Frequency Support provided by Inverted Based-Generation using Grid-Forming Controllers: A Comparison during Islanded Operation

Francisco Gonzalez-Longatt
Department of Electrical Engineering, Information Technology and Cybernetics
University of South-Eastern Norway
Porsgrunn, Norway
fglongatt@fglongatt.org

Jose Luis Rueda
Department of Electrical Sustainable Energy
Delft University of Technology
Delft, The Netherlands
J.L.RuedaTorres@tudelft.nl

Peter Palensky
Department of Electrical Sustainable Energy
Delft University of Technology
Delft, The Netherlands
P.Palensky@tudelft.nl

Harold R. Chamorro
Department of Electrical Sustainable Energy
KTH, Royal Institute of Technology
Stockholm, Sweden
hrcv@kth.se

Vijay Sood
Department of Electrical, Computer and Software Engineering
Ontario Tech University
Ontario, Canada
vijay.sood@ontariotechu.ca

***Abstract*—Inverter based generation (IBG) is a necessary technology in the energy transition and reaching ambitious objectives of zero-net emission. However, the colossal penetration of IBG may create several issues. Using Voltage source converters (VSCs) equipped with the so-called grid forming control is thought of as a long-term solution of IBG-dominated power systems. This paper shows a glance of the dynamic performance during a system frequency event (SFE) considering three of the most common grid forming controller types used to emulate synchronous generation operation: Virtual Synchronous Machine (VSM), the Synchronverter and grid forming droop control; and compared with a classic synchronous generator (SG). Numerical results of time-domain simulations of a tests system show the enormous advantage of the grid-forming converters controls to provide an extremely fast frequency response when compared to the case of the traditional SG.**

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

I. INTRODUCTION

Modern power systems are underway to significant changes; those changes are related to all the electricity business activities [1], [2], [3]: (i) generation: more environmentally friendly and weather dependent technologies [4], (ii) transmission/distribution: more flexible assets where DC is crucial part [5], (iii) consumption: new technologies behind the meter as energy storage, electric vehicles, and now the concept of passive customer disappearing and the concept of the prosumer is a reality in several countries around the world [6], [7]. There are several aspects in common to the power system changes, but the common denominator is the colossal integration of IBG [8], [9].

The IBG is a critical element in the realisation of the energy transition, as it is a critical element in the massive deployment of new low-carbon technologies, where a power electronic converter (PEC) provides the vital interface between two or more energy systems [6], [10].

A general question that many researchers tried to answer is: *what is the issue arising from the massive integration of power converters?* Realistically, this question is vast, and it can be taken in many senses; it is undoubtedly true that the vast penetration of IBG cases a diminution in the number of synchronous generators (SGs) available in the power system. Therefore, this research question must be carefully evaluated from two sides: (i) the issues caused by the IBG and (ii) the issues arising from reducing the number of SGs connected to the power system. There are a vast amount of recent research papers and projects that have identified two crucial issues [11], [12]: (i) Low (to none) supply of total system rotational inertia and (ii) Reduced and limited fault levels affecting short circuit ratio.

The issues related to the massive penetration of IBG and reduction of SGs have been identified and recognised by several institutions/organisations, e.g., system operators, academia, and manufacturers [13]. In addition, many documents cite reoccurring themes associated with the typical features of the IBG [14]:

- The lack of robustness (especially during extremely high overcurrent events and massive voltage drops),
- Failure of the Phase-locked loop (PLL) to follow very deep voltage sags [15],
- Fault ride-through (FRT) failures, and

- Adverse interactions.

In April 2020, the IEEE Power System Dynamic Performance Committee recognised the need of including the new forms of dynamic behaviour of the electrical power systems with high penetration of power electronic interfaced technologies [16]; 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 classes have been introduced [16]: (i) Converter-driven stability and (ii) Resonance stability.

