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FREQUENCY STABILITY ASSESSMENT OF INVERTER-DOMINATED MICROGRIDS USING VIRTUAL INERTIA CONTROL TECHNIQUES

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ABSTRACT

The increasing penetration of renewable energy resources such as solar photovoltaic (PV) systems, wind energy systems, and battery energy storage systems (BESS) has transformed conventional power systems into inverter-dominated microgrids. Although inverter-based systems offer advantages such as clean energy generation, improved controllability, and enhanced operational flexibility, they significantly reduce overall system inertia because they lack the physical rotating masses of conventional synchronous generators. This reduction in inertia leads to rapid frequency deviations, high Rate of Change of Frequency (RoCoF), weak damping characteristics, and poor transient stability, thereby posing significant challenges to the secure operation of modern microgrids. This paper investigates the stability analysis of microgrids with high inverter penetration and examines the impact of virtual inertia on grid frequency stability. A renewable energy-based microgrid comprising Solar PV, Wind Energy System, Battery Energy Storage System, inverter interfaces, and electrical loads is modeled in MATLAB/Simulink. Frequency dynamics are analyzed using the swing equation and RoCoF equation, while a virtual inertia controller is integrated with the inverter to emulate the inertial response of synchronous generators. Simulation studies are performed under two operating conditions: without virtual inertia and with virtual inertia support. The results demonstrate that virtual inertia significantly improves system performance by reducing the maximum frequency deviation from 0.65 Hz to 0.22 Hz, decreasing RoCoF from 1.25 Hz/s to 0.42 Hz/s, and shortening the settling time from 4.8 s to 2.1 s. The study concludes that virtual inertia is an effective solution for enhancing frequency stability, damping capability, and transient response in inverter-dominated microgrids, thereby supporting the reliable integration

of renewable energy resources in future smart grids.

1. INTRODUCTION

With the growth of electricity demands, shortage of fossil fuels resources and growing environmental issues, the shift from conventional power generation system to renewable energy based power system has driven up in the speed. Increasingly, renewable electricity technologies like solar PV (photonvoltaic) systems, wind energy systems, battery power storage systems (BESS), and fuel cells are being added to the modern electrical grid because they have improved sustainability and are environmentally friendly.(1) Renewable energy deployment is encouraged through government and utility programmes around the world. Promotion of renewables is through government and utility programmes worldwide to promote reduction of GHGs and energy security. This has made renewable energy resources an integral part of the current power systems.(2)

Developing decentralized power generation architectures called microgrids is a result of the widespread adoption of renewable energy resources. The components of the microgrid include a collection of distributed energy resources (DERs), renewable energy generation systems, energy storage systems, power electronic converters, communication infrastructure, and electrical loads.(3) Microgrids can be connected to the grid to coordinate with it, or they can be operational in a standalone (islanded) mode. Microgrids are expected to have a number of benefits over traditional, centralised electricity generation systems, such as higher reliability, lower transmission losses, higher power quality, higher renewable penetration and increased resilience in times of electricit y system disturbances. Hence, microgrids are said as one of the most promising applications for the smart grid in the future.(4)

Today's microgrids are mainly composed of inverter-based renewable energy systems. Power from solar PV (PV) systems is direct current (DC) power, and power from battery energy storage systems (BESS) is also direct current (DC). Power from solar PV systems and power from BESS is all direct current (DC) and requires power electronic inverters to connect it to alternating current(AC)power grid.(5) Likewise, inverter topologies are also employed in modern wind power generation systems with variable-speed wind turbines to achieve efficient electrical-energy conversion and to synchronize with the electric grid. Hence, the penetration of inverter-based generation has grown substantially over the last few years and electricity power systems are experiencing significant change in their behavior.(6)

While there are a number of benefits associated with inverter-based systems, including qualities of fast dynamic response, greater controllability, modularity, and increased renewable energy integration support, they do also present some significant challenges when it comes to operation. Unlike traditional synchronous generators, inverter-based generation does not have a physical rotating mass and, thus, cannot offer a native rotation rate to the power system.[7] Traditional power systems have synchronous generators with rotating rotors that store kinetic energy, which is automatically rejected during disturbances and used to sustain the power system frequency and stability. Inversion-based renewable power plant is however not connected to the grid as such and doesn't have this natural inertia.[8]

