Grid Towards Ending the Reliance on Inertia for Grid Stability," 2021.

[8] National Grid, "System Operability Framework 2016," *UK Electr. Transm.*, no. November, pp. 68–72, 2016, Accessed: Mar. 30, 2021. [Online]. Available: www.nationalgrid.com/sof.

[9] N. Hatziargyriou *et al.*, "Stability definitions and characterisation of dynamic behavior in systems with high penetration of power electronic interfaced technologies," Dec. 2020. doi: 10.1109/JSYST.2015.2444893.

[10] R. Jadeja, A. Ved, T. Trivedi, and G. Khanduja, "Control of Power Electronic Converters in AC Microgrid," in *Power Systems*, vol. 27, no. 11, 2020, pp. 329–355.

[11] U. Tamrakar, D. Shrestha, M. Maharjan, B. Bhattarai, T. Hansen, and R. Tonkoski, "Virtual Inertia: Current Trends and Future Directions," *Appl. Sci.*, vol. 7, no. 7, p. 654, 2017, doi: 10.3390/app7070654.

[12] Q. C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011, doi: 10.1109/TIE.2010.2048839.

[13] S. Eberlein and K. Rudion, "Small-signal stability modelling, sensitivity analysis and optimisation of droop controlled inverters in LV microgrids," *Int. J. Electr. Power Energy Syst.*, vol. 125, no. April 2020, p. 106404, Feb. 2021, doi: 10.1016/j.ijepes.2020.106404.

[14] S. D'Arco and J. A. Suul, "Equivalence of virtual synchronous machines and frequency-droops for converter-based Microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 394–395, 2014, doi: 10.1109/TSG.2013.2288000.

[15] D. Gmbh, "Grid-forming Converter Templates," 2020.