The dynamic behaviour of IBG significantly differs from conventional SGs due to the predominant voltage-source converter (VSC) interface with the grid [16]. The IBG has a very peculiar dynamic behaviour that can lead to local instabilities; they are called converter-driven instabilities [16]. The instability phenomena are typically caused by the incorrect setting of the controller or inappropriately designed controllers. However, substituting conventional SGs with IBG is a two-edged sword; incorrect control settings can cause instability problems, but if appropriate control loops are enabled with adequate settings, IBGs provide a solution to many problems in the power systems, e.g., low rotational inertia [14]. The PEC-interfaced technologies that replace conventional synchronous generators can be enabled with controllers to respond to contingency events and system imbalances very quickly. In fact, IBG technologies can react much faster than mechanical synchronous machines [14]. There are two paths to consider when proposing solutions to the issues related to the IBG-dominated power system: short terms and long-term solutions. One of the potential long-term ?) solutions is related to controlling the grid side inverter, based on Voltage source converter (VSC), by using grid forming control.

The authors of this paper are actively working on the grid forming control strategy from the system point of view. The research team already published a glance at the dynamic performance during short-circuit of three common grid forming controllers [14]. However, the research team consider that an appropriate assessment/comparison of the grid forming control to the classical SGs will provide valuable inside to the scientific community regarding the main differences/similarities between them.

This research paper shows a glance of the dynamic performance during a system frequency disturbance in a test system considering three common grid forming controller types emulating synchronous generation: Virtual Synchronous Machine (VSM), the Synchronverter (SynC) and grid forming droop (Droop) control; comparing their behaviour against a classic SG during a power imbalance. In this paper, the test system consists of a simple generation unit connected to a load through an equivalent impedance, and a parametric assessment of the system frequency response is performed using numerical time-domain simulations. Only under frequency events are considered in this paper, and they are caused by a sudden increase in the load demand. Section II shows the main aspects of grid supporting and grid following converters. Section III is dedicated to a very short description of the SG emulation control and presents details of the three grid forming controllers implemented in this paper. Section IV shows the results of the time-domain simulations and the discussion rising of analysing the frequency response of the different technologies. Finally, section V contains 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) [14].

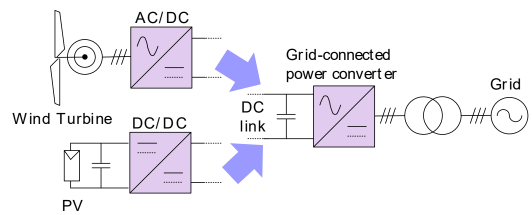
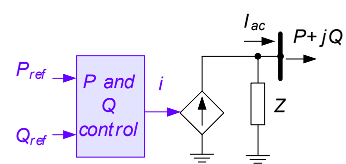


Fig. 1. PECs used in the integration of environmentally friendly generation technologies into power systems [14].

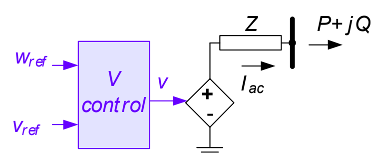
Two main groups of converters can be defined considering the operational control model:

- Grid-forming control and
- Grid-following (also known as grid-feeding).

Grid following converters are typically represented as an ideal current source (I_{ref}) connected to the grid in parallel with high impedance (Z) [14], [17] -see Fig. 2a.



(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.

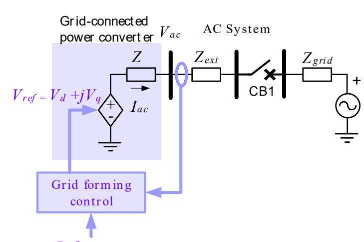


Fig. 3. Equivalent model of grid-forming converter using VSC.

A grid forming converter is a converter enabled with functionalities that support the grid operation [14]. 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) (see Fig. 2.a and Fig. 3).

