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Inertial issues in renewable energy integrated systems and virtual inertia techniques

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ABSTRACT

The global proliferation of renewable energy drastically altered the characteristics of power systems. Integration of clean energy sources reduces the inherent rotational inertia, making the system precarious and susceptible to various disturbances. The major challenges encountered are fast frequency fluctuations, voltage fluctuations, high rate of change of frequency (RoCoF), and frequency nadir. In order to address and adapt to a future low-inertia scenario, it is crucial to understand the effect of inertia on various parameters. This paper introduces a comprehensive review of the fundamental aspects of inertia and challenges that arise due to the reduction in inertia. Researchers have tackled this issue by employing various virtual inertia (VI) emulation techniques, which also have been extensively reviewed in the literature along with their merits, limitations, and recent developments. The impact of RES penetration on system dynamics is analyzed by simulating an IEEE-9 bus system with renewable energy source (RES) in MATLAB/Simulink. Furthermore, a three-phase fault is also introduced, to emphasize the effect of reduced inertia by observing the rotor angle and frequency deviation. The results validate that RES integration and fault location are observed to have a significant impact on stability parameters, making them extremely unstable.

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1. INTRODUCTION

A worldwide inclination towards renewable energy has emerged due to the negative environmental repercussions and scarcity of carbon-based fuels. The conventional power system relies on rotating machines such as synchronous generators (SG) for energy production. Since they are synchronized to the grid, the stored kinetic energy can compensate for any sudden imbalance. Unfortunately, rising urbanization and industrialization have resulted in a massive increase in gas-guzzling over fossil fuels. As a result, there can be seen an escalation in greenhouse gases (GHG) emissions in the atmosphere, severely destroying our planet's ecology [1], [2]. The energy sector contributes the most to GHG emissions, accounting for 73.2% of the total (as shown in Figure 1). This has paved the way for many countries to transition to more clean and sustainable energy by incorporating renewable sources (such as photovoltaic (PV) system and wind) [3]. China, for instance, has pledged to generate 35% of its energy from renewables by 2030 [4], [5]. India has set a lofty goal to produce 175 GW of energy from renewable energy sources (RES) by 2020 and so does the countries of the European Union and the United States [5], [6]. The substantial increase in the incorporation of sustainable energy sources to the grid utilizing power electronic converters, coupled with a corresponding decrease in conventional rotating machines, culminated in a highly fluctuating and reduced system inertia.

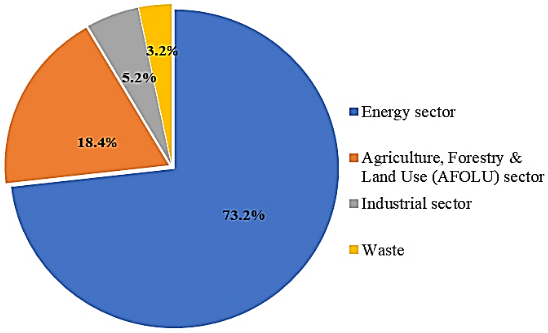


Figure 1. Chart showing annual GHG emissions worldwide

In traditional power systems, inertia from synchronous machines compensates for fluctuations and deviations of frequency (e.g., variations in load/generation) for a short time frame. Moreover, the stored kinetic energy can be utilized as spinning reserves that can compensate for a power deficit or surplus. But as the grid modernized, the generation mix has remarkably reduced the system inertia [7]. Figure 2 depicts the rising demand for renewable energy over the years from 1800-2021 [8]. This has led to increased variations in frequency and a high rate of change of frequency (RoCoF) under power imbalances, compromising system stability. Power system inertia has a vital role in combating frequency variations and damaging oscillations, thereby making the system safe and reliable [9]. When renewable energy source is assimilated through converter interfaces [10], [11], such systems tend to have low inertia, which impairs the stability of the system. Several control mechanisms must therefore be deployed at converter interfaces for RES penetration to provide frequency regulation. Low inertia can also cause considerable voltage swings in DC microgrids (MGs), limiting efficiency, and stability. To achieve DC voltage stability, a survey of effective inertia management techniques, voltage deviation, and voltage oscillation for DC systems must also be considered [12]–[15].

Much of the previous literature focuses on inertia enhancement techniques rather than addressing the actual parameters that get affected by the decrease in inertia. It is possible to significantly enhance the proportion of renewable energy and ensure system stability by emulating the inertial features of synchronous generators using virtual inertia (VI) emulation techniques. The development of research, in VI emulation and control, through time is plotted in Figure 3, which emphasizes the scientific community's increasing interest in this area. The majority of current research programs and initiatives focus on ways to increase system inertia and find solutions to problems caused by low system inertia. However, studies contrasting diverse VI topologies in terms of the stability they offer to the electrical network are limited.

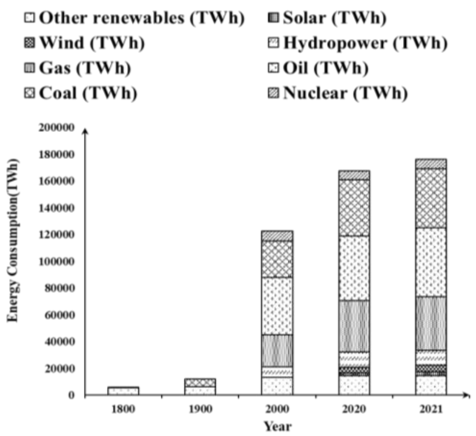


Figure 2. Global energy mix from 1800-2021

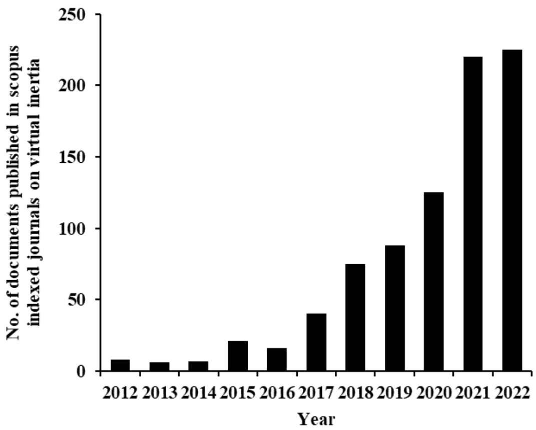


Figure 3. Year-wise research carried out in the field of VIE

In several works of literature, the effects of renewable energy integration and stability problems are also infrequently discussed. This paper attempts to give an extensive review of the effect of renewable energy sources on grid inertia in terms of stability. The issues arising from the infiltration of RES in terms of rotor angle and frequency stability will give an idea about the possible ways to avoid such low-inertia scenarios.

