DOI: 10.48011/sbse.v1i1.2482

Comparison of Virtual Synchronous Generator Strategies for Control of Distributed Energy Sources and Power System Stability Improvement

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Abstract: The high integration of distributed generation (DG) system based on renewable energy sources (RES) in the power system requires changes regarding the control mode of these sources with some urgency. Such changes seek to maintain the stability of the power systems. Thus, there is a demand for using control techniques on DGs/RESs that can mitigate the disturbances caused by low inertia and the lack of control over the dispatched powers. As a solution, one can use virtual synchronous generator (VSG) techniques making the voltage source inverter (VSI) control behave similarly to the traditional synchronous generator (SG). This paper presents a literature review and performance tests for the main VSG topologies used in DGs/RESs: ISE, VSYNC, VISMA and Synchronverter. The implementation of VSG in the DGs/RESs has made possible increase inertia in the grid and, additionally regulate the active and reactive powers separately and bidirectionally. So, it has been possible to meet power system requirements; being able to operation both grid-connected or island-mode, which is ideal for microgrids. The results obtained confirm the literature reports. It was observed that the Synchronverter topology presented advantages over the other VSG topologies.

Keywords: renewable energy; power system; virtual synchronous generator; microgrids.

1. INTRODUCTION

Nowadays, DG systems based on RES have been playing an increasingly important role in power systems (Zhang et al., 2018). In 2017, RES accounted for 34% of global electricity generation; it is believed that they will have reached 54% by 2040 (IEA, 2018). The penetration of RES in power systems is necessary and inevitable (F.S. Rahman, 2017).

While the integration of DGs/RESs can potentially reduce the need for traditional system expansion and reduce losses by locating generation near demand (Ton and Smith, 2012), controlling a potentially huge number of DGs/RESs creates a daunting new challenge for operating and controlling the grid safely and efficiently. Therefore, this challenge can be partially fulfilled by microgrids (MG) (Tamrakar et al., 2017), being the best option to integrate DGs/RESs units in terms of operational flexibility and grid reliability (Hatziargyriou et al., 2007).

A MG is a group of interconnected loads and DG within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A MG can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode (Ton and Smith, 2012).

Increasing the penetration level of DGs/RESs will result in the impact of low inertia, consequently decreasing damping effect on the grid dynamic performance; thus, affecting stability (Van et al., 2010). The reason is that DGs/RESs, e.g., wind and solar photovoltaics, are normally coupled to the power grid through fast-response power converters, which do not possess any inertia (Fang et al., 2018), causing frequency variations in the system that are beyond standard limits and compromise the stability of the system. Another problem is the fact that the DGs/RESs do not have control over the production of active power, being dependent of the MPPT (Maximum Power Point Tracking) algorithm which seeks to extract the maximum power from renewable resources of intermittent nature such as speed of wind or solar irradiation. When generation and demand of power imbalance occurs, that results in a frequency deviation from nominal. This is one of the most important requirements of the islanded operation modes (Bevrani et al., 2014).

Regarding the technical aspects that need to be considered, system inertia plays an extremely important role as it determines the sensitivity of system frequency to supply demand imbalances. The lower the system inertia, the faster the frequency will change if a variation in load or generation occurs, which effectively cause undesirable load-shedding, cascading failures, or large-scale blackouts under frequency events (Majumder, 2013). These were the reasons for recent blackouts in electrical systems from countries like Australia (Operator, 2017) and England (Eso, 2019).

Another fact is that, for economic reasons, synchronous generators (SG) are responsible for the supply of reactive energy to ensure voltage stability in the conventional system. With their replacement by DGs/RESs, this compensation will be affected (Machowski, 2008).

The voltage stability refers to the ability of the grid to maintain the voltage at tolerable levels after a disturbance occurs, and it is directly related to the control of reactive power (to grid with inductive predominance), thus, through techniques for vector control, DGs/RESs are capable of injecting or consuming reactive power. However, due to the limitation imposed by converters, their reactive power generation capacity is more reduced in comparison to conventional generation (Liu et al., 2016b).

As DGs/RESs use a voltage source inverter (VSI) to maintain interconnection to the grid and there has been widespread use of batteries in improving grid stability (Barzilai et al., 2016), thus, such option can solve this problem by using the concept of virtual synchronous generator (VSG) through a control algorithm which is going to make the VSI has a similar behavior to a SG. The VSG is a combination of control algorithms, RESs, energy storage system (ESS), and power electronics that emulates the SG of a conventional power system (Zhong, 2016). Consequently, there is larger autonomy in the operation of DGs/RESs without the need of establishing fast communication lines between generators and central control (Zhong and Weiss, 2011). The basic idea is illustrated in Fig. 1.

