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Virtual Inertia: Current Trends and Future Directions

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Abstract: The modern power system is progressing from a synchronous machine-based system towards an inverter-dominated system, with a large-scale penetration of renewable energy sources (RESs) like wind and photovoltaics. RES units today represent a major share of the generation, and the traditional approach of integrating them as grid following units creates frequency stability issues. Numerous research has pointed towards equipping inverters with virtual inertia control algorithms so that they appear as synchronous generators to the grid, maintaining and enhancing system stability. This paper presents a literature review on the current state-of-the-art virtual inertia emulation techniques, and explores potential research directions and challenges. The major virtual inertia emulation topologies are compared and classified. Through literature review and simulations of some selected topologies it has been shown that similar inertial response can be achieved by relating the parameters of these topologies through time constants and inertia constants, although the exact frequency dynamics may vary slightly. The suitability of a topology depends on system control architecture and desired level of detail in emulation of the dynamics of synchronous generators. A discussion on the challenges and research directions points out several research needs, especially for systems level integration of virtual inertia systems.

Keywords: Frequency stability, microgrid control, renewable energy, virtual inertia.

1. Introduction

The demand for clean energy in the modern power system is on the rise. Driven by factors such as fuel prices, laws, and regulations, renewable energy sources (RESs) like photovoltaic (PV) and wind energy are now gradually starting to dominate the energy generation mix, replacing traditional generation sources, such as coal and nuclear [1,2]. The popularity of distributed PV plants further escalates the penetration of renewables in the modern power system. The global installation of wind and PV generation exceeded 400 GW and 200 GW, respectively, by the end of 2015 [3]. Countries like Ireland and Germany already have annual RES penetrations of more than 20% [4]. In Denmark, wind power alone has the capacity to meet 40% of the country's instantaneous electricity demand, which is the highest among all countries. The rapid development of RES is causing the modern power grid to gravitate towards an inverter-dominated system, as illustrated in Figure 1. PV systems and most modern wind turbines are interfaced through inverters. Although this is advantageous from the point-of-view of harvesting RES, the inverter-based generation does not provide any mechanical inertial response, and hence compromises frequency stability [4–6].

Recent reports and studies have shown issues in frequency stability due to lack of inertial response. The independent system operator (ISO), Electricity of Reliability Council of Texas (ERCOT)

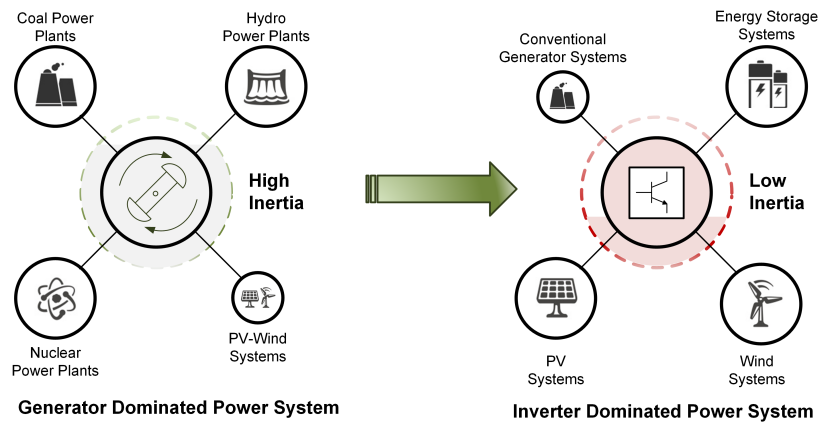


Figure 1. Evolution towards an inverter dominated power system.

has reported a continuous decline in the inertial response of its system and recommends additional inertial response [7,8]. Figure 2 illustrates the change in frequency in the ERCOT interconnection for two time periods for the same amount of generation loss. The change in frequency per generation loss is increasing yearly, and this trend is highly correlated with increased RES penetration over the same time-period. Similarly, the European Network of Transmission System Operators for Electricity (ENTSO-E) has reported increased frequency violations in the Nordic grid correlated with increased RES penetration [9]. As a consequence, inertial response from wind turbines are now mandatory in many countries [10,11] and the trend is extending towards PV plants as well. Hence, the need for research on virtual inertia, which in the past was of an academic nature, is gaining practical relevance.

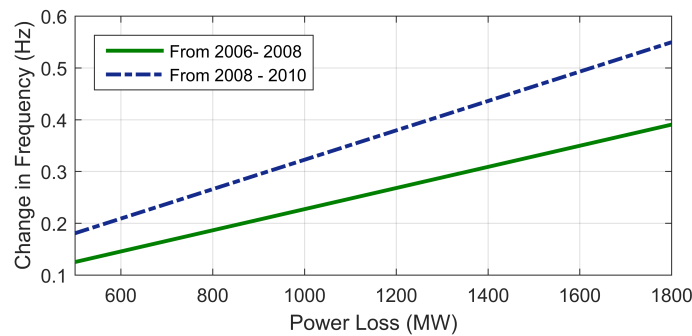


Figure 2. Increase in frequency changes in ERCOT connection due to generation loss [7].

In order to maintain the power generation and load balance, various control actions are implemented in a power system over multiple time-frames as illustrated in Figure 3. The governor response is the primary control action which takes place within the first few seconds (typically 10–30 s) of a frequency event and aims at reducing the frequency deviation. The automatic generation control is the secondary control action which take place within minutes (typically 10–30 minutes) and restores the system frequency back to the nominal value. The tertiary control action is the reserve deployment when actions are taken to get the resources in place to handle present or future disturbances in the system. Whenever there is an imbalance between the generation and consumption in a power system, the generators cannot respond instantaneously to balance the system. The kinetic energy stored in the rotors is responsible for counteracting this imbalance through inertial response until the primary frequency control has been activated. As conventional generators are displaced by RES, the inertial response also decreases. This leads to an increased rate-of-change-of-frequency

(ROCOF), and a low frequency nadir (minimum frequency point) in a very short time. The primary frequency control cannot respond within the small time frame (typically less than 10 s) to arrest the system frequency change. This period is highlighted as section AB in Figure 3. It is clear from the figure that in systems with lower inertia, the frequency nadir is considerably lower along with a high ROCOF. Such situations can lead to tripping of frequency relays (causing under-frequency load shedding (UFLS)) and, in the worst case, may lead to cascaded outages [12,13]. The solution to such scenarios is to add virtual inertia in the system. The basic requirements of a virtual inertia system is that it has to operate in a very short time interval (typically less than 10 s) and in autonomous fashion. The emulation of inertia through power electronics converters has the advantage of faster response compared to synchronous generators (SGs) [14]. Deployed appropriately, virtual inertia could enhance system stability.

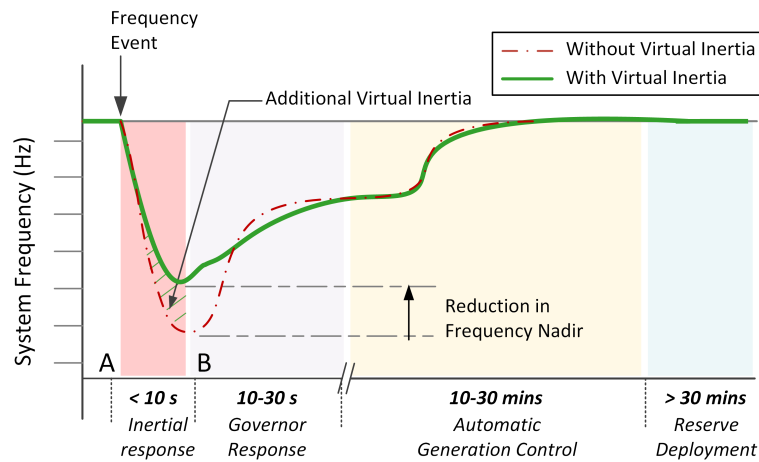


Figure 3. Multiple time-frame frequency response in a power system following a frequency event.

This paper presents a literature review of the various topologies used for virtual inertia emulation. The major topologies for virtual inertia emulation and the consequent improvements in these topologies are reviewed through a literature search followed by a restudy through simulations. The frequency issues due to high penetration of RES is introduced first in Section 2. The “first generation” of virtual inertia systems are introduced next in Section 3, where the focus in the literature has been on developing topologies and control algorithms to effectively emulate inertia of SGs through power electronic based converters. After a literature review of the virtual inertia topologies, three main topologies are compared and evaluated in a common benchmark in Section 4. The “second generation” of virtual inertia systems is then reviewed in Section 5, where the focus is on optimizing these systems in terms of dynamic performance and energy usage. Finally, a review of the challenges involved with integrating virtual inertia systems into the existing power system and some future research directions are discussed in Section 6. Section 7 discusses the conclusions of the paper.

2. Frequency Issues in Weak Power Systems with High Penetration of RES

Microgrids have been identified as the best option to integrate distributed generation (DG) units in terms of flexibility and reliability [15–17]. The microgrids can be operated in three possible modes: grid-connected, islanded, or isolated. In the isolated mode of operation, the microgrid is designed such that it is never connected to the grid. A microgrid is said to have been islanded when a microgrid that is grid-connected disconnects from the grid, either in a planned fashion or due to a fault/disturbance in the main grid. Regardless, these microgrid systems represent weak power systems and the high penetration of inertia-less PV and wind energy systems has a severe effect on the frequency stability. The rapid changes in the generation can cause frequency variations in the systems that are outside standard limits and compromise the stability of the system.