Moreover, a synoptic view of various types of virtual inertia techniques, along with their benefits and drawbacks, is also conferred, which will give an idea about the most suitable virtual inertia topology to be used.

The results obtained from this study will be beneficial for both academics and companies to comprehend the stability problems imposed by low inertia as well as ways to resolve them utilizing various VI techniques. This assessment is crucial in addressing a future low-inertia scenario. The remainder of the paper is structured as follows: i) Section 2 goes through the fundamentals of inertia in conventional and RES-integrated systems; ii) Following that, section 3 examines the effect of inertia on various system characteristics, providing a more in-depth understanding of the stability difficulties in low inertia systems; iii) Section 4 discusses various VI topologies and their most recent improvements; iv) In section 5, an IEEE-9 bus system is simulated, and a comparative study is performed with the inclusion of a 2 MW solar photo voltaic (SPV) system to validate the stability difficulties in inverter-dominated sources induced by decrease in inertia; and v) Section 6 shows the compilation of the results with the review's conclusion.

2. THE COMPREHENSIVE THEORETICAL BASIS

As a physical property of rotating machines, inertia indicates how sensitive the rotor speed is to variations in torque. The main contributors to power system inertia are the conventional synchronous generators (e.g., thermal and hydroelectric generating units). Swing equation describes the rotor dynamics and establishes an electromechanical relationship between useful power and frequency [16] and is expressed as in (1). For i^{th} synchronous generator, the relation between active power and frequency can be denoted as:

$$2H_iS_i = \frac{P_m - P_e}{df_i/_{dt}} \quad (1)$$

where H_i is the inertia constant, S_i is the rated apparent power, f_i is the rated frequency and f_o is the nominal frequency.

Swing equation, for an entire system, considering the damping factor and deviation in electrical and mechanical power, can be denoted as given in (2).

$$2H_{sys}\frac{d\Delta\omega_{sys}}{dt} = \Delta P_m - \Delta P_e - D_{sys}\Delta\omega_{sys} \quad (2)$$

Where $\Delta\omega_{sys}$ is the change in total aggregated system inertia, H_{sys} is the total system inertia constant, ΔP_m and ΔP_e are changes in mechanical and electrical power, and D_{sys} is the system damping factor. The transition from traditional generating units to a diverse array of new-generation technologies creates variations in system inertia. Inertia emulation in the form of virtual inertia emulation techniques must therefore be considered as a part of total system inertia and is given in (3) [17]–[19]:

$$H_{sys} = \frac{\sum_{j=1}^{n1} H_jS_j + \sum_{k=1}^{n2} H_{VIE,k}S_{VIE,k}}{S_{sys}}$$

$$= \frac{\sum_{j=1}^{n1} E_{KE,j} + \sum_{k=1}^{n2} E_{VIE,k}}{S_{sys}} \quad (3)$$

where H_j and S_j represents inertia constant (in seconds) and apparent rated power (in MVA) of the j^{th} synchronous generator, respectively, $n1$ is the number of synchronous generators connected to the system, S_{sys} is the rated base power (in MVA), $H_{VIE,k}$ and $S_{VIE,k}$ are the virtual inertia constant (in seconds) and rated power (in MVA) of the k^{th} virtual inertia source, respectively. $E_{VIE,k}$ is the kinetic energy contribution from VI source, and $n2$ represents the number of sources that contributes synthetic inertia.

3. IMPACT OF INERTIA ON VARIOUS SYSTEM PARAMETERS

3.1. Impact on rotor angle stability

Inertia is seen to influence rotor angle stability significantly. Rotor deviation is seen to be higher after an imbalance with the decrease in inertia. After an imbalance, the rotor accelerates or decelerates, which leads to significant rotor swings, thereby making the system more unstable. Sreeram *et al.* [20] used a conventional synchronous machine to probe the effect of changing inertia on parameters such as frequency response and rotor angle, as illustrated in Figure 4. The graph illustrates that a system with low inertia takes a greater duration to attain its steady-state value and has a greater maximum overshoot.

Large-signal stability of a sizeable multi-machine system solar PV system was investigated in [21], [22]. Dynamic stability issues due to large-scale wind power integration are discussed in [23], [24].

The results indicate that rotor angle stability mainly depends on the site, mode of operation, wind power penetration level, and the converter control topology in converter-connected wind generation. Other factors on which rotor angle stability depends are the degree of integration of RES, reactive power scheme, and the network configuration [25].

3.2. Impact on frequency stability

Power system frequency stability is primarily influenced by synchronous inertia. Several indices characterize the dynamic behavior of frequency in a system, such as f_{nadir}, RoCoF, and the time taken to reach the lowest frequency (t_{nadir}). With reduction in inertia, the inertial response also gets reduced which increases both RoCoF and frequency nadir [26]. Figure 5 illustrates the frequency response curves for a set of values inertia constants on a single generator connected to an idealized infinite bus system [20]. The figure depicts that a system with low inertia is seen to have high RoCoF and frequency nadir as compared to the system with higher inertia. Declination in frequency due to low inertia can also lead to high saturation currents in devices such as transformers and induction motors and can adversely affect the performance of conventional power plants.