III. SYNCHRONOUS GENERATION EMULATION CONTROL: GRID FORMING CONVERTER

The grid forming converter control is a technique that allows the IBG to performs as a controllable voltage source behind an impedance. The use of this circuit-based approach permits the power electronic converter (PEC) to emulate synchronous generators' behaviour (inside the inherent differences between a PEC and SG). Fig. 4 shows a no exhaustive summary of the main control techniques used to emulate a synchronous generator's behaviour. More details and referenced summary of those control techniques can be found at [18].

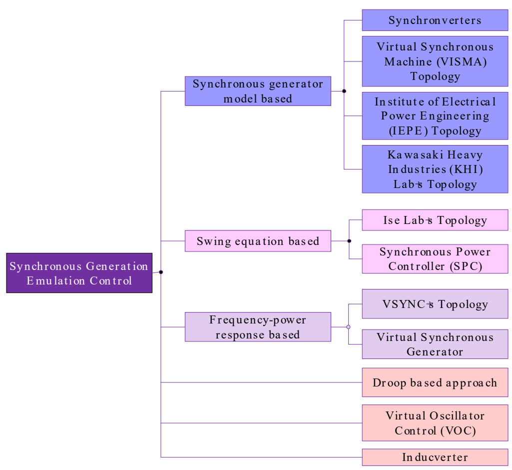


Fig. 4. Classification of different control strategies used for the implementation of synchronous generation emulation (no exhaustive) [14].

In this paper, the grid forming converter used for modelling and simulation purposes consists of a VSC modelled as a controllable AC voltage source behind low-output impedance (Z_{vi}) -see Fig. 5.

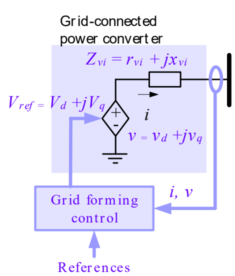


Fig. 5. Grid forming converter with virtual inertia (VI) concept.

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 [14]:

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

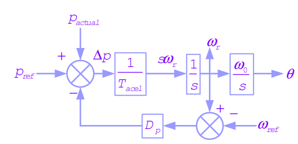
The following subsections show a brief explanation about the modelling used in this paper; three common grid forming controller types emulating synchronous generation are implemented: Virtual Synchronous Machine (VSM), the Synchronverter (SynC) and grid forming droop (Droop) control.

A. *Virtual Synchronous Machine (VSM)*

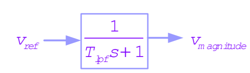
The general block diagram of the VSM control scheme for VSC is depicted in Fig. 6.

The VSM controller is built considering the control of the VSC using the d-q axis [14]. The actual active (p_{actual}) and reactive (q_{actual}) power produced by the power converter is calculated from the voltage and current measurements ($v = v_d + jv_q$, $i = i_d + ji_q$):

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



(a) Electromechanical behaviour



(b) Voltage support control

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

The emulation of the electromechanical behaviour of the SG is performed in the VSM controller by using the well-known swing equation in the form of two first-order differential equations (state variable angle and speed):

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

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 (SynC)*

The innovative idea of the SynC was proposed by Q. Zhong and G. Weiss in a scientific paper titled "*Synchronverters: Inverters that mimic synchronous generators*" in 2011 [19]. The model of SynC used in this paper is based on the paper [19]. The main difference between the SynC and the VSM is the implementation of the electromechanics dynamic. In the SynC mechanical part of the machine is governed by [14]:

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

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

$$T_{actual} = M_f i_f \sin\theta \quad (5)$$

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:

$$v = \frac{d\theta}{dt} M_f i_f \sin\theta \quad (6)$$

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

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

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

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

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 (Droop)

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 [20], [14]:

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

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 [21] that the frequency calculation of the droop control and VSM are similar when parameters are tuned accordingly [22].

IV. Experiments

This paper investigates the system frequency response (SFR) of three common grid forming controller types emulating synchronous generation during a system frequency disturbance (a sudden increase of the power demand). This scientific paper considers 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). For assessing purposes, the test system consists of a single generation unit connected to a lumped load through a step-up transformer (T) and two transmission lines (see Fig. 7). One technology is enabled at the time to assess individual performance.