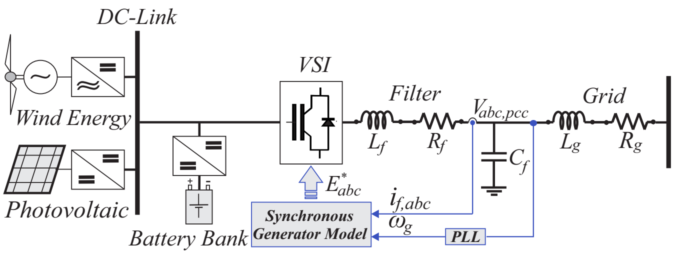

Figure 1. Basic idea of the virtual synchronous generator.

The power circuit consists mainly of a VSI and a filter LC, where the resistance R_g and the inductance L_g represent the impedance of grid.

There are several VSG topologies in the literature. Some topologies of VSG employ an approach which makes the DGs/RESs units sensitive to frequency changes in the power system. Other approaches try to simplify this by using just the swing equation to approximate the behavior of SG and there are topologies that try to mimic the exact behavior of the SG through a detailed mathematical model that represents their dynamics (Hatziargyriou et al., 2007).

This work aims to make a brief description of the main topologies of VSG (Bevrani et al., 2014; Hatziargyriou et al., 2007) and analyze its dynamic behavior when connected to the grid. Among the listed topologies are the VSYNC, the ISE, the VISMA and the Synchronverter.

This paper is organized as it follows: Section 2 presents the various topologies. Simulation results are presented in Section 3, and then in the conclusions.

2. VIRTUAL SYNCHRONOUS GENERATOR

This section discusses the main topologies that have been proposed in literature and tested in this work.

2.1 VSYNC

This control topology was developed by the European VSYNC research group (Van et al., 2010). This is the simplest VSG control technique to implement, as it does not incorporate all the detailed equations involved in a SG (Hatziargyriou et al., 2007). Under this control technique, DGs/RESs are sensitive to the grid frequency variations, and its main purpose is to neutralize the frequency disturbances in a grid. Its control structure is shown in Fig. 2.

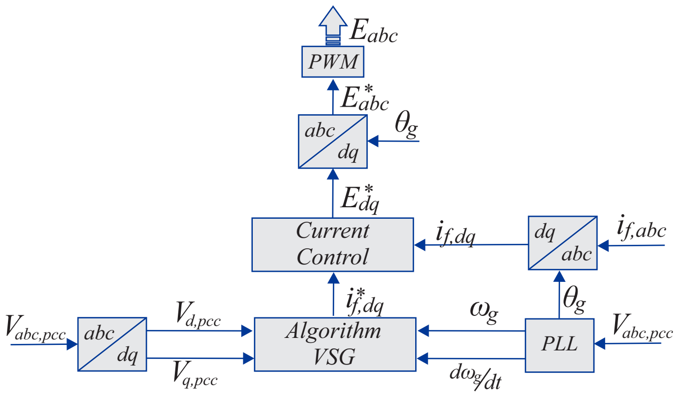

Figure 2. Control structure VSG-VSYNC.

The active and reactive powers references of the DGs/RESs are controlled using the equation (Van Wesenbeeck et al., 2009):

$$P^*_{VSYNC} = K_I \frac{d\omega_g}{dt} + P^{set}_{VSYNC}, \tag{1}$$

$$Q^*_{VSYNC} = Q^{set}_{VSYNC}, \tag{2}$$

in which ω_g and $V_{abc,pcc}$ are the angular frequency and the voltage of point of common coupling (PCC), and K_ω and K_I are design parameters. A phase locked loop (PLL) is used to measure the change in system frequency and $\frac{d\omega_g}{dt}$.

In (1), the first term corresponds to linearized inertia emulation and the second set value of active power.