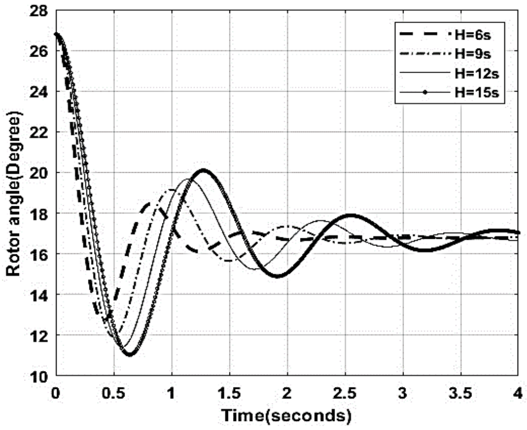


Figure 4. Graph showing the variation of rotor angle for different values of inertia constants

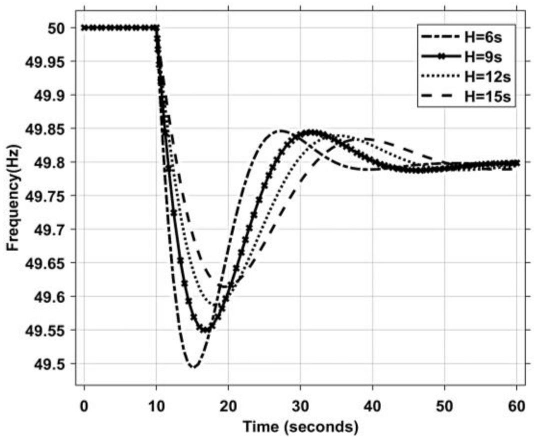


Figure 5. Impact of inertia on frequency stability for different values of inertia constants

4. PROMINENT INERTIA EMULATION TECHNIQUES

Effective and reliable techniques must be implemented to mitigate the adverse effects of low inertia. Virtual inertia (VI) emulation techniques are an excellent solution to counteract the effects of reduced inertia. Figure 6 shows the fundamental building blocks of VI topologies, which include energy storage systems, control mechanisms, and power inverters. VI techniques emulate the inertial characteristics of synchronous generators utilizing parameters such as injected power, frequency, and amplitude.

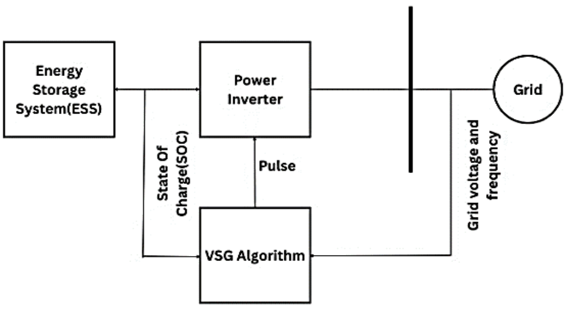


Figure 6. Block diagram representation showing the concept of VI

4.1. Topologies

There are different configurations for virtual inertia control since 2008. This section overviews the prominent VI topologies used so far. Figure 7 shows some of the most prominent VI topologies, which include virtual SYNchronous control (VSYNC), the Institute of Electrical Power Engineering (IEPE), Kawasaki Heavy Industries (KHI's), and Information System Engineering (ISE) lab's topology. Among these, the most widely used based on the literature survey conducted is discussed in this section.

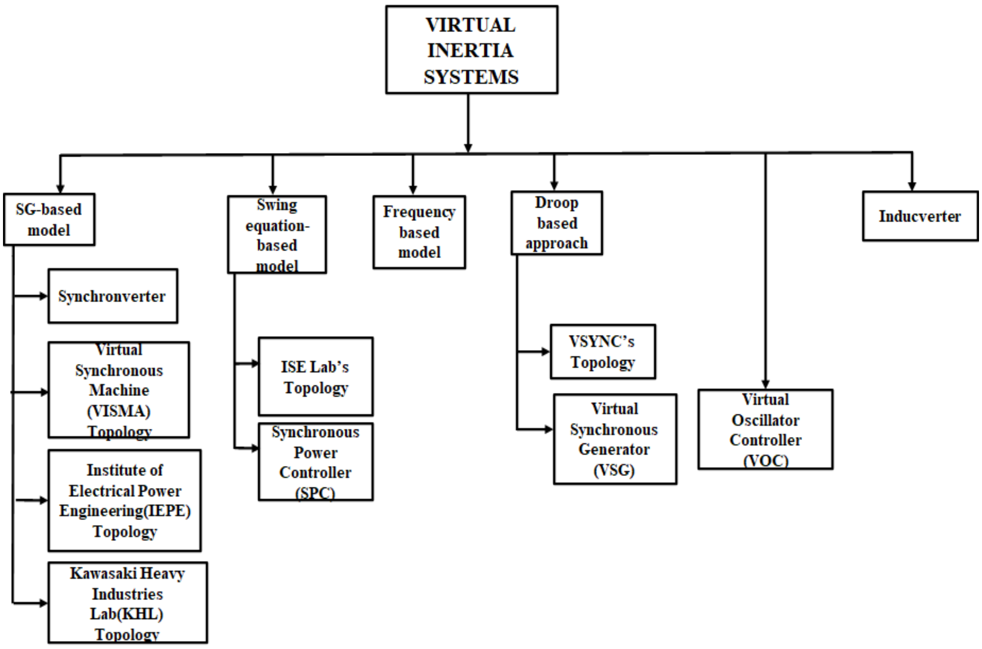


Figure 7. Classification of virtual inertia control topologies

4.1.1. Synchronverter

Synchronverter, proposed by Unni *et al.* (in 2011) [4], combines characteristics of an inverter and synchronous machines to emulate inertia and is self-synchronizing in nature. Power output is regulated using a frequency-droop mechanism, as shown in Figure 8. Improvements in synchronverters include topologies such as self-synchronizing synchronverters without the use of phase locked loop (PLL) [27], digital-type synchronverter designs, and bounded frequency and voltage types. Single-phase variants with PLL, suffer from instability issues, especially in weak grids [28]. Topology without the use of PLL ensures a low cost of development, simplicity in tuning, and less computational time. PLL (in synchronverters), when utilized in a weak grid, must be operated within the bounded frequency and voltage [28], [29].