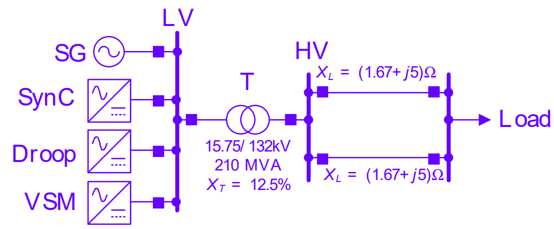


Fig. 7. *Test System*: A single generation technology connected to an infinite bus.

The 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 of the grid forming controllers considered in this paper; it is important to mention that the electromechanical related parameter of the controllers 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 a time-domain simulation of the test system subject to a sudden increase of the active power demand at the load.

For comparative purposes, the time series of the dynamic behaviour of the technologies are capture considering: electrical frequency as measured by protection relays, the frequency is measured at the common bus of the technologies, bus LV (see Fig. 7). Each time-domain simulation is stopped 10.0 seconds after the sudden increase of the active power demand (ΔP @ t = 0.0 sec). The performance assessment of the system frequency response is done considering simulation scenarios starting with 1% load increase until reaching a 100% step increase at the active power of the load; it represents 100-time domain simulations. Fig 8-11 shows the time-domain dynamic response of the frequency at the terminal of the generator (bus LV) considering the $\Delta P \in [1\%,100\%]P_{load}$. The SG exhibit the classical frequency response where the frequency drops very fast during the inertial response reaching a minimum, and then the primary frequency controller (governor) kick in and recover the balance generation/demand constraint of the frequency.

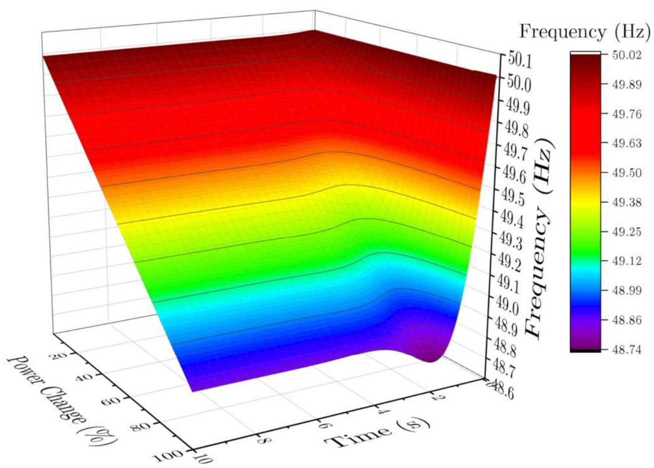


Fig. 8. System frequency response following the of SG.

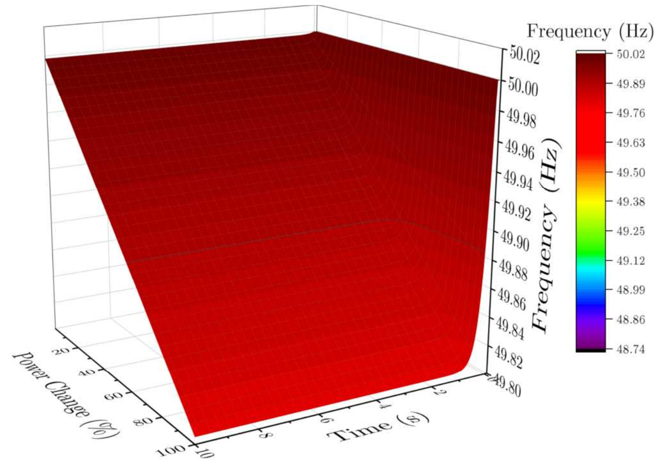


Fig. 9. System frequency response following the of SynC.