From the reference powers, the reference currents are calculated and then go through a current PI controller. The current control is performed by the vector control technique, thus:

$$i^*_{d,f} = \frac{V_{d,pcc}P^*_{VSYNC} - V_{q,pcc}Q^*_{VSYNC}}{(V_{d,pcc} + V_{q,pcc})^2}, \tag{3}$$

$$i^*_{q,f} = \frac{V_{d,pcc}Q^*_{VSYNC} - V_{q,pcc}P^*_{VSYNC}}{(V_{d,pcc} + V_{q,pcc})^2}. \tag{4}$$

In (Karapanos et al., 2011), it was demonstrated the effectiveness of inertia emulation using VSG-VSYNC topology through real-time simulations, and the obtained results prove that there was a successful decreased in the amplitude of the frequency deviations within the simulated power system induced by load variations. The field test show promising results where changes in frequency are clearly counteracted by active power flows, and changes in voltage level are compensated by reactive power flows generated by the VSG-VSYNC (Van et al., 2010).

The main disadvantages of this control topology is that it cannot be implemented in islanded modes where the virtual inertia unit has to operate as a grid forming unit (Hatziargyriou et al., 2007), and an additional problem is the fact this procedure is associated with the dynamic behavior of PLL when operating in weak system (Wang et al., 2015).

2.2 ISE

This topology of VSG was developed by Osaka University researchers (Sakimoto et al., 2011). The VSG-ISE does not use a full SG model, so the approximate behavior of SG is obtained using just the swing equation, as shown in Fig. 3.

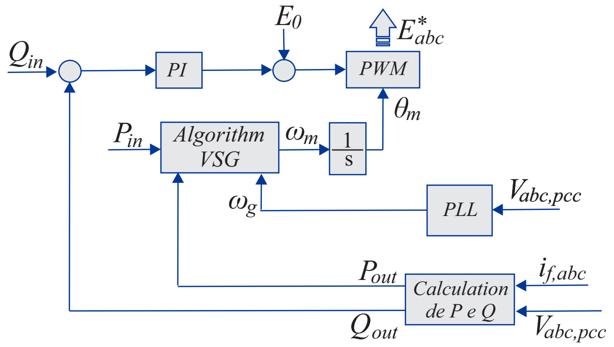

Figure 3. Control structure VSG-ISE.

Therefore, the control algorithm is based on:

$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dt} + D_{pi}\Delta\omega, \tag{5}$$

$$\Delta\omega = \omega_m - \omega_g, \tag{6}$$

where P_{in}, P_{out}, J, ω_g, ω_m, and D_{pi} respectively are the input power (it is equivalent to turbine power), the output power of the VSG-ISE, the moment of inertia virtual rotor, the grid angular speed, the virtual angular speed of rotor, and the damping factor. The active (P_{out}) and reactive (Q_{out}) powers are calculated, and the grid frequency (ω_g) is obtained via PLL.

The voltage and current signals are measured in the VSG-ISE terminals, and then calculate output active and reactive powers. Being P_{in} and Q_{in} the reference power active and reactive. Then, by solving (5) in each control cycle, the virtual angular speed is calculated and by passing through an integrator, the virtual phase angle θ_m is produced (Alipoor et al., 2015).

The effectiveness of the technique can be seen in (Liu et al., 2016a), where it has been studied the parallel operation of a SG and VSI, with the topology VSG-ISE in an islanded MG. The main disadvantage are power fluctuations and the frequency generated (Hatziargyriou et al., 2007), and because it does not act as a grid forming.

2.3 VISMA

This topology was presented in 2007 by the institute of electrical power engineering (IEPE) research group in Germany. The VSG-VISMA tries to mimic the exact behavior of the SG through a detailed mathematical model that represents their dynamics.

The control structure is divided into two parts, one of which is electrical and it is represented by the second order electrical model of the SG and the other part is mechanical which is represented by the mechanical model of the generator (swing equation) (Chen et al., 2011). Fig. 4 shows the reference voltage (E^*_{abc}) as it is produced from the current ($i_{f,abc}$) which is measured after the line filter.

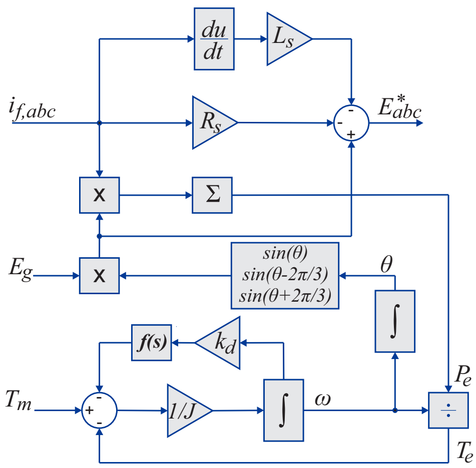

Figure 4. Control structure VSG-VISMA.