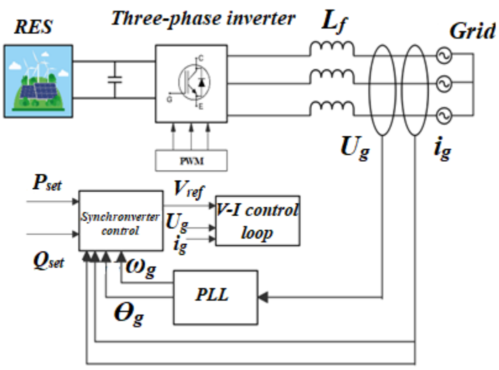


Figure 8. Block diagram of synchronverter showing various control loops

Further enhanced performance is assured by components such as virtual inductors, capacitors, resistors, and anti-windup. Modifications, including control loops for angle, frequency, and power, help them integrate multiple RES into the system [29], [30]. A second-to-third-order model of a synchronverter accurately mimics the features of a synchronous machine. However, parameter tuning with a damping correction loop is critical to ensure optimum performance and stability [30]. To obtain an inertial response from the load side, virtual synchronous motors are used [31]. Synchronverters can also act as grid-forming units that emulate inertia from distributed generators (DGs), which are less susceptible to noise and synchronization issues while ensuring enhanced inertial support. Furthermore, such a design permits the operation of traditional power systems without significant structural changes [32].

4.1.2. VISMA or virtual synchronous machine (VSM)

VISMA are grid-forming converters with frequency droop and virtual inertia control techniques [33]. The functional diagram of VISMA is depicted in Figure 9. When integrated with the digital controller, this model mimics the characteristics of a conventional synchronous machine. Phase locked loop is used for the sole purpose of frequency estimation by calculating RoCoF and is eliminated during regular operation since numerical instability issues are more dominant in this topology [34], [35] proposes a three-phase model over a d-q based model to improve ruggedness under asymmetrical load conditions or sudden grid disturbances. If a lower-order SG model is employed, the emulated inertia and phase angle will be the critical drivers of the power flow. Contrarily, protection features can be implemented as parallel loops or at the hardware level, overriding VSM references; nevertheless, their impact on inertia emulation and the ensuing behavior can be challenging to forecast. VISMA with zero inertia constant, VSM0H is yet another variant of VISMA topology, which does not employ the use of a PLL. Highly improved modifications of VSM do not involve the use of a larger DC-link capacitor or battery energy storage system and contribute to much inertia in the system and are also shown to have improved transient response.

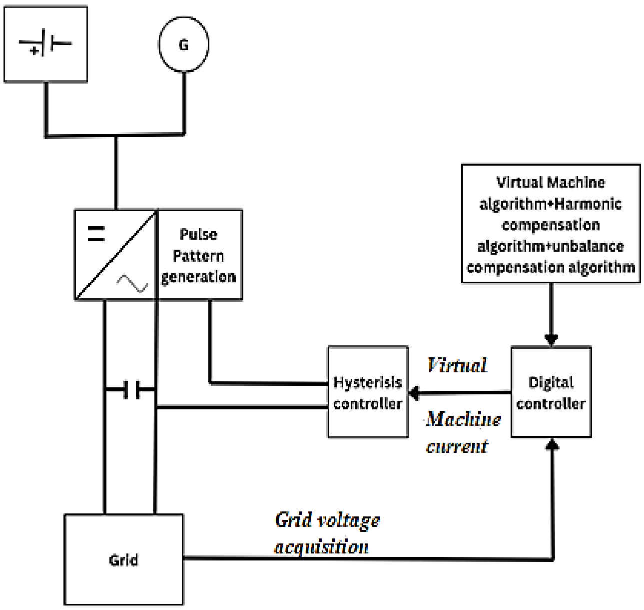


Figure 9. Block diagram model of VISMA/VSM

4.1.3. Synchronous power controller (SPC)

SPC is a popular topology for inertia emulation that mimics the characteristics of synchronous machines, and droop control is utilized to provide auxiliary services [36], [37]. The control algorithm is analogous to that in the ISE topology, except that it has multiple control loops consisting of an outer voltage control loop and an inner current loop via virtual admittance [32]. This topology has the advantage of inherent over-current protection. Numerical instability is the least, but the complexity issues are more in this type of emulation topology [38]. Reduced oscillations in the system can be attained by using a second-order model [39].

4.1.4. Virtual synchronous generator (VSG)

VSG is a frequency-response-based inertia emulation technique proposed by VSYNC's research group, which provides frequency regulation and dynamic frequency control [40], [41]. Even though it enables dynamic frequency control, the measurement of RoCoF also presents instability problems in multiple distributed generators. VSG can be considered a current source that responds to frequency changes. Using VSG, which consists of a high-power inverter, intelligent controls, and a suitable energy storage system, it is possible to address problems with fault current characteristics and system stability in microgrids, along with voltage and reactive power control. Figure 10 shows the control algorithm for VSG. PLL tracks change in system frequency and its derivative but cannot be implemented in weak grids as they pose instability issues and steady-state errors during harmonic distortions.

VSG is used for virtual inertia emulation in wind systems, with the drawback of being unable to operate in isolated mode [42]. VSG topology has been widely used in remote microgrids also [43]. VSYNC's VSG is another topology designed to emulate the inertial characteristics of traditional synchronous generators and can also react to frequency variations.