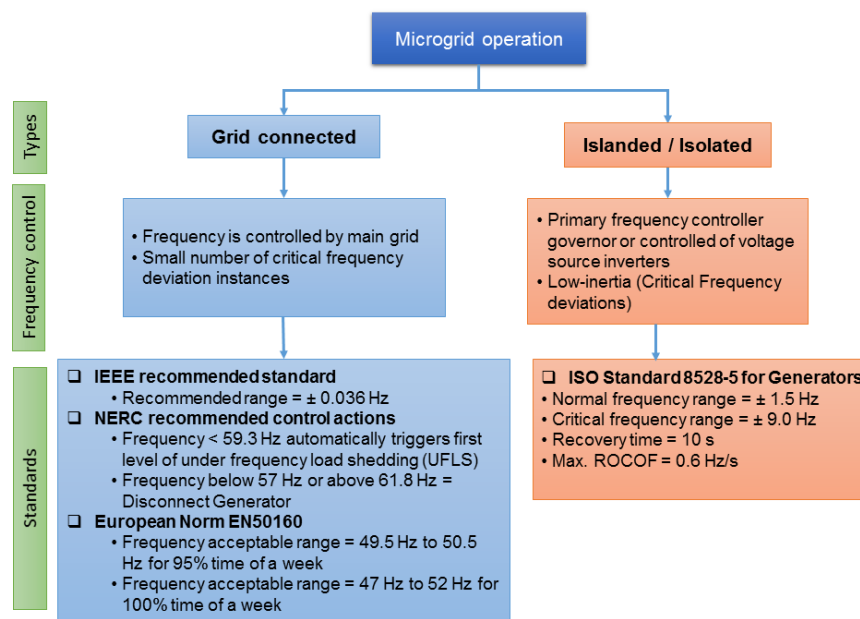


Figure 4. Frequency standards for micro grid systems [18–20].

Figure 4 shows the recommended standard frequency range for grid-connected and isolated/islanded microgrids. In the grid connected mode, the frequency is controlled by the main grid and the frequency deviations are relatively small, but this scenario is slowly changing with increased integration of large-scale inertia-less generation. IEEE recommends a tight frequency operating standard of $\pm 0.036\text{ Hz}$ for grid-connected systems. The North American Reliability Corporation (NERC) recommends triggering the first level of UFLS when the system frequency drops below 59.3 Hz (for a nominal frequency of 60 Hz for the US power grid). The activation of UFLS is the last automated reliability measure to counteract frequency drop to re-balance the system [21]. NERC recommended control actions recommend disconnecting the generator if the frequency drops below 57 Hz or rises above 61.8 Hz [18], but these recommended values may differ according to manufacturers. The European Norm EN50160 also imposes similar tight ranges for grid-connected microgrid systems. There are no specific standards defined for frequency limits for isolated microgrid systems, as this will depend highly on the generation and the load mix in a particular microgrid system. From a generator point-of-view, standards like the ISO 8528-5 recommend standards [20] for frequency operation and can provide a guideline for frequency limits. With the small amount of SG in isolated microgrids, the frequency excursions and ROCOF are higher and the need for virtual inertia is of higher importance. In such isolated microgrids, to emulate inertia either dedicated energy storage systems (ESS) can be used [22,23], or inertia can be emulated by operating PV/wind below their maximum power point(MPP) [24,25]. However, the allowable frequency nadirs and ROCOFs in the microgrids in islanded/isolated conditions may be relaxed compared to grid-connected operation. This will be especially vital for the design of virtual inertia systems for isolated microgrids as these microgrids often have limited energy resources and relaxing the frequency operating region can result in energy saving and reduction in power ratings of virtual inertia systems.

3. First Generation: Virtual Inertia Topologies

3.1. Concept and Classification of Virtual Inertia Topologies

The frequency variation in a power system after a frequency event/disturbance can be approximated by the swing equation [26]:

$$P_{gen} - P_{load} = \frac{d(E_{K.E.})}{dt} = \frac{d(\frac{1}{2}J\omega_g^2)}{dt} \quad (1)$$

$$P_{gen} - P_{load} = J\omega_g \frac{d\omega_g}{dt} \quad (2)$$

where, P_{gen} is the generated power, P_{load} is the power demand including losses, J is the total system inertia, and ω_g is the system frequency. The inertia constant of the power system H is the kinetic energy normalized to apparent power S_g of the connected generators in the system:

$$H = \frac{J\omega_g^2}{2S_g}. \quad (3)$$

Equation (2) can then be written as:

$$\frac{2H}{\omega_g} \frac{d\omega_g}{dt} = \frac{P_{gen} - P_{load}}{S_g} \quad (4)$$

Equation (4) can also be represented in terms of frequency instead of angular frequency as follows:

$$\frac{2H}{f} \frac{df}{dt} = \frac{P_{gen} - P_{load}}{S_g} \quad (5)$$

where, $\frac{df}{dt}$ is the ROCOF of the system. With reduced inertia, the ROCOF of the system increases which causes larger changes in frequency of the system in the same time-frame, thus requiring additional inertia in the system as more RES are integrated into the power system. The concept of emulating inertia using power electronic converters was first developed by Beck and Hesse [27]. Many other topologies and approaches have been developed in the literature since.

Virtual inertia is a combination of control algorithms, RES, energy storage systems (ESS), and power electronics that emulates the inertia of a conventional power system [13]. The concept of virtual inertia is summarized in Figure 5. The core of the system is the virtual inertia algorithm that presents the various energy sources interfaced to the grid through power electronics converters as synchronous machines. Most modern wind turbines are operated as variable speed wind turbines and interfaced through back-to-back converters, completely decoupling the inertia from the grid. Similarly, PV systems and ESS have a DC-DC converter and an inverter in the front-end, and do not contribute to the inertial response [4,28]. Virtual inertia systems based on current/voltage feedback from the inverter output generate appropriate gating signals to present these resources as SGs from the point-of-view of the grid [29]. Although the basic underlying concepts are similar among the various topologies in the literature, the implementation is quite varied based on the application and desired level of model sophistication. Some topologies try to mimic the exact behavior of the SGs through a detailed mathematical model that represent its dynamics. Other approaches try to simplify this by using just the swing equation to approximate the behavior of SGs, while others employ an approach which makes the DG units responsive to frequency changes in the power system. This section discusses the various topologies that have been proposed in literature. Figure 6 shows a general classification of various topologies that are available in the literature for virtual inertia emulation. The most relevant literature related to the topologies are also listed. Among the

listed topologies, the synchronverter, the Ise Lab's, virtual synchronous generator (most popular in literature from each classification), and the droop control are selected for a detailed description. A brief description of the remaining topologies is also presented under Section 3.6.

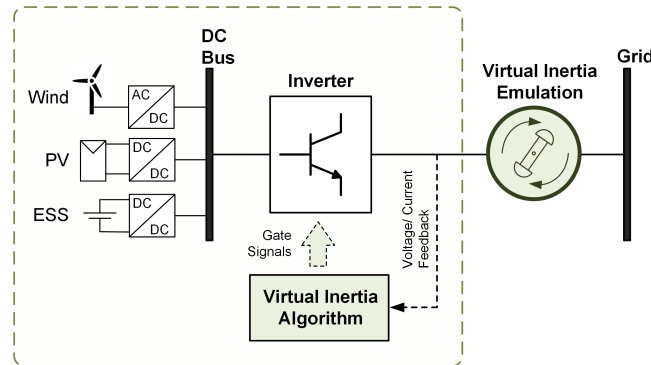


Figure 5. Concept of virtual inertia.