Where L_s and R_s represent the inductance and resistance of the stator windings, J is the moment of inertia, K_d is the mechanical damping factor, ω is the virtual angular velocity, θ is the angle of rotation, T_e and T_m are the electrical and mechanical torque. The reactive power is defined by excitation system control. Such control is given by an adjustable amplitude E_g. Active power control can be regulated by setting the T_m, the negative torque leads to a motor operation and positive torque to a generator operation (Chen et al., 2011).

In (Chen et al., 2012), the voltages of grid are measured to calculate the reference currents for the VSI, and hence, the VSI behaves as a current source connected to the grid. Then, the results were compared with VSI behaving as a voltage source, so it is notorious that the VSI as a source of voltage has almost the same static and dynamic properties of SGs.

The VSG-VISMA has the advantage of grid forming, but it has disadvantages due to: high number of parameters to be adjusted and uncontrollability of voltage amplitude and frequency.

2.4 Synchronverter

This topology was presented in 2009 (Zhong and Weiss, 2009), and it also uses the full mathematical model of SGs. The structure of a VSG-Synchronverter can be divided into two parts: a power circuit and a control circuit.

The control circuit can be implemented via software, as it is show in Fig. 5. The parameters to be tuned in controller design are the P–f droop coefficient D_p and the virtual inertia J for the active power loop, along with the Q–V droop coefficient D_q and the factor K of the reactive power loop. The details about how to design this loop can be found in (Zhong and Weiss, 2011).

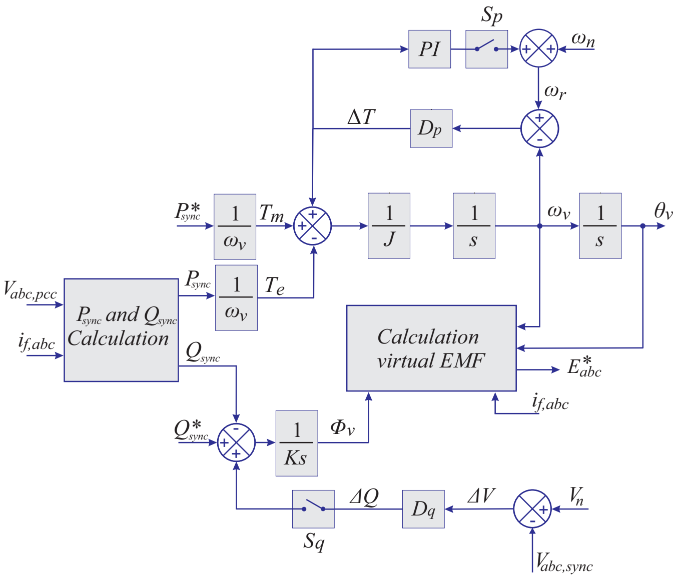

Figure 5. Block diagram of the control of the VSG-Synchronverter.

Depending on the positioning of the switches (S_p and S_q), there can be two operation modes of VSG-Synchronverter. When it is connected to the grid, according to grid operating conditions, it can take part in the automatic regulation of active and reactive power via frequency and voltage droop control, or it excludes those effects and generates the exact set-points of active and reactive power (Ming and Zhong, 2014). More details on the operating modes can be observed in (Silva Jr and Barros, 2019a) and (Silva Jr and Barros, 2019b).

As the PLL is nonlinear, the synchronization of VSI with the grid suffers several disadvantages. In (Zhong et al., 2014), it is shown the VSG-Synchronverter self-synchronization to the grid, which completely overcomes the need for PLL. In this paper, the PLL has been used for the initial synchronization.

Therefore, the VSG-Synchronverter acts as a grid forming and has two modes of operation (set mode and droop mode), with advantages over other VSG topologies.

3. SIMULATION RESULTS

The control topologies were simulated with a sampling frequency of 100 kHz and the switching frequency of the VSI was 10 kHz. The VSI/VSGs were connected to a three-phase 690 V/50 Hz grid. The ideal model for the battery bank was used. All VSG topologies were tested using the same grid parameters, in order to present an adequate performance comparison. All parameters used in the simulation are given in Tab. 1.