Despite being one of the simplest techniques, VSG topologies with current controllers and those based on the swing equation model, the output current is unregulated and is either curtailed by virtual inductors or boost inductors. To regulate the output current, a virtual impedance-based VSG model was developed that has the functionalities to regulate current at a different frequency and different sequence. VSG can also be implemented in a grid-connected PV plant which uses a fuzzy secondary control rather than droop or conventional VSG control [44]–[46]. A further modification in the controller to enhance inertia is by using three virtual modules of the rotor, primary control, and secondary control. Cascaded controller-based VSG topologies and those without a centralized controller have the potential to use their energy storage to boost the system's overall inertia for frequency stability while preserving synchronization. VSG techniques are also classified based on different order models of the control algorithm, which is summarized in Figure 11. Various control strategies used in VSG topology are proportional-integral (PI) controller, H-infinity control technique, self-adaptive PV controller, power decoupling improvement, the addition of energy storage system (ESS), and advanced computational intelligence. Others include neural-network-based controllers, adaptive dynamic programming (ADP), and artificial intelligence (AI)-based controller.

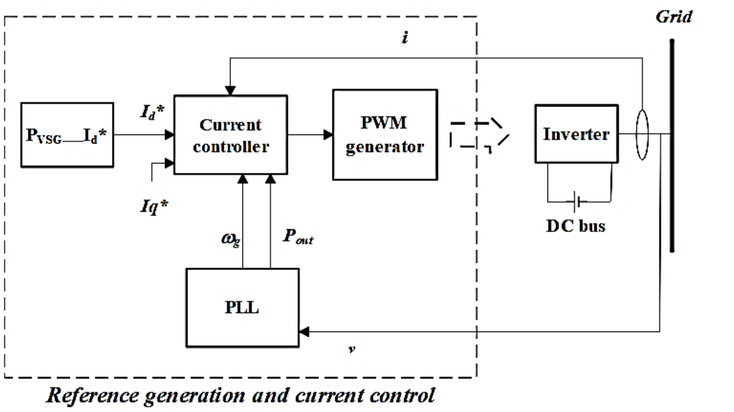


Figure 10. Block diagram of VSG control algorithm

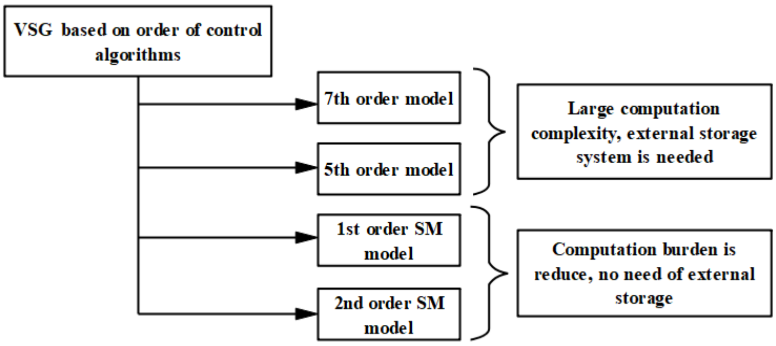


Figure 11. VSG topologies based on the order of the model

Table 1 outlines the principal benefits and drawbacks of fundamental topologies from various research publications. Based on the literature survey conducted, the VI topologies that are prominently used in various journals are plotted as depicted in Figure 12. It can be inferred that VSG is the most widely used and the most preferred topology for virtual inertia emulation. Over time, VISMA and synchronverter topology have also gained prominence; modifications to these topologies have already been considered.

Table 1. Summary of virtual inertia topologies

Si. No.	VI Techniques	Key features	Limitations
1	SG based model	– Precise imitation of synchronous generator characteristics – Measurement of RoCoF is not required – PLL is used for initial synchronization with the grid – No measurement issues and undesirable noise	– Numerical instability concerns – Numerical instabilities can be encountered – No inherent protection against transient over currents
2	Swing equation-based model	– Simple in comparison to synchronous generator-based model – No requirement for RoCoF measurement – PLL for phase synchronization only	– Susceptible to P-f oscillations – No protection against over-current – Errors are introduced if not properly tuned
3	Frequency-power response-based model	– Current controlled VSI implementation – Over-current protection is offered – RoCoF measurement is needed	– PLL degrades the performance in this model, especially in weak grids – Instability due to noise – Operation in islanding modes is difficult. – Mimics inertial response under frequency variations
4	Droop-based approach	– Communication-free – Follows traditional droop control mechanism	– Transient response is delayed – Can be operated in islanded mode

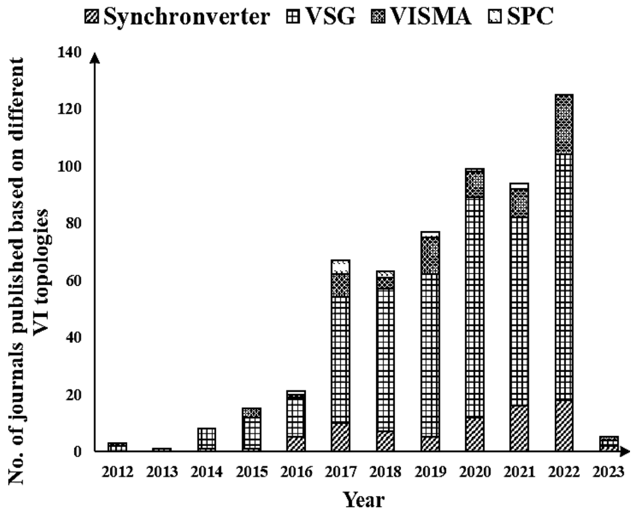


Figure 12. Relevance of VI topologies based on published journals

5. METHODOLOGY AND RESULTS

The effect of inertia on the dynamics of a multi-machine system is analyzed using MATLAB/Simulink [47]. For this, an IEEE-9 bus test (also called P. M Anderson 9 bus system) is considered to have three generator sets, six transmission lines, three transformers, and three PQ loads adapted for a frequency of 50 Hz. Bus-1 is considered as the reference bus, while buses 2 and 3 are generator buses [48]. The design of each transmission network parameter is adapted for a frequency of 50 Hz. Mathematical modelling and explanation of the 9-bus system are avoided for simplicity. The single-line diagram, along with the simulation model of the proposed system, is shown in Figures 13 and 14, respectively.