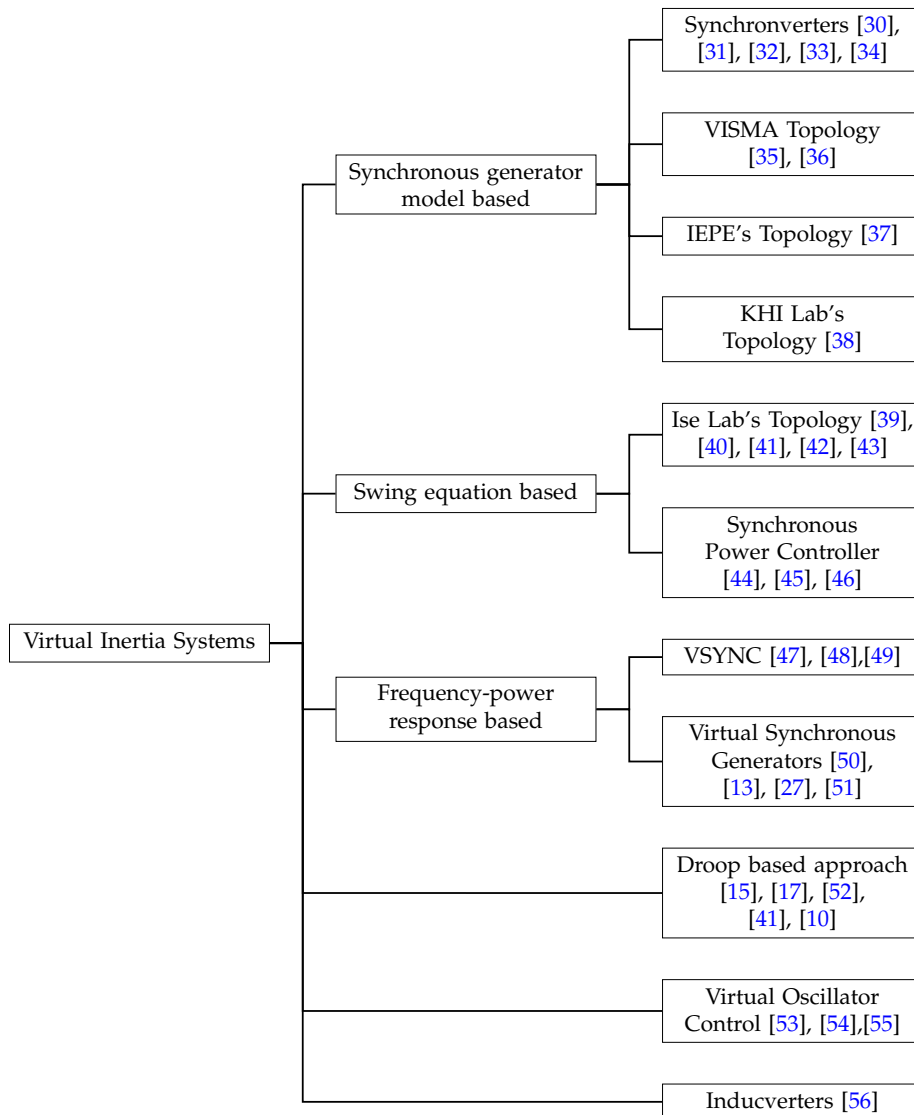


Figure 6. Classification of different topologies used for virtual inertia emulation

3.2. Synchronverters: A synchronous generator model based topology

Synchronverters operate the inverter-based DG units as synchronous generators representing the same dynamics from the point-of-view of the grid [30]. This is based on the notion that such a strategy allows traditional operation of the power system to be continued without major changes in the operation structure [57]. The topology is well developed in the literature by Q.C. Zhong. A frequency drooping mechanism is used to regulate the power output from the inverter similar to how the SG regulates its power output [58]. The following basic equations are used to capture the dynamics of the SG:

$$T_e = M_f i_f \langle i, \widetilde{\sin\theta} \rangle \quad (6)$$

$$e = \dot{\theta} M_f i_f \widetilde{\sin\theta} \quad (7)$$

$$Q = -\dot{\theta} M_f i_f \langle i, \widetilde{\cos\theta} \rangle \quad (8)$$

where, T_e is the electromagnetic torque of the synchronverter, M_f is the magnitude of the mutual inductance between the field coil and the stator coil, i_f is the field excitation current, θ is the angle between rotor axis and one of the phases of the stator winding, e is the no load voltage generated, and Q is the generated reactive power. In equations (6) and (8), $\langle \cdot, \cdot \rangle$ represents the standard inner product of two vectors in $\mathbb{R}^3$. The three-phase stator current, i , $\widetilde{\sin\theta}$, and $\widetilde{\cos\theta}$ are vectors defined as follows:

$$i = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}; \widetilde{\sin\theta} = \begin{bmatrix} \sin\theta \\ \sin(\theta - \frac{2\pi}{3}) \\ \sin(\theta - \frac{4\pi}{3}) \end{bmatrix}; \widetilde{\cos\theta} = \begin{bmatrix} \cos\theta \\ \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta - \frac{4\pi}{3}) \end{bmatrix} \quad (9)$$

Equations (6), (7), and (8) are first discretized and then solved in each control cycle in a digital controller to generate the gating signals for the DG unit under consideration. Figure 7a shows the basic schematic of the synchronverter. The dashed box represents the control part of the synchronverter, the details of which are illustrated in Figure 7b. The inverter output current and grid voltage are the feedback signals utilized to solve the differential equations within the controller. Additionally, the continuous reference active and reactive power that the synchronverter needs to inject/absorb to/from the DC bus can be set along with desired moment of inertia J and damping factor D_p . The selection of these parameters is crucial from the point-of-view of the stability of the system as shown in [59]. The control inputs are the mechanical torque, T_m and $M_f I_f$, which can be generated through the reference active and reactive power, respectively. The frequency and voltage loops, as indicated in Figure 7b, are used to generate the control inputs. The outputs of the controller are the voltage amplitude e and the phase command θ for the pulse width modulator (PWM) generator.

The underlying equations of a synchronverter topology form an enhanced phase locked loop (sinusoid-locked loop), making it inherently capable of synchronizing its frequency with the terminal voltage [31]. Single phase variants of the synchronverter have also been designed in [60]. The basic version of synchronverter requires a phase locked loop (PLL) to synchronize with the grid, however PLLs are known to have issues with stability in weak grids [61–63]. To counteract this issue, self-synchronized synchronverters are introduced in [33]. The synchronverter topology also inspired the operations of rectifiers as synchronous motors in [34]. This helps in obtaining inertial response from the load side of the power system. Moreover, the voltage-source based implementation means that synchronverters can be operated as grid forming units, and ideally suited for inertia emulation from DGs that are not connected with the main grid. The fact that the frequency derivative is not required for the implementation is a major advantage as derivative terms often induce noise in the system. Although the synchronverter is able to capture the exact dynamics of a synchronous generator, the complexity of the differential equations used results in issues with numerical instability while solving the complicated modeling equations. Moreover, a voltage-source

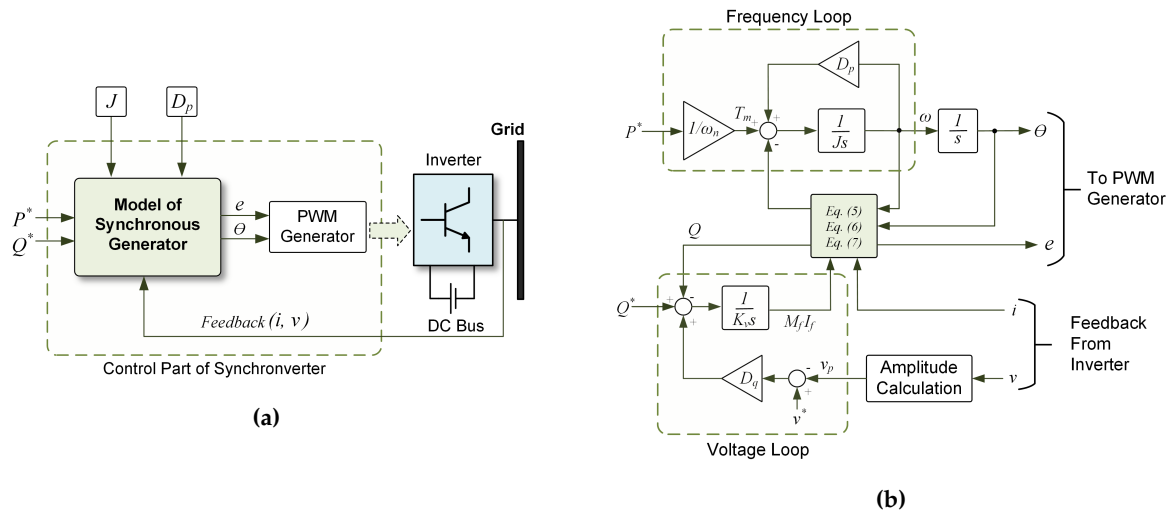


Figure 7. Synchronverter Topology: (a) Overall schematic showing operating principle. (b) Detailed control diagram showing the modeling equations.

based implementation means there is no inherent protection against severe grid transients, possibly requiring external protection systems for safe operation.

3.3. Ise Lab's Topology: A swing equation based topology

The topology developed by Ise lab for virtual inertia emulation is similar to the synchronverter approach described previously, but instead of using a full detailed model of the SG, the topology solves the power-frequency swing equation every control cycle to emulate inertia [39]. The schematic diagram of the topology illustrating the operation principle is shown in Figure 8a. The controller senses the inverter output current i and the voltage of the point of connection v , and computes the grid frequency ω_g and active power output of the inverter P_{out} . These two parameters are inputs to the main control algorithm block along with P_{in} which is the prime mover input power [40]. Within the control algorithm, the swing equation given by Equation (10) is solved every control cycle thus generating the phase command θ for the PWM generator. The typical swing equation of a SG is:

$$P_{in} - P_{out} = J\omega_m \left(\frac{d\omega_m}{dt} \right) + D_p \Delta\omega \quad (10)$$

$$\Delta\omega = \omega_m - \omega_g \quad (11)$$

where, P_{in} , P_{out} , ω_m , ω_g , J , and D_p are the input power (similar to the prime mover input power in a SG), the output power of the inverter, virtual angular frequency, grid/reference angular frequency, moment of inertia, and the damping factor, respectively. A model of the governor, as shown in Figure 8b, is utilized to compute the input power P_{in} based on the frequency deviation. The governor is modeled as a first-order lag element with gain K and time-constant T_d . P_0 represents continuous power reference for the DG unit. The delay in the governor model leads to higher ROCOF and thus higher frequency nadirs as a consequence. The voltage reference e can be generated through $Q - v$ droop approach as described in [41].

Similar to the synchronverter, derivative of frequency is not needed to implement the control algorithm. This is highly beneficial as frequency derivatives are known to introduce noise in the system which makes the system difficult to control. Additionally, this topology can be used to operate DG units as grid forming units, however, issues with numerical instability still remain. This fact, along with improper tuning of parameters J and D_p , can lead to oscillatory system behavior [40].