Due to the replacement of synchronous generators with renewable energy sources based on inverters, decrease in inertia and stability concern in modern power systems has emerged. Low-inertia systems are highly dynamic and have a large frequency spread due to load changes, renewable fluctuations, generation failures and faults. The high values of Rate of Change of Frequency (RoCoF), frequency deviation and low damping and poor transient stability result from insufficient inertia. In severe instances, these can cause protection trips, generator tripouts,

cascading system trips, and overall system failure. The situation becomes even more serious when the power grid is missing and the system has to be self-regulating power and frequency stability as in case of islanded Microgrids.[9]

Frequency stability of power system is one of the major matters in power system operation and reliability. The ability of a power system to meet the frequency limits within acceptable bounds during and after disturbances. If produced power is lower than demand, the frequency will decrease and if produced power is higher than load requirement, system frequency will increase. Frequency deviations result from any imbalance among the generation and load. In conventional, high inertia systems, motion characteristics are relatively slow – as synchronous generators give immediate support to motion.[10] In an inverter-dominated system with low-inertia load, on the other hand, because load inertia is not physical, frequency changes will occur very quickly, making frequency regulation difficult.

Due to the shortcomings of low-inertia power systems, a number of advanced control techniques were proposed over the last few years. One of the most effective described solutions to enhance frequency stability in inverter-dominated microgrids is virtual inertia.One of the most effective described solutions is virtual inertia that can be adopted to enhance frequency stability in inverter-powered microgrids.[11] A control method for inverter based systems' behaviour is the virtual inertia or synthetic inertia, which allows the inverter to behave like a traditional synchronous generator in terms of their response to inertial. The intelligent control algorithms and rapid energy storage devices can quickly inject or absorb active power in a frequency disturbance to support frequency regulation and enhance stability.[12]

Several benefits of the implementation of virtual inertia include; lower frequency deviations, lower RoCoF, better damping characteristics, rapid transient response and increased reliability within microgrids. To mimic the behavior of a synchronous generator in an inverter-based system, there has been a number of approaches suggested including the use of Virtual Synchronous Generator (VSG), synchronverter technology, Grid-forming Inverter Control (GPIC), and Adaptive Virtual Inertia (AVI) techniques. These techniques have been found to be effective in the enhancement of dynamic performance and stability of power systems that are supported with renewable energy.

With these challenges and opportunities, the study aims at investigating the stability analysis of microgrids with high inverter penetration and the virtual inertia effect on the grid frequency stability. This research aims at investigating the frequency response of inverter-dominated microgrids under various operating scenarios of the island grid and assessing the efficiency of the virtual inertia on enhancing the performance of the inverter-dominated microgrid. Some of the key performance parameters taken into account are Frequency deviation, RoCoF, Damping characteristic, and Transient response.[12] The results of this effort will help to realize stable, reliable and sustainable microgrids that will be able to incorporate a high percentage of renewables that are still secure and efficient.

2. Literature Review

2.1 Renewable Energy Integrated Microgrids

With the growing share of renewable energy resources, the traditional power generation systems are becoming “decentralized and sustainable” energy networks. Lasseter (2002) was one of the first to introduce the notion of microgrids and underlined the role of distributed energy resources in enhancing system reliability and decrease transmission losses.The idea of microgrids was introduced by Lasseter (2002) and he emphasised the significance of distributed energy resources in improving system reliability and decreasing transmission losses.[13] Later, Hatziargyriou et al. (2007) studied the operating point of a renewable energy (RE) based micro-grid in both connected and island mode, concluding that the voltage and frequency stability are greatly influenced by fluctuations in renewable energy. Guerrero et al. (2011) suggested hierarchical control strategies for renewable energy-integrated microgrids and proved their performance in two power sharing and frequency regulation in microgrids.[14] Moreover, Blaabjerg et al. (2017) conducted a comprehensive review on the power electronic technologies required for integration of renewable energies and highlighted that inverter based power generation system has high level of dynamic response and better controllability at the expense of reduced system inertia.(15) Similarly, Kroposki et al. (2018) identified that as more inverter-based renewable energy is (IBRE) integrated into electric power systems, new stability concerns have arisen, especially in low-inertia power systems.

The challenges of inverter-dominated systems is described next.Next, the challenges associated with inverter dominated systems are described.