Different system parameters of the IEEE-9 bus test system are tabulated in Table 2. Three different cases are taken into consideration:

i) Case-1: The 9-bus test system with conventional synchronous generators is considered in this case, and a three-phase fault is induced into the system at 0.2s near generator-2. The rotor angle and frequency response are compared to that of a conventional system without fault.
ii) Case-2: The change in dynamics of the system could be better understood by replacing generator-3 with a 2 MW solar PV source. Further, a symmetrical fault is also introduced into the model near generator-2 to further indicate the instability caused by renewable energy source penetration.
iii) Case-3: In this scenario, the location of RES is made in proximity to the fault so as to provide a better comparative analysis by replacing generator-2 with a 2 MW Solar PV source along with a three-phase.

Simulation results of three cases are then compared to indicate the impact of RES penetration into a multimachine system. The simulation model and schematic diagram of 9-bus system with solar PV and with symmetrical fault are illustrated in Figures 15 and 16, respectively.

5.1.1. Case-1

In this case, all three generating units balance the load, thereby maintaining the balance of the system. However, when a three-phase symmetrical fault is intercalated near bus-8, the stability of the system gets affected. The 9-bus test system is simulated in MATLAB/Simulink, and variations in rotor angle and frequency are observed. Each of the generating unit magnitudes, rotor angle, and frequency are computed using phasor measurement unit (PMU) block. The graph showing the comparison of results in terms of rotor angle and frequency is given in Figures 17(a) and 17(b).

The rotor angle and frequency of generator-2 (gen-2) is seen to be much affected by the three-phase fault as compared to generator-3 (gen-3) and generator-1 (gen-1). The least affected is gen-1, which is farther from the fault site. The system stability was restored at 0.35 s due to the inherent inertia of the system offered by the three SGs. From Figure 17(b), the frequency response shows a similar variation with respect to rotor angle and is profoundly seen to deviate for gen-2.

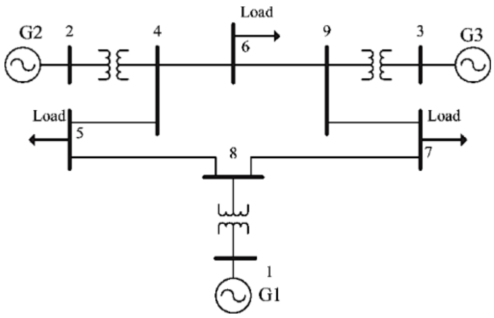


Figure 13. One-line diagrammatic representation of a 9-bus test system [49]

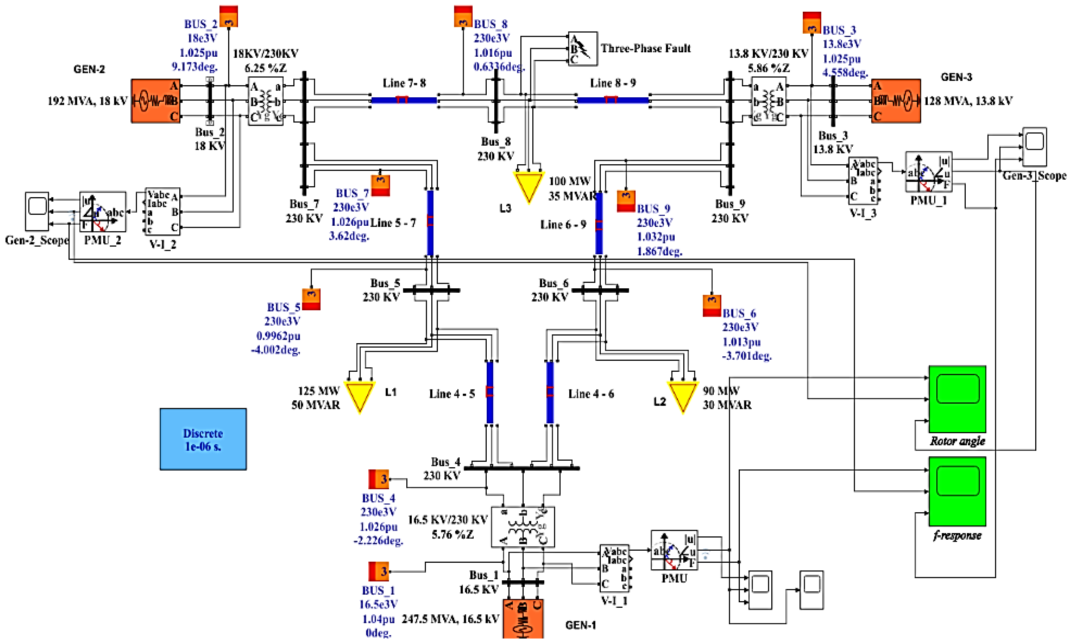


Figure 14. Simulation model of the conventional IEEE-9 bus system

Table 2. Parameters of IEEE-9 bus system

Total no. of generators	Total no. of buses	Total no. of loads	Total no. of lines	Generator specification			Load specification		
				Gen-1	Gen-2	Gen-3	L1	L2	L3
3	9	3	6	247.5 MVA, 16.5 kV	192 MVA, 18 kV	128 MVA, 13.8kV	125 MW, 50 MVAr	90 MW, 30 MVAr	100 MW, 35 MVAr