Table 1. Parameters Used in Simulation

Parameter	**Value**	**Parameter**	**Value**
L_f	$1\ mH$	L_g	$4.2\ mH$
R_f	$0.1\ \Omega$	R_g	$0.487\ \Omega$
C_f	$22\ mF$	K	$10\ kvar/V$
D_{pi}	5	J_{sync}	$0.0075\ kg.m^2$
J_{ISE}	$0.5-0.8\ kg.m^2$	D_p	$7\ N.m/(rad/s)$
L_s	$2\ mH$	D_q	$5\ kvar/V$
R_s	$0.02\ \Omega$	$k_p, sync$	0.01
J_{VISMA}	$0.1-0.2\ kg.m^2$	$k_i, sync$	1
k_d	2.5	$V_{link-CC}$	$1500\ V$
K_I	0.5	K_ω	100

The results obtained are presented in Fig. 6, and in order to facilitate understanding of the operating modes, the simulations were performed in two scenarios. In the first scenario, the relationship between active power and frequency was observed. On the other hand, in the second scenario, there were the reactive power and the voltage.

3.1 First Scenario

The simulation was started at $t = 0$ s. At $t = 1$ s the reference concerning active powers increased ($P^*_{VSG} > 0$, generator mode) and at $t = 3$ s the set-point of P^*_{VSG} has been changed for the motor mode. As it can be observed, the active power adapted very well to the change, following its references. Except for the mode P-ω of VSG-Synchronverter, in which the active power generated depends on the operating conditions of the grid, acting on maintaining its stability.

It was sought to use in each topology the maximum reference value of the active power, without loss of stability. The results obtained demonstrate that VSG-ISE and VSG-Synchronverter have larger capacity to deliver active power to the grid, being able to inject into the network a value of 250 kW. On the other hand, VSG-VISMA and VSG-VSYNC are able to inject 200 kW and 120 kW, respectively.

It was also observed that both ISE-VSG and VISMA-VSG presented the possibility of changing the moment of virtual inertia. It was seen the larger virtual inertia causes smaller overshoot over the frequency. Thus, with the application of control topologies ISE-VSG and VISMA-VSG it would be possible to increase the virtual inertia of the DGs/RESs, consequently increasing the frequency stability of the grid. This type of adjustment is not possible in VSG-Synchronverter, which can lead to stability loss. To VSG-VSYNC the inertia emulation is achieved by proper choice of control parameters of a PLL. For this work, PLL parameters were not changed.

Then, the Synchronverter-VSG operating modes were observed concerning different grid operating conditions. At $t = 1$ s, the grid frequency was increased to 51 Hz from the initial value of 50 Hz. For set mode, the active power follows its reference quickly and accurately under different operational conditions of grid. To make it possible, a PI controller is added to regulate the output ΔT of the frequency droop block D_p in order to obtain the zero value; thus, it is going to generate the reference frequency ω_n (nominal frequency of the grid) back to the original condition.

In mode P-ω, it has been observed that an increase in frequency automatically attenuates the active power generation delivered by the Synchronverter-VSG to the grid, acting in maintaining grid stability.

The results demonstrate that the performance of the VSG with implementation of DGs/RESs makes possible to obtain high control over the active power, being able to be operated in either battery bank charging or discharging mode. Therefore, this procedure is able to maintain demand/generation balance. Lastly, it was observed that perfect decoupling between active and reactive powers in steady state would only be possible using the Synchronverter-VSG topology.

3.2 Second Scenario

The simulation was started at $t = 0$ s. At $t = 1$ s, the reference regarding reactive powers has increased ($Q^*_{VSG} > 0$, over-excited supply a capacitive reactive power) at $t = 3$ s the set-point of Q^*_{VSG} has been changed for the under-excited mode, supplying inductive reactive power. It was sought to use in each topology the maximum reference value of the reactive power, without loss of stability.

From the obtained results, it has been proven that it is also possible to have control over reactive power, where VSGs can act in both over-excited and under-excited modes by acting in maintaining voltage stability of the grid. Thus, being able of applying reactive power injection in the presence of a short circuit in the grid, making DGs/RESs operate at tolerated levels concerning low voltage ride-through (LVRT).

The results obtained demonstrate that VSG-ISE have larger capacity to deliver reactive power to the grid, with value of 140 kvar. On the other hand, the other topologies are able to inject 100 kvar. It was also observed that the voltage generated by VSG-VSYNC has a higher oscillation compared to the other topologies.

At $t = 1$ s, the grid voltage was increased to 710 V from a initial value of 690 V. For the Synchronverter-VSG operating set mode, the reactive power follows its reference, and in order to make this possible, the switch S_q is off, then Φ_v is generated from the tracking error between Q^*_{sync} and Q_{sync} by the integrator with the gain of 1/K. Therefore, the generated reactive power Q_{sync} tracks the set-point Q^*_{sync} without any error at the steady state regardless of the voltage difference between V_n and $V_{abc,sync}$.