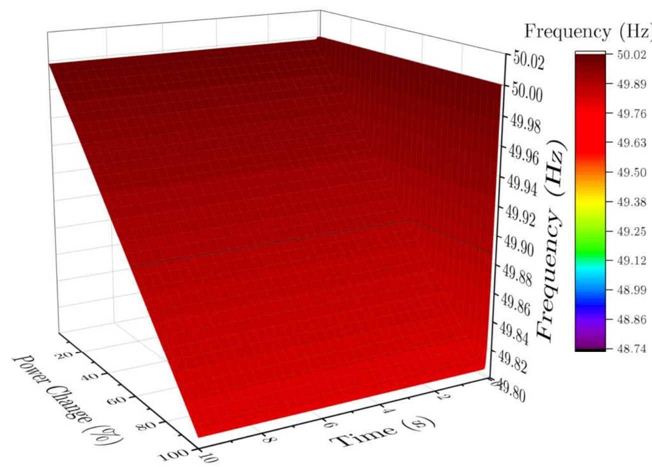


Fig. 10. System frequency response following the of Droop.

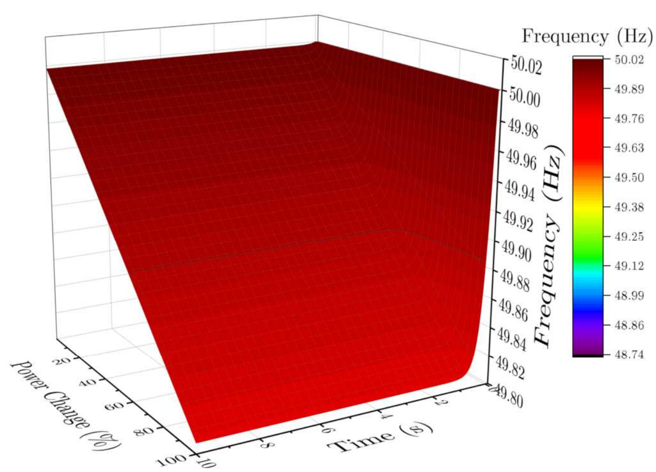


Fig. 11. System frequency response following the of VSM.

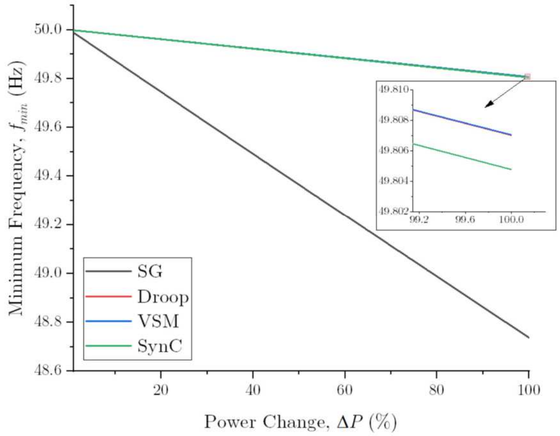


Fig. 12. Comparison of the steady-frequency reach by each technology.

It is straightforward to see (from Fig 8) that as the size of the power change increases, the steady-state frequency reaches lower values. Therefore, it is not a surprise that the SynC, Droop and VSM exhibit a similar dynamic performance between them, the frequency droop very fast immediately after the disturbance and the reaching the steady-state frequency within 1.0 seconds in the slowest case (maximum power change 100%). However, when compared the IBG technologies to the SG, it is clear that the SG has the slowest system frequency response with a more complex dynamic response: fast drop, reaching a minimum and the reach a steady-state frequency above the minimum frequency.

One of the main differences in the frequency response between the grid forming converter is evident in the steady-state frequency; Fig 12 shows a difference within 2mHz.

V. Conclusions

This paper presented a single glance of the system frequency response of three common grid forming controller types emulating synchronous generation considering under frequency events: 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 under-frequency events and comparing the performance to the classic synchronous generator. The authors are looking into the development of efficient protection mechanism against under frequency events in power converted dominated power systems. The 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.

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