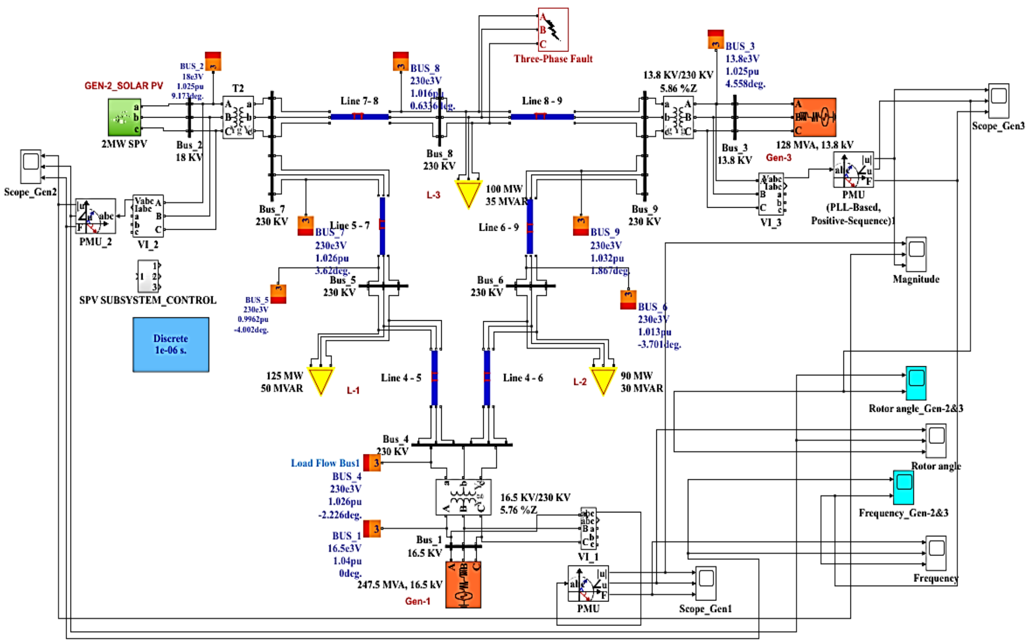


Figure 15. Simulation model of a RES integrated 9-bus system with three-phase fault

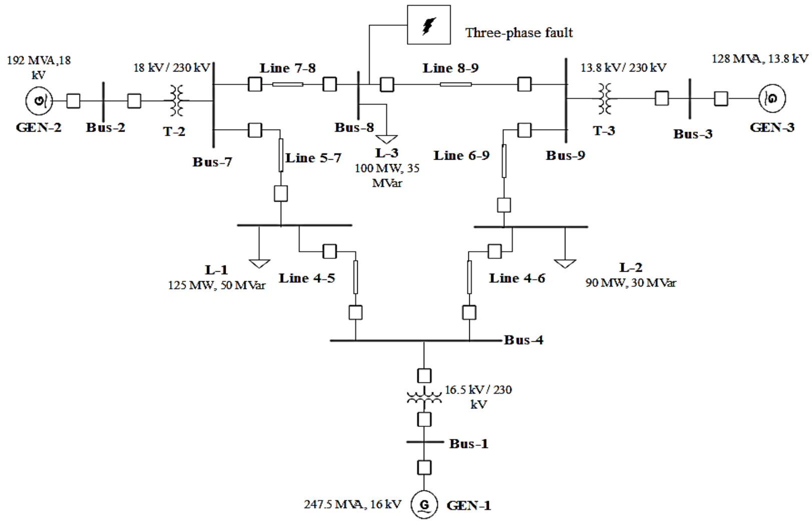
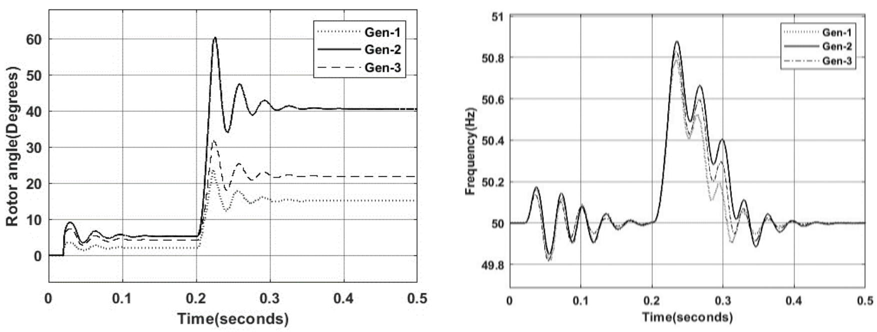


Figure 16. Schematic representation of IEEE-9 bus system with three-phase fault



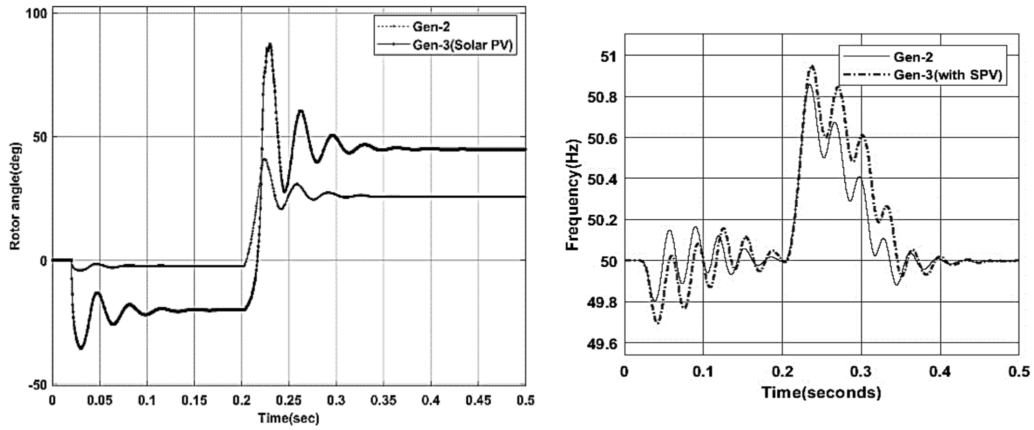
(a) (b)

Figure 17. Graph showing the comparison of IEEE-9 bus system with solar PV as gen-3 and with three-phase fault at gen-2 in terms of (a) rotor angle deviation and (b) frequency deviation

5.1.2. Case-2

In Case-2, Gen-3 is replaced by 2 MW solar PV, along with a three-phase fault, with the fault location remaining unchanged as in case-1. The system stability is affected due to reduced inertia, which the synchronously rotating gen-3 previously contributed. The variations in rotor angle and frequency are shown in Figures 18 (a) and 18(b).