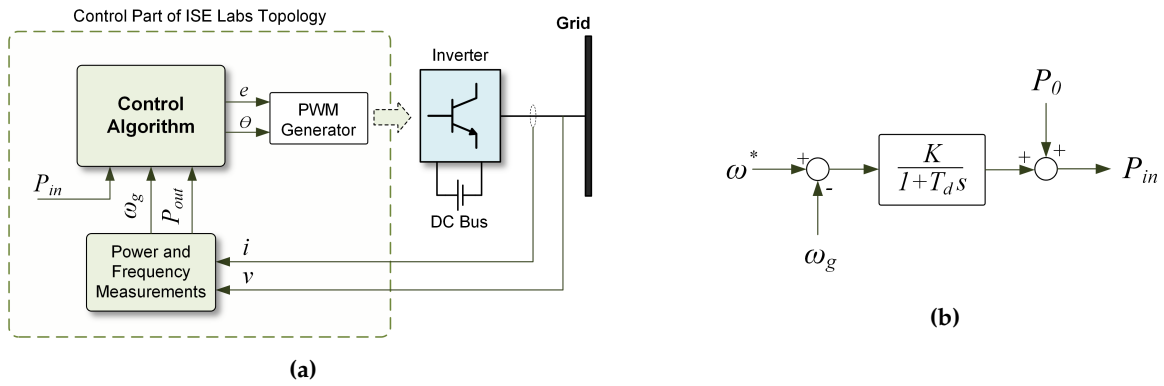


Figure 8. Ise Lab's Topology: (a) Overall schematic showing operating principle. (b) The governor model to compute input power.

3.4. Virtual Synchronous Generators: A frequency-power response based topology

The main idea behind virtual synchronous generators (VSG) is to emulate the inertial response characteristics of a SG in a DG system, specifically the ability to respond to frequency changes [26]. This emulates the release/absorption of kinetic energy similar to that of a SG, thus presenting the DG units as a dispatchable source [64,65]. Compared to traditional droop controllers which provide only frequency regulation, the VSG approach is able to provide dynamic frequency control [22]. This dynamic control is based on the derivative of the frequency measurement and behaves similarly to inertial power release/absorption by a SG during a power imbalance. Thus, the VSG is a dispatchable current source that regulates its output based on system frequency changes. This is one of the simplest approaches to implement virtual inertia in DG systems as it does not incorporate all the detailed equations involved in a SG. However, operating multiple DG units as current sources is known to cause stability issues [66].

The output power of the VSG converter is thus controlled using Equation (12):

$$P_{VSG} = K_D \Delta\omega + K_I \frac{d\Delta\omega}{dt} \quad (12)$$

where, $\Delta\omega$ and $\frac{d\Delta\omega}{dt}$ represent the change in angular frequency and the corresponding rate-of-change. K_D and K_I represent the damping and the inertial constant, respectively. The damping constant is similar to the frequency droop and helps return the frequency to a steady-state value and reduce the frequency nadir. The inertial constant arrests the ROCOF by providing fast dynamic frequency response based on the frequency derivative. This is especially important in an isolated grid where the initial ROCOF can be very high, leading to unnecessary triggering of relays. The VSG topology is illustrated in Figure 9. A PLL is used to measure the change in system frequency and ROCOF [64]. Then, using Equation (12), the active power reference for the inverter is computed. The current references are then generated for the current controller based on this reference power. The topology illustrated here assumes a direct-quadrature (d - q) based current control approach, but any other current control techniques (as described in [67,68]) may be used. For d - q control, d -axis current reference can be calculated as [23]:

$$I_d^* = \frac{2}{3} \left(\frac{V_d P_{VSG} - V_q Q}{V_d^2 + V_q^2} \right). \quad (13)$$

The q -axis current reference is set to zero as it is assumed that only the active power is being controlled. The current controller based on the grid current feedback generates the gate signals to drive the inverter. Thus, the inverter behaves as a current-controlled voltage source inverter [13,67].

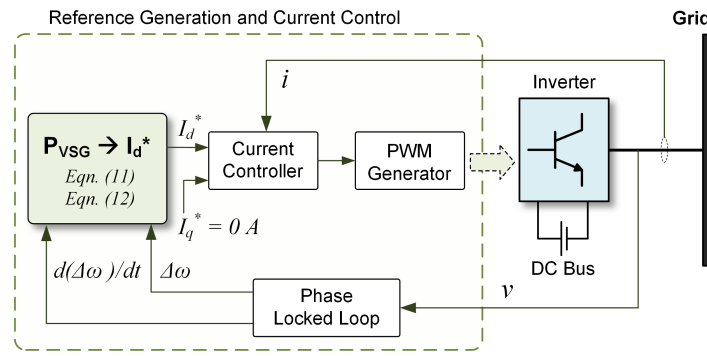


Figure 9. Virtual synchronous generator topology.

This topology is used by the European VSYNC research group [49,64] and has demonstrated the effectiveness of inertia emulation using VSG topology through real-time simulations [47] and several field tests [69]. In [23], an experimental verification of the topology is presented in case of remote microgrids. The VSG topology has also been widely employed for virtual inertia emulation from wind systems as reported in [6,48,70]. The main drawback of this topology is that it cannot be implemented in islanded modes where the virtual inertia unit has to operate as a grid forming unit. Moreover, the system emulates inertia during frequency variations, but not in input power variations [46]. The measurement of the frequency derivative through PLLs is a challenging issue for this kind of implementation [71,72]. The performance of PLLs can degrade and compete against each other, especially in weak grids [56,73]. PLL systems are known to have issues with steady-state errors and instability especially in weak grids with frequency variations, harmonic distortions and voltage sags/swells [61–63]. In [74], it is shown that the instability issues are even more pronounced when a proportional-integral (PI) controller is used to implement the inner-current control loop of the inverter. Hence, a VSG requires a robust and sophisticated PLL for a successful implementation [75]. Another disadvantage of the VSG approach is that the derivative term used to compute the ROCOF makes the VSG sensitive to noise which can lead to unstable operation.

3.5. Droop-based Approaches

The approaches described so far try to mimic or approximate the behavior of SGs to improve inertial response of inverter-dominated power systems. Different from these techniques are the frequency-droop based controllers that have been developed for autonomous operation in isolated microgrid systems [76,77]. Based on the assumption that the impedance of the grid is inductive, the frequency droop is implemented as:

$$\omega_g = \omega^* - m_p(P_{out} - P_{in}) \quad (14)$$

where, ω^* is the reference frequency, ω_g is the local grid frequency, P_{in} is the reference set active power, P_{out} is the measured active power output from the DG unit, and m_p is the active power droop. Similarly, the voltage-droop is implemented as:

$$v_g = v^* - m_q(Q_{out} - Q_{in}) \quad (15)$$

where, v^* is the reference voltage, v_g is the local grid voltage, Q_{in} is the reference set reactive power, Q_{out} is the measured reactive power output from the DG unit, and m_q is the reactive power droop.

The schematic of a frequency-droop controller based on Equation (14) is shown in Figure 10. Often a low pass filter is used when measuring the output power to filter out high frequency components from the inverter [15]. In the literature [52,73,78], it has already been shown that the

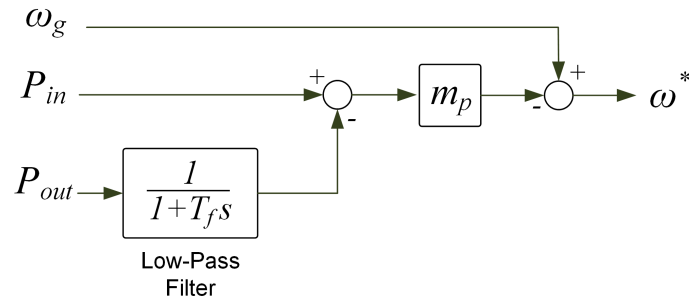


Figure 10. Schematic for frequency droop control.

228 use of this filter makes the droop-based control approximate the behavior of virtual inertia systems.
 229 The proof was first presented by Arco et. al [73] and is repeated here for convenience.

Proof. Based on the schematic of Figure 10:

$$P_{out} = (1 + T_f s) \left\{ \frac{1}{m_p} (\omega_g - \omega^*) + P_{in} \right\} \quad (16)$$

Rearranging,

$$P_{in} - P_{out} = \frac{1}{m_p} (\omega^* - \omega_g) + T_f \cdot \frac{1}{m_p} \cdot s \cdot \omega^* \quad (17)$$

230 □

This equation is of the similar form of the virtual synchronous generator described in Equation (12). The exact approximation is as follows:

$$K_I = T_f \cdot \frac{1}{m_p} \quad (18)$$

$$K_D = \frac{1}{m_p} \quad (19)$$

231 Hence, the filters used for power measurements in these controllers constitute a delay which is
 232 mathematically equivalent to virtual inertia, while the droop gain is equivalent to damping. However,
 233 the traditional droop-based systems described by Equations (14) and (15) are known to have slow
 234 transient response. Moreover, the inductive grid assumption may not always be valid. Methods to
 235 improve the droop controllers, such as using virtual output impedance [17] or improving dynamic
 236 behavior of the droop scheme [15], have been proposed. In [10] and [79], a technique to emulate
 237 virtual inertia by a modified droop approach is also presented.