In mode Q-V, it has been observed that an increase in the grig voltage automatically attenuates the reactive power generation delivered by the Synchronverter-VSG to the grid, due to droop control actuation.

4. CONCLUSIONS

This paper presented a literature review and performance comparison of the main virtual synchronous generator topologies used in distributed generation systems based on renewable energy sources. It was shown that, fundamentally, the objective of all the topologies is dynamic frequency response through voltage source inverter and control over the active and reactive powers generated, what makes possible the control over the stability of microgrids. Besides, having full control over the dispatched energy can increase generation at peak electricity times, battery bank discharging, and off-peak electricity times, battery bank charging. The choice of the topology used depends on the desired level of similarity to the dynamics of synchronous generator. Topologies such as the VSG-Synchronverter and VSG-VISMA have the exact dynamics of synchronous generator and moreover are grid forming. The VSG-Synchronverter has two modes of operation (set mode and droop mode), with advantages over the other tested virtual synchronous generator topologies. The VSG-Synchronverter showed advantages, making possible larger injections of active power into the grid and the capacity of automatic regulation of active and reactive power via frequency and voltage droop control, acting in maintenance of grid stability.

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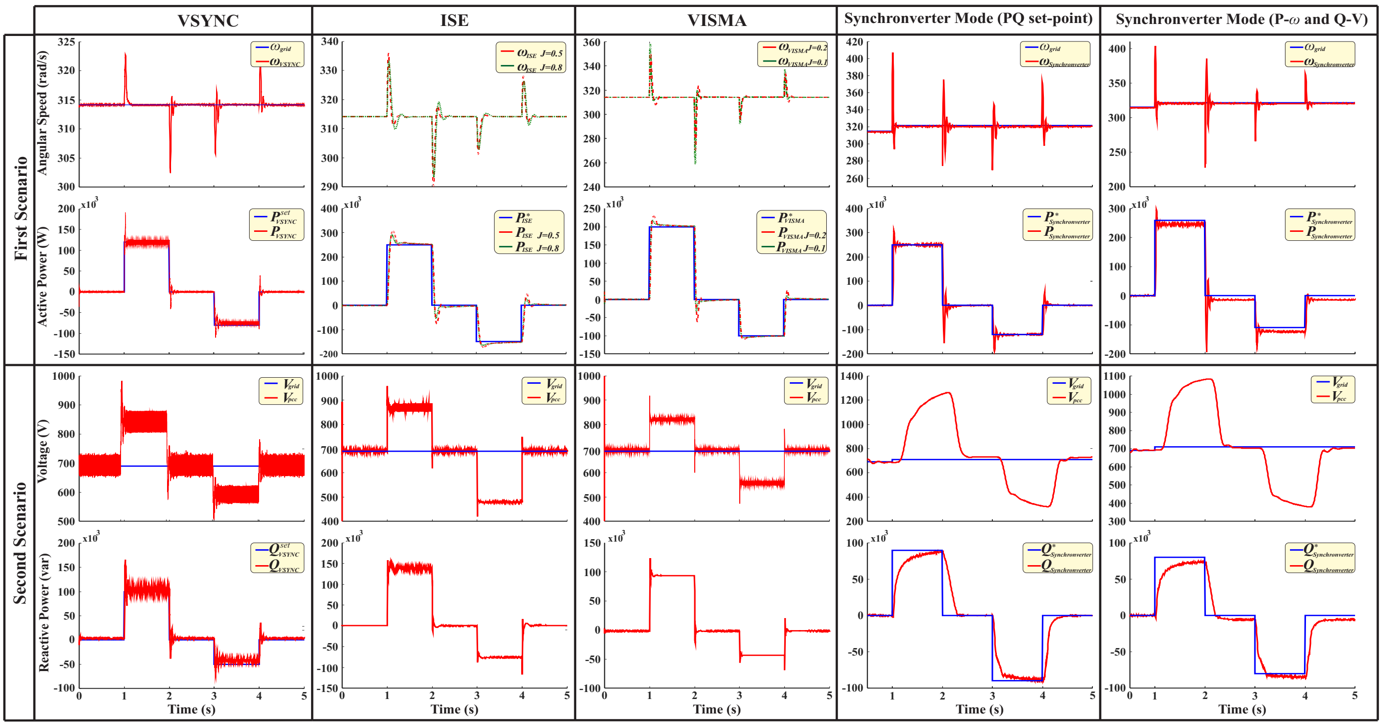

Figure 6. Real-time simulation comparison of the VSG topologies.

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