As can be observed from Figure 18(a), the rotor angle stability is much worsened when SPV replaces Gen-3. The increased rotor angle deviation is due to the reduction in inertia contributed by synchronously rotating generator-3. A similar observation can be made in frequency (Figure 18(b)), as it varies in proportion to the rotor angle. The most affected are the rotor angle and frequency of generator-3 (solar PV) in this case.

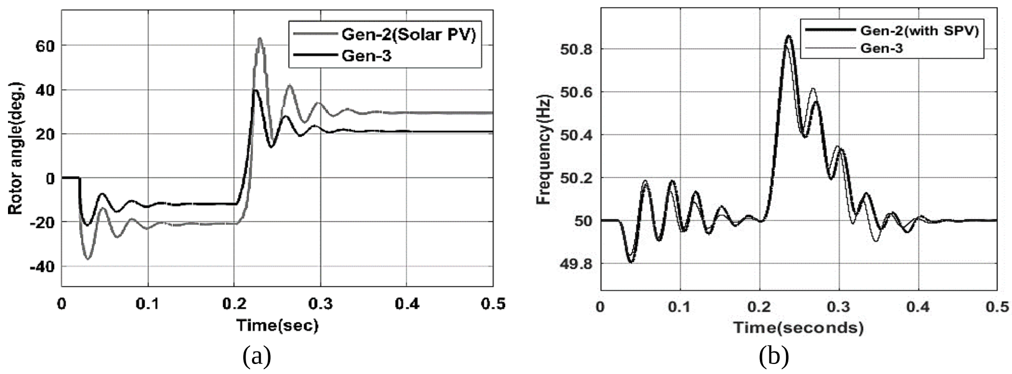


(a) (b)

Figure 18. Graph showing (a) rotor angle deviation and (b) variation in frequency, with solar PV as gen-3 and with three-phase fault at gen-2

5.1.3. Case-3

In case-3, the 2 MW solar PV is now integrated at the site of generator-2 with the fault location remaining unaffected. The deviations in rotor angle and frequency are observed, and the outputs are obtained, as shown in Figures 19(a) and 19(b). Due to the replacement of the conventional SG unit with solar PV at generator-2 and the fault induced at the same site, the rotor angle variation is seen to be much higher than in case-2. This is due to the replacement of a more dominant unit (generator-3) with a 2 MW SPV source. A similar deviation in frequency can also be visualized, as shown in Figure 19(b).



(a) (b)

Figure 19. Variation in (a) rotor angle and (b) frequency, with solar PV at generator-2 and with three-phase fault

Table 3 presents the comparative analysis of the above three cases. Comparison is done based on their peak values and steady-state values obtained for rotor angle and frequency response in three different cases. Case-1 represents a traditional SG-based system without the integration of SPV. The system frequency and rotor angle are not considerably affected in this case, due to the inherent inertia offered by the rotating

SGs. When a symmetrical fault is introduced into the system (near generator-2), a significant increase in rotor angle and frequency is observed, as can be seen in Table 3. In case-2, since a 2 MW renewable energy source is introduced at the site of generator-3, and with a fault near generator-2, peak values of rotor angle and frequency are seen to be much higher than in case-1, indicating a less stable system. This is due to the integration of SPV, which results in a reduction in system inertia. In case-3, RES is introduced at the site of generator-2, and the fault is introduced at the same location. Thus, due to the lack of inherent inertia, and due to the fault near gen-2, there is a significant rise in peak values of rotor angle and frequency than in case-1 and 2. Hence, it can be deduced that the inclusion of clean energy diminishes the intrinsic inertia, which causes the rotor angle and frequency to deviate at a significant rate, making the system highly unstable.

Table 3. Comparative analysis of an IEEE-9 bus system with and without RES integration

Cases	Parameters observed	Rotor angle curve		Frequency response curve
		Steady state mag.(deg.)	Peak value (deg.)	Peak value (Hz)
Case 1: without RES but with a 3-phase fault near generator-2	Gen-1	15.08	23.63	50.79
	Gen-2	40.54	60.58	50.88
	Gen-3	21.82	32.16	50.83
Case 2: with RES at generator-3 but with a 3-phase fault near generator-2	Gen-1		Not affected	
	Gen-2	25.71	40.94	50.86
	Gen-3	45.01	87.3	50.97
Case 3: with RES and fault at generator-2	Gen-2	29.31	63.56	50.84
	Gen-3	20.95	39.95	50.81

6. CONCLUSION

An extensive literature review implying the critical role of inertia in the modern power system is presented. The correlation between inertia and the stability is explored, as well as the potential repercussions that can occur due to reduced inertia are discussed. The study indicates that the integration of renewable energy reduces the inherent inertia of the system, and various parameters such as rotor angle and frequency undergo significant fluctuation in low inertia scenarios. To validate these observations, stability analysis of an IEEE-9 bus test system was conducted, revealing the instability caused by the inclusion of a 2 MW solar PV source, as demonstrated in cases 2 and 3. The integration of renewable energy causes the rotor angle and frequency to deviate considerably, making the system much more unstable in the event of a three-phase fault. This is primarily because SGs have been replaced with converter-interfaced generating sources like SPV. This also suggests that the inherent inertia of the system is lost and is a prime factor in affecting the dynamics of a system. Insufficient system inertia can also cause high-frequency drops, which can lead to frequency security constraints getting infringed or play a key role in cascading outages. Future advances, by the inclusion of RES, will cause system inertia to become highly variable and take values that were previously regarded as quite low. Thus, new approaches to cope with the reduction in inertia, such as virtual inertia emulation strategies, need to be focused. Furthermore, this literature also provides current advancements in virtual inertia emulation techniques, which are critical in tackling the issues due to low inertia. The knowledge obtained from these innovations is crucial because it allows us to alleviate the issues associated with low inertia and encourage higher penetration of clean energy into the grid, all while maintaining system stability.

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