238 3.6. Other Topologies

239 Some other topologies that have been proposed in the literature are virtual synchronous
 240 machine, referred to as "VISMA" in the literature, Institute of Electrical Power Engineering (IEPE's)
 241 topology, Kawasaki Heavy Industries (KHI) lab's topology, synchronous power controllers (SPC),
 242 virtual oscillators, inducverters, etc. The basic concept of inertia emulation remains the same in
 243 all these techniques. The VISMA topology as proposed in [35] uses $d - q$ (synchronous reference
 244 frame) based mathematical model of a synchronous machine in a digital controller. Instantaneous
 245 measurements of the grid voltage are used to compute the stator currents of the virtual machine
 246 and these currents are injected through a hysteresis current control approach using a power inverter.
 247 However, numerical instability issues have been reported while implementing the VISMA model.

To improve robustness a three-phase model has been proposed in [36] over a $d - q$ based model to improve robustness of VISMA, especially under unsymmetrical load conditions or rapid disturbances in the grid. A comparison between implementing the VISMA algorithm as a current source versus a voltage source has also been performed in [37]. The VISMA model implemented as a voltage source is referred to as IEPE's topology in the literature [29]. Instead of using voltage as input as with the VISMA topology, IEPE's topology uses the DG output current as input and generates reference voltages for the virtual machine. The IEPE topology is better suited for islanded operation, but there are issues with transient currents particularly during the synchronization processes when operated in grid connected mode. In the KHI topology, instead of using detailed dynamic model of SG an equivalent governor and automatic voltage regulator (AVR) model is implemented in a digital controller to generate voltage amplitude and phase reference for the virtual machine [38]. The reference is then used to generate current references based on algebraic-phasor representation of the SGs.

Another popular topology for virtual inertia emulation is the SPC as proposed in [44,80,81]. The general structure of the control algorithm is similar to the structure proposed in the Ise lab's topology, but instead of operating the converter as a voltage controlled system or a current controlled system, it implements a cascaded control system, with an outer voltage loop and an inner current control loop through the use of a virtual admittance. In general, such a cascaded control structure provides inherent over-current protection during severe transient operating conditions which is lacking in other open-loop approaches such as synchronverters or the Ise labs topology [82] described previously. This also avoids the discontinuities encountered in solving the mathematical models, thus making the system more robust against numerical instabilities. The nested loop structure however does entail complexity in tuning the control system parameters. Furthermore, at its core instead of using the swing equation for inertia emulation, a second order model with an over-damped response is proposed. This helps to reduce the oscillations in the system [46]. Improved forms of this second-order model was presented in [45,46].

Inducverters [56] is one of the recent topologies that has been proposed which tries to mimic the behavior of induction generators instead of SGs. This method has the advantage of auto-synchronization without a PLL [83]. A virtual-inertia based static synchronous compensator (STATCOM) controller is proposed in [78] which behaves as synchronous condenser. The virtual inertia controller was used to exploit the fact that no PLL is required, hence providing improved voltage regulation compared to traditional STATCOMs with PLL units. Virtual Oscillator Controller (VOC) is another approach where instead of mimicking synchronous/induction generators, a non-linear oscillator is implemented within the controller to synchronize DG units without any form of communication [53,54]. This approach is particularly beneficial for a grid largely dominated with DGs, as the controller is intrinsically able to maintain synchronism and share the total system load [55].

3.7. Summary of Topologies

A summary table highlighting the key features and weakness of various virtual inertia control topologies is presented in Table 1.

Table 1. Summary of Virtual Inertia Control Topologies

Control Technique	Key Features	Weaknesses
Synchronous generator model based	• Accurate emulation of SG dynamics • Frequency derivative not required • PLL used only for synchronization	• Numerical instability issues • Typically voltage-source implementation; no over-current protection
Swing equation based	• Simpler model compared to SG based model • Frequency derivative not required • PLL used only for synchronization	• Power and frequency oscillations • Typically voltage-source implementation; no over-current protection
Frequency-power response based	• Straightforward implementation • Typically current-source implementation; inherent over-current protection	• Instability issues due to PLL, particularly in weak grids • Frequency derivative required, system susceptible to noise
Droop-based approach	• Communication less • Concepts similar to traditional droop control in SGs	• Slow transient response • Improper transient active power sharing

4. Design Procedures and Simulation Results

In this section, three of the major virtual inertia topologies are restudied in a diesel generator based remote microgrid system. The design procedures and simulation results presented are aimed at supplementing the concepts of virtual inertia topologies reviewed in Section 3. Three of the topologies — the synchronverter, the Ise lab's topology, and the VSG — are implemented and their performance is studied in a common benchmark. Moreover, a procedure is provided to choose appropriate parameters for the virtual inertia systems. The three virtual inertia systems are designed in a common framework so that the different parameters used are more relatable to each other. To this end, constants in each topology are selected such that the virtual inertia system injects/absorbs the same amount of active power for a given frequency change. Moreover, the inertial constant and the damping constant have the same proportion and are related through a time constant T_f of 0.01 s in all the simulations. This leads to an inertia constant H of 1 s in all simulation cases for the virtual inertia unit. The schematic used for the virtual inertia simulation benchmark is shown in Figure 11. The generator is rated at 13 kVA, while the PV unit is rated at 6 kWp [23]. A separate, dedicated inverter unit rated at 10 kW is used as the virtual inertia unit. In all the cases the steady-state power output from the inverter is set to 1000 W. It is assumed that, the DC side of the inverter is connected to a 400 V DC source and is assumed to remain constant in all the simulations. Step changes in the load are used to emulate the change in load or PV generation in all the systems. For simplicity, the inverter is modeled as either a controlled current source or a controlled voltage source depending on the virtual inertia topology used neglecting the switching behavior.

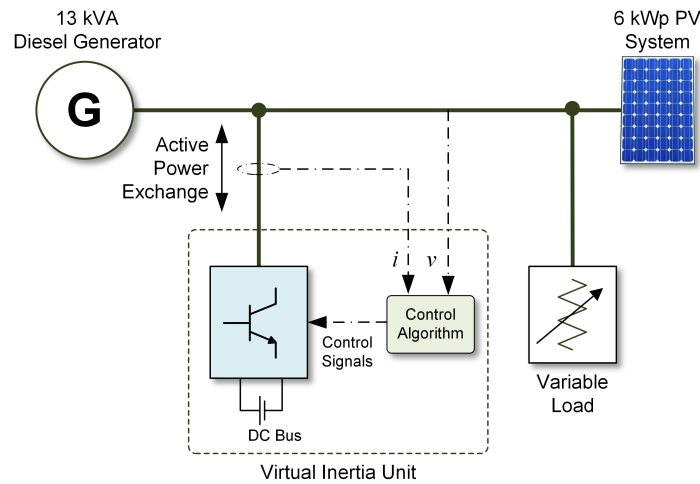


Figure 11. Schematic diagram of the virtual inertia simulation benchmark.

4.1. Design of synchronverter topology

The main parameters to be computed to implement a synchronverter are the moment of inertia J and the damping factor D_p . The parameter D_p can be calculated using Equation (20) from [30].

$$D_p = -\frac{\Delta T}{\Delta \omega} = -\frac{\Delta P}{\omega_g \Delta \omega}. \quad (20)$$

Once D_p is calculated, the moment inertia J can be computed using the desired time constant for the system, τ_f :

$$\tau_f = \frac{J}{D_p}. \quad (21)$$

In this case, D_p was calculated to be 14.072 assuming ΔP of 100% (10 kW) for 0.5% change in the angular frequency (1.885 rad/s). Then for a time-constant of 0.01 s, the J value was calculated to be 0.140 (Note that the frequency unit here is in rad/s). The inertia constant from the synchronverter is:

$$H = \frac{J \omega_g^2}{2P_{rated}} = 1s. \quad (22)$$

The frequency and ROCOF of the system after a step-increase of 2 kW on the load, with and without the synchronverter, are presented in Figure 12a and 12b, respectively. The dip in frequency and the ROCOF of the system was reduced with the addition of the synchronverter as expected. The additional inertia from the synchronverter increased the settling time for the frequency compared to when there was no synchronverter in the system. As shown in Figure 12c, the synchronverter increases its active power output in response to the frequency event much like the behavior of a SG.

4.2. Design of Ise Lab's topology

For the design of the Ise lab's VSG, the same values for the constants J and D_p that were calculated for synchronverter in Section 4.1 were used. For the implementation of the governor model, a K value of 0.01 with a time delay T_d of 0.16s was used. The frequency and ROCOF of the system after a step-increase of 2 kW on the load, with and without the Ise lab's VSG, is presented in Figure 13a and 13b, respectively. The dip in the frequency and the ROCOF of the system was reduced with addition of the virtual inertia unit as expected. The additional inertia from virtual inertia system increased frequency settling time compared to the case without the virtual inertia system. The settling time, however is higher than with the synchronverter. Figure 13c shows the power injected by the

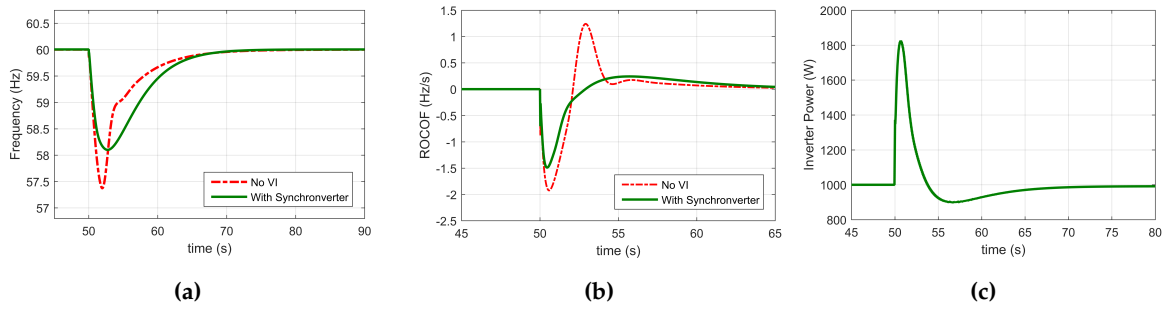


Figure 12. Simulation Results from a Synchronverter: (a) System frequency after a step-increase of 2 kW load. (b) ROCOF after a step-increase of 2 kW load. (c) Increase in inverter power in response to system frequency decrease [30].

inverter during the step-load increase. There is a short transient at 50 s, which is a consequence of numerical oscillation in solving the swing equation. The peak-power injected is similar to that of the synchronverter, but the time taken for the power to return to the steady-state value of 1000 W is much longer, leading to a larger energy usage from the DC side.

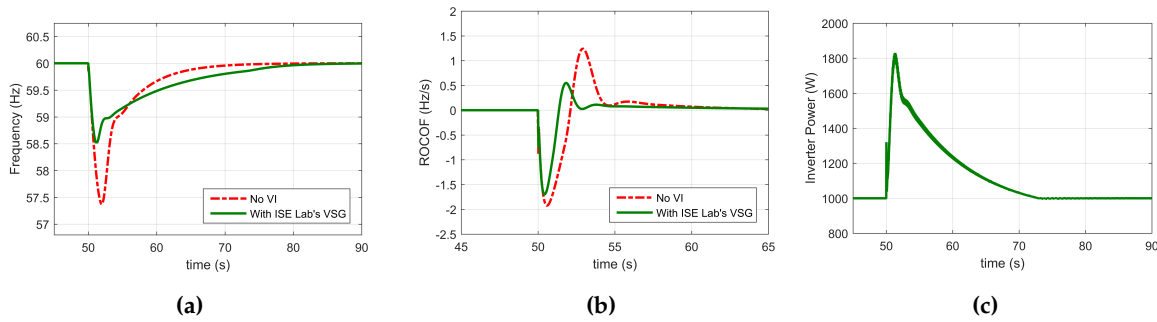


Figure 13. Simulation Results from ISE lab's topology: (a) System frequency after a step-increase of 2 kW load. (b) ROCOF after a step-increase of 2 kW load. (c) Increase in inverter power as a response to system frequency decrease [39].

4.3. Design of virtual synchronous generator topology

For implementing the VSG topology, the main parameters to be designed are the inertia constant K_I and the damping constant K_D . The parameter K_D can be calculated using:

$$K_D = \frac{\Delta P}{\omega_g \Delta \omega}. \quad (23)$$

Once K_D is calculated, the inertia constant K_I can be computed using the desired time constant for the system, τ_f :

$$\tau_f = \frac{K_I}{K_D}. \quad (24)$$

In this case, the damping constant, K_D , was calculated to be 14.07, assuming ΔP of 100% (10 kW) for 0.5% change in the angular frequency (1.885 rad/s). Then, for a time-constant of 0.01 s, the K_I value was calculated to be 0.14. The inertia constant from the VSG is:

$$H = \frac{K_I \omega_g^2}{2P_{rated}} = 1s. \quad (25)$$

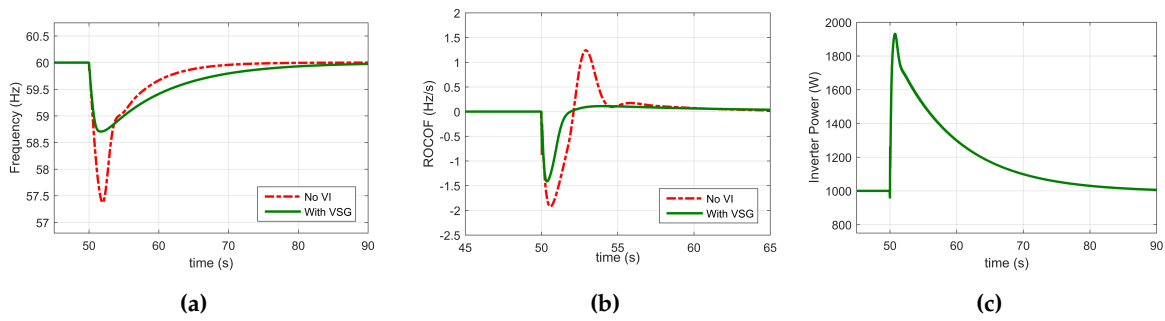


Figure 14. Simulation Results from a Virtual Synchronous Generator: (a) System frequency after a step-increase of 2 kW load. (b) ROCOF after a step-increase of 2 kW load. (c) Increase in inverter power as a response to system frequency decrease [64,65].

The frequency and ROCOF of the system after a step-increase of 2 kW on the load, with and without the VSG, is presented in Figure 14a and 14b, respectively. The dip in frequency and the ROCOF of the system was reduced with addition of the VSG as expected. As with the previous cases, the additional inertia from the VSG slowed the system down, and the settling time for the frequency was increased compared to the case without virtual inertia. The peak-power injected was slightly higher than that of the synchronverter and Ise lab's topology, but again the time taken for the power to return to the steady value of 1000 W is much longer than for the synchronverter leading to a larger energy usage from the DC side.

4.4. Summary of Simulations

The simulation results are summarized in Table 2 in terms of parameters like the minimum frequency, maximum ROCOF, settling time, peak power, and energy exchange. The settling time is defined here as the time required for the frequency to return to and stay within ± 0.25 Hz of the final steady-state frequency after a disturbance. The energy exchange is calculated over the time period where the inverter exchanges power with the system. With all three topologies, the minimum frequency and ROCOF were reduced by similar amounts. The peak power delivered by the inverter varied slightly, with the highest value of 1929 W for the VSG topology. The most pronounced differences were in the settling time for the frequency and the energy exchange. The settling time with all the three cases increased compared to when there was no virtual inertia. This was expected as adding virtual inertia slows down the frequency dynamics. The ISO8528-5 standard for generators sets recommends a settling time of 10s [20]. The settling time, however, increased to 13.2 s with synchronverter and an even higher value of 17.7 s and 17.9 s with the Ise lab's and VSG respectively. This led to a relatively higher energy exchange in these two topologies of 3.8 Wh and 4.9 Wh compared to that 0.8 Wh with the synchronverter. Moreover, as there is a short-energy recovery period in the power plot of the synchronverter as seen in Figure 12c which led to a lower energy exchange estimate for the synchronverter.

Table 2. Performance comparison of synchronverter, Ise lab's and virtual synchronous generator topologies.

Parameter	No VI	Synchronverter	Ise Lab	VSG
Minimum Frequency	57.3 Hz	58.1 Hz	58.6 Hz	58.3 Hz
Maximum ROCOF	1.9 Hz/s	1.5 Hz/s	1.6 Hz/s	1.7 Hz/s
Settling time	11.3 s	13.2 s	17.7 s	17.9 s
Peak power delivered	0W	1825 W	1800 W	1929 W
Energy exchanged	0 Wh	0.8 Wh	3.8 Wh	4.9 Wh

Therefore, by appropriately selecting parameters for the topologies through the time constant T_f and/or the inertia constant H , similar inertial response can be achieved in terms of frequency deviation reduction and power exchange from the inverter. Based on the topology, the exact dynamics represented by the system may vary. The selection of a particular topology depends on the application and the desired level of replication of the dynamics of the SG. Topologies like the synchronverter, Ise Lab's topology may be more suitable for isolated power system as they can operate autonomously as grid forming units, as well as for reasons discussed in Section 3. The VSG topology on the other hand behaves more like a grid following unit with added inertial response capabilities and is more suited towards interconnected operations. If a closer approximation of SG dynamics is desired, the synchronverter or Ise lab's topology are ideal choices. If the main aim, however, is to make the DG unit responsive to frequency change, the VSG approach provides a far simpler implementation.

5. Second Generation: Optimization of Virtual Inertia Systems

The first generation of virtual inertia systems in the literature focused on developing novel topologies for emulation of inertia using power electronic converters. These topologies have matured since as pointed out in Section 3. Recently, the field is more focused towards improving and optimizing the performance of these topologies from the point-of-view of enhanced dynamics, stability, and minimizing energy storage requirements.

5.1. Second Generation of Synchronverters

Improved versions of the synchronverter have been proposed in [32,84] which makes the synchronverter more robust and allows for an more accurate dynamic representation of SGs. One of the main improvements (among others) in [84] is virtually increasing the filter inductance of the synchronverter, which improved the stability compared to the original synchronverter. This modification allowed for an improved control over the response speed of the frequency loop proposed in [30]. In a similar theme, an auxiliary loop around the frequency-loop was proposed in [85] which allowed for a free control of the response speed of synchronverter. This auxiliary loop did not effect the steady-state drooping mechanism of the synchronverter which is very desirable. By changing the inertia constant J and a different tunable constant D_f , the desired response speed was achieved. In [86], a synchronverter with analytically determined bounds for frequency and voltage was introduced. In traditional synchronverters, saturation units are employed for this purpose, but such an approach can create stability issues due to wind-up. Instead, analytically determined bounds based on the system parameters were proposed to improve stability.

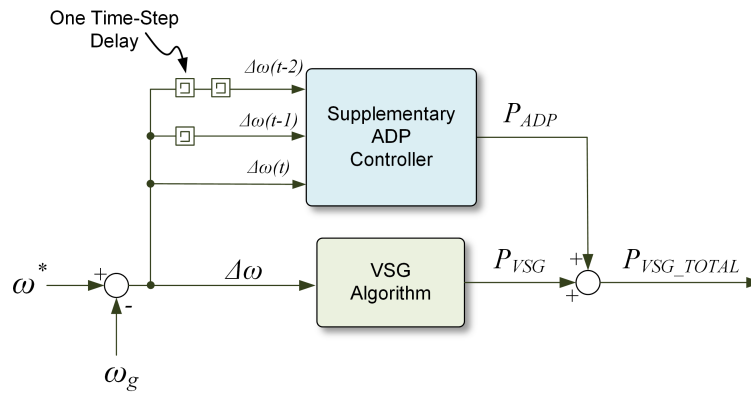
5.2. Second Generation of Ise Lab's Topology

In the traditional Ise Lab's topology, active power oscillation during the inertia emulation has been pointed out as a major issue in the literature [40]. Typically, during a frequency event, the DG unit needs to release/absorb a high amount of power, which may exceed their power ratings. This is not a problem for conventional SGs as they have inherently overrated operation capabilities, but in the case of inverters, the switches have to be over-sized to handle such peak power, leading to an increase in inverter size and, consequently, cost [62]. In [40], an alternating moment of inertia emulation approach was proposed to make the system less susceptible to such oscillations. The J parameter was changed based on the relative "virtual angular velocity" and its rate of change. The proposed alternating moment of inertia approach not only stabilized the system under consideration, but other nearby virtual inertia units as well. Similarly, in [87] another technique of adjusting the "virtual stator reactance" of the virtual inertia unit has also been proposed to reduce such active power oscillations. This approach was somewhat similar to the approach described for synchronverters in [84]. The technique was also found to aid in proper transient active power sharing when operating multiple virtual inertia units in a microgrid environment. In [88], a particle swarm optimization technique

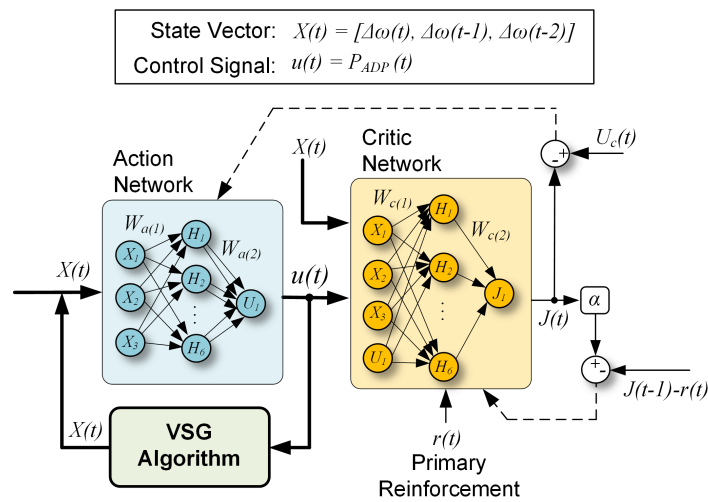
was developed to properly tune the parameters of the system and achieve smooth transitions after a disturbance when operating multiple virtual inertia units.

5.3. Second Generation of Virtual Synchronous Generators

In terms of improvement in VSG topologies, some researchers have developed techniques to try to minimize the frequency nadirs/peaks in the system at the expense of higher energy usage and peak transient power exchange through the virtual inertia systems [89,90]. Other researchers, meanwhile, have focused on reducing the energy storage requirements and limiting peak transient power in virtual inertia systems even though it leads to slightly higher frequency nadirs/peaks [50, 91]. A self-tuning VSG was developed in [50] using an online optimization technique to tune the K_I and K_D parameters of the VSG control algorithm, described in Section 3.4, to minimize the frequency excursions, the ROCOF, and the power flow through the ESS. Although the frequency excursions were slightly higher in the case of the self-tuning algorithm, the power flow through the ESS was reduced by 58%. Moreover, the technique used less energy per Hz of frequency reduction than a constant parameter VSG.



(a)



(b)

Figure 15. Modified Virtual Synchronous Generator using Adaptive Dynamic Programming (a) Overall schematic of the controller. (b) The action and critic neural network based structure.

On a similar note of energy saving, an online neural-network based controller was proposed in [91]. It used an adaptive dynamic programming (ADP) based approach to optimize the system and

minimize energy usage while limiting the transient power. The controller supplemented the power references generated by the main VSG algorithm with the aim of improving the dynamics of virtual inertia as shown in Figure 15a. The proposed ADP controller used a neural network structure with two different networks— an action network and a critic network as shown in Figure 15b. The idea behind the design of the critic network was to adapt its weight such that the optimal cost function $J^*(X(t))$ satisfies the Bellman principle of optimality as given by:

$$J^*(X(t)) = \min_{u(t)} \{J^*(X(t+1)) + r(X(t)) - U_c\}. \quad (26)$$

where, $r(t)$ is the reinforcement signal for the critic network and U_c is a heuristic term used to balance. The input to the supplementary ADP controller was the state vector $X(t)$ where the elements were the frequency error and the one and two time-step delayed frequency error signals. Based on a reinforcement learning approach, the ADP controller generated auxiliary power reference signals P_{ADP} to return the frequency back to its steady-state value faster and as a consequence reduced the energy exchange as explained in [91]. The main issue of adding virtual inertia to the system is it can increase the frequency settling time, leading to increased energy exchange from the ESS, which subsequently shortens the life of the ESS. The online controller was able to reduce the frequency settling time and the transient peak power. Figure 16a (extracted from the paper [91]) shows the frequency of a PV-hydro system under step load changes with and without the ADP controller. The frequency excursion was slightly higher than using constant parameter VSG, but there was a reduction in the frequency settling time. This lead to lower energy usage and lower transient power as observable in Figure 16b. Table 3 summarizes the improvement achieved in [91] through ADP-based virtual inertia controller.

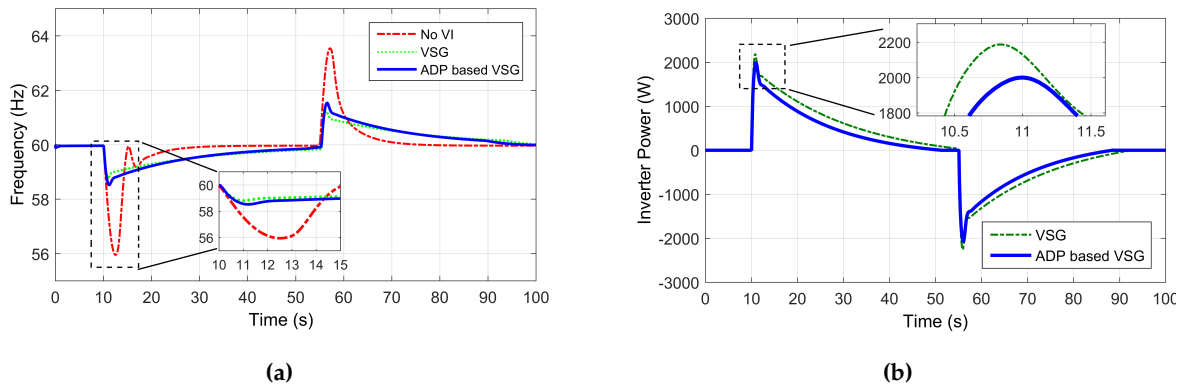


Figure 16. Comparison of traditional VSG controller with the online learning based controller: (a) Frequency of the system for step load changes. (b) Power exchange with the system [91].

Table 3. Performance comparison of the system without VI, simple VSG based and ADP based VSG [91].

Parameter	No VI	Simple VSG	ADP based VSG
Peak Power for Event A	0 W	2184 W	1979 W
Settling time for Event A	12.6s	35.1s	31.3 s
Peak Power for Event B	0 W	-2235 W	-2029 W
Settling time for Event B	11.1 s	29.1 s	26.6 s
Energy delivered (Wh)	0 Wh	8.2 Wh	6.2 Wh
Net energy exchanged (Wh)	0 Wh	1.6 Wh	0.9 Wh

A similar online learning controller was proposed for virtual inertia emulation in a double fed induction generator (DFIG) based system in [89]. In this case, the controller was trained so as to

restrict the frequency excursions to a minimum while maintaining the rotor speed of the DFIG within a safe operating range, rather than saving the energy flow from ESS. Other techniques to optimize the virtual inertia have been proposed in [90] using Linear-quadratic-regulator (LQR) and in [92] using fuzzy logic to minimize frequency deviations and ROCOF.

6. Challenges and Future Research Directions

6.1. Virtual Inertia as an Ancillary Service

Many research works have proposed the possibility of using virtual inertia as an ancillary service to improve frequency stability of large power grids. In [93], a control scheme to integrate DC microgrids as virtual inertia emulating units in the traditional AC grid has been presented. With the control scheme, the resources within the DC microgrid can be dispatched as an ancillary service for inertial response. Another major source of under-utilized energy lies in modern data centers. Data centers need a high degree of reliability, and as a result large amounts of backup energy storage which are unused during normal operating conditions. Research work in [94,95] have shown methods to utilize these resources using demand response techniques. This concept can be extended to use data center resources for virtual inertia emulation. Virtual inertia based interfaces, as mentioned in [93], can be integrated with data center resources for frequency regulation. A unit commitment model that combines system inertia from the conventional plants, and the virtual inertia from wind plants into system scheduling has been presented in [96], allowing an economic analysis of the virtual inertia system.

Modern wind farms are already obligated through various laws and regulations to provide inertial ancillary services [97–100]. The uncaptured inertia in wind turbines, referred to as “hidden inertia”, can be captured through the techniques described in previous sections. Commercial wind turbine manufacturers, like WindINERTIA [101] and ENERCON [102], already provide virtual inertia response. Moreover, leading inverter manufacturers like FRECON, Schneider Electric, and ABB already provide out-of-the-box inertial response capabilities. Using electric vehicles (EVs) to provide ancillary services has become a popular research topic [103]. Typically the control algorithm of the bidirectional converters in EVs can be modified for virtual inertia emulation [104,105].

6.2. Inertia Estimation

Research has been conducted in [106] to estimate the total inertia constant of the power system. The research was aimed at determining spinning reserve requirements for the power system. However, virtual inertia emulated using ESS and RES is not going to be constant as in the case of traditional synchronous generation. The available inertia in the system will depend upon whether RES units are online or not, and resource availability (wind speed, irradiance, and state of charge in case of ESS) [107]. System inertia estimation is thus going to be critical for planning purposes for system operators in the future power system with high RES penetrations. Furthermore, such estimates can provide helpful insights into the stable real-time operation of a power system. Inertia estimation using frequency transients measured using synchronized phasor measurement units (PMUs) was proposed in [107,108]. In [109], a method to estimate the inertial response of power system under high wind penetration based on the swing equation is presented. Accurate detection of frequency events and precise ROCOF measurements are critical for proper inertia estimation [110]. In the context of modern power systems, with RES units participating in the inertial response, the inertia of the system will also largely depend on the RES resource availability at any given time as well. So, PV and wind forecasts data can be used to complement and further improve the inertia estimation techniques described before. Accurate inertia estimation methods will help setup a framework for system operator's to procure inertial services.

6.3. Improved Modeling, Control and Aggregation of Virtual Inertia Systems

Most research has focused on specific implementations of virtual inertia and the broader impacts of inertial response. Accurate, mathematical models which represent the dynamics of the system, which are essential for parameter tuning and understanding behavior when virtual inertia systems are interconnected to the power system, are currently lacking. In [82,111], a small-signal model for a virtual inertia system has been developed. The model was used to identify critical operating modes through Eigenvalue analysis, and a technique to assess the sensitivity of the system to the parameter gains has been demonstrated. Similarly, a small-signal model of a synchronverter was developed in [59]. Such a model helps in improved tuning of the controller gains and provides granular control over how the overall system needs to be operated. An analytical approach to study the effect of microgrids with high RES penetration on the frequency stability has been described in [112]. Performance indices completely independent of the test system have also been proposed to better facilitate impact analysis. The behavior and coordination between virtual inertia systems and existing SGs are going to critical issues need further research. In the future, with numerous virtual inertia units, the coordinated and aggregated operation, and optimal placement will also be important research questions.

6.4. Market Structure for Virtual Inertia Systems

Currently no market exists for virtual inertia nor for inertia from conventional SGs. SGs and some loads in the power system inherently provide inertial response and are treated as a free resource. As the power system becomes inverter-dominated, the inertial requirements will become a valuable tradeable commodity, and generating units will demand financial compensation. A market-based approach can be a cost effective solution to ensure sufficiency of inertial services in the future power market [113]. The inertial response can be provided by wind turbines or even PV systems with inherent storage technologies [114]. Schemes to operate PV systems below their MPP with reserve for inertial response is also a possible option with the suitable market for such resources. A scheme to trade inertia is presented in [11]. The paper furthermore argues inertia should not be traded in terms of power or energy, but rather in terms of an inertia metric. A unit commitment framework for fast frequency services in the power system with transient stability constraints representing the dynamic performance requirements was proposed in [115]. It was shown that additional inertia prevented expensive units being committed post-frequency event and reduced the overall system production cost in a power system. Other papers propose a penalty factor for generators that do not provide inertial response, but so far there is no clear structure on how the inertia market should operate and is an open research area.

One method that deserves further exploration is deploying inertia as "service" for power quality. For instance, as a microgrid operator, one can offer inertial services based on certain criteria such as maximum allowable ROCOFs and/or frequency deviation. The Quality of Service (QoS) metrics which have been proposed for cloud computing services (e.g., [116]) can be garnered for power systems to measure the power quality in terms on inertial response availability. The quality may be assessed in terms of response time after a frequency disturbance and/or inertia made available. This will foster a framework for microgrid operators to incorporate inertial response services in the system based on the requirements of its end-users.

6.5. Energy storage resources for virtual inertia systems

Typically, capacitors and batteries have been proposed as energy storage resources for dynamic frequency control using power electronic converters [44,49,64,84]. In [117], an ultra-capacitor based ESS is proposed to reduce the impact of RESs variability of frequency stability of an isolated power system, but these energy resources often incorporate prohibitive cost investments, and because fast-frequency needs to be compensated by the virtual inertia systems it may effect the lifetime of the

ESS. As a solution, a parallel combination of batteries and ultra-capacitors was proposed in [22] which significantly reduced the impact of high frequency dynamics on the batteries as the ultra-capacitors supplied the high frequency components. This also allowed for a cheaper and smaller battery unit [118]. Flywheel based energy storage for virtual inertia was proposed in [119]. Novel solar panel technologies with inherent storage capabilities could be another way of providing inertia through PV systems [114]. Recently, researchers have started to focus on alternate means of energy resource for virtual inertia. One of the main areas that is gaining attention is the so-called “thermal-inertia” of heating, ventilation, and air conditioning (HVAC) systems of commercial buildings. As discussed in [120–122], the power consumption of the power electronics based HVAC units can be controlled to provide inertial response while ensuring that the customer comfort is not effected. Similarly, the large HVAC installation in data-centers could be another potential to tap for inertial response in the future grid with large scale integration of RES units.

7. Discussions

This paper presented a literature review of virtual inertia systems in the modern power system under high RES penetration. Numerous topologies for virtual inertia emulation which constituted the “first generation” of virtual inertia systems were identified. It was shown that fundamentally the objective of all the topologies is to provide additional dynamic frequency response through power electronic converters as the dynamic frequency response from the traditional SGs are on the decline. Based on the required architecture and desired level of sophistication in emulating the exact behavior of SGs, the appropriate topology can be selected. For example, for replication of the exact dynamics of SGs, topologies such as the synchronverter, VISMA and inducverters can be used. More simplistic topologies like Ise lab’s topology, SPC can be used if an approximate replication is sufficient. The VSG approach, on the other hand, is more suitable when the objective is to provide just the dynamic frequency response without emulating the exact behavior of SGs. An important takeaway through the literature review was that the droop based controllers which were regarded as separate control method for inverter systems are in fact fundamentally similar to virtual inertia systems as formalized by the literature pointed out.

Next, the second generation of virtual inertia systems with focus on optimization of existing virtual inertia topologies were reviewed. Such algorithms can prevent degradation of ESS lifetime and allow reduced curtailment of RES units that participate in inertial response. Furthermore, the enhancements help in improved dynamics and overall stability. Some of the challenges and possible areas where further research is required were also discussed. The current state-of-art of topics such as inertia estimation, improved controls and aggregation techniques, the virtual inertia market, and ESS for virtual inertia systems were also presented. This was followed by a discussion on possible research directions on these topics.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ADP: Adaptive Dynamic Programming
 DFIG: Double Fed Induction Generator
 DG: Distributed Generation
 ENTSO-E: European Network of Transmission System Operators for Electricity
 ERCOT: Electricity of Reliability Council of Texas
 ESS: Energy Storage System
 HVAC: Heating, Ventilation and Air Conditioning
 IEEE: Institute of Electrical and Electronics Engineers IEPE: Institute of Electrical Power Engineering
 ISO: International Organisation for Standardization
 LQR: Linear Quadratic Regulator
 KHI: Kawasaki Heavy Industries
 MPP: Maximum Power Point
 NERC: North American Electric Reliability Corporation
 PI: Proportional-Integral
 PLL: Phase Locked Loop
 PWM: Pulse Width Modulation
 QoS: Quality of Service
 RES: Renewable Energy System
 ROCOF: Rate of Change of Frequency
 SG: Synchronous Generator
 SPC: Synchronous Power Controller
 VI: Virtual Inertia
 VISMA: Virtual Synchronous Machine
 VOC: Virtual Oscillator Control
 VSG: Virtual Synchronous Generator
 UFLS: Under Frequency Load Shedding

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