The increasing deployment of inverter-based renewable energy sources (IRES) has transformed the relationship between the dynamic characteristics of a power system and conventional synchronous generators.With the adoption of conventional synchronous generator generation in place of inverter-based renewable energy systems (IRES), the dynamic characteristic of power systems has changed drastically.(16) For low inertia systems, Ulbig et al. (2014) studied the frequency stability problems and found that lower inertial level results in large frequency fluctuations and high Rate of Change of Frequency (RoCoF). Tielens and Van Hertem (2016) began to investigate system inertia, and found that inverter-based systems have weak damping and a poor transient response.(17) In addition, Milano et al. (2018) noted that traditional frequency control methods are not applicable to modern grid structures with lower inertia and called for the use of advanced control methods. Tamrakar et al. (2017) studied transient stability of inverter based microgrids and found that the stability of low inertia is counterproductive for frequency recovery and fault response. Based on these studies, an issue with high inverter penetration is the instabilities and oscillating special characteristics that can trigger issues with frequency stability, oscillations, a loss of active damping, and protection coordination.(18)

Eris is also observed in frequency stability and RoCoF studies.Eris is also observed in frequency stability and RoCoF studies.

The power frequency stability of a power system is another important topic in operating a power system which has gained the interest of many research efforts recently. Kundur (1994) reported extensive mathematical models to perform power system stability analysis and highlighted the role of system inertia in keeping the frequency of operation stable.(19) Bevrani (2009) has summarized the different modern solutions adopted for frequency control in electrical power systems and identified the increasing demand for quick responsive frequency response mechanisms in such power systems that use renewable energy sources. Proposed decentralized droop control methods for islanded microgrids and proving the improvement in the frequency regulation performance (Guerrero, et al., 2013). It was shown by Ulbig et al.

(2014) that lower systems have higher RoCoF after disturbances, which puts more work into the generator and may lead to generator tripping and instability in lower inertia systems. In a similar manner, Milano et al. (2018) found that the lower the value of inertia, the higher the frequency deviation after disturbances, and the need for implementing frequency support strategies and synthetic inertia and Virtual Synchronous Generator (VSG).(20)

One of the most promising methods developed recently to enhance frequency stability in inverter dominated power system is virtual inertia. The idea of synthetic inertia (SI) for wind turbine systems was introduced by Morren and de Haan (2005), and they showed that by providing a fast response of active power, the frequency response can be improved.(21) The idea of virtual synchronous machine (VSM) was suggested by Beck and Hesse (2007) which aimed at simulating the behavior of a synchronous generator by inverter systems. Zhong and Weiss (2011) presented a synchronverter technology that enables the inverter to emulate the electromechanical dynamics of a synchronous generator, thereby enhancing the dynamic stability. D'Arco and Suul (2013) examined VSG control and reported that the VSG was found to help significantly reduce the frequency deviation and enhance the damping characteristic. Later, Liu et al. (2018) and Fang et al. (2019) proposed adaptive virtual inertia control approaches that employed battery energy storage system (BESS) and intelligent control algorithms and verified the effectiveness in terms of frequency and transient stability under different operating conditions.(22)

2.2 Research Gap

The literature survey indicates that significant research work has been carried out related to renewable energy based microgrids, inverter dominated systems and virtual inertia techniques. But the majority of the available literature are based on frequency regulation or implementation of virtual inertia separately. Only a few studies on the comprehensive stability analysis of microgrids under various operating conditions, with high inverter penetration have been reported incorporating virtual inertia support. There are also limited comparative studies on system performance in the presence and absence of virtual inertia when considering the frequency deviation, RoCoF, system damping and transient response. Hence, in the present study, the impacts of virtual inertia on grid frequency stability in inverter dominated microgrids and its effectiveness on enhancing the overall system stability and dynamic behaviors is investigated.

3. METHODOLOGY

3.1 Proposed Microgrid Model

A micro grid using Renewable Energy sources which is experiencing high penetration rate of inverter is used in this study to examine the effect of virtual inertia on the stability of frequency. The proposed Micro Grid (MG) comprises of Solar Photovoltaic (PV) system, Wind Energy System (WES), Battery Energy Storage System (BESS), Inverter interfaces, and Electrical loads. SPV & wind energy systems serve as the main sources of renewable power generation, but the BESS offers rapid active power support in disturbances. The AC microgrid is powered by all renewable energy resources via power electronic inverters that control the voltage and frequency of the grid.

The Solar PV system uses solar irradiance to generate an electric power and feeds the energy into the microgrid through an inverter interface. Wind Energy System is a wind turbine/generator system employed to convert wind energy to electrical energy. BESS is used to store excess energy and perform fast charge/discharge when the frequency disturbance occurs. The inverter is an interface between the renewable sources and AC network, and it regulates active and reactive power flow. Micro grid is tested for its dynamic performance and frequency stability under different load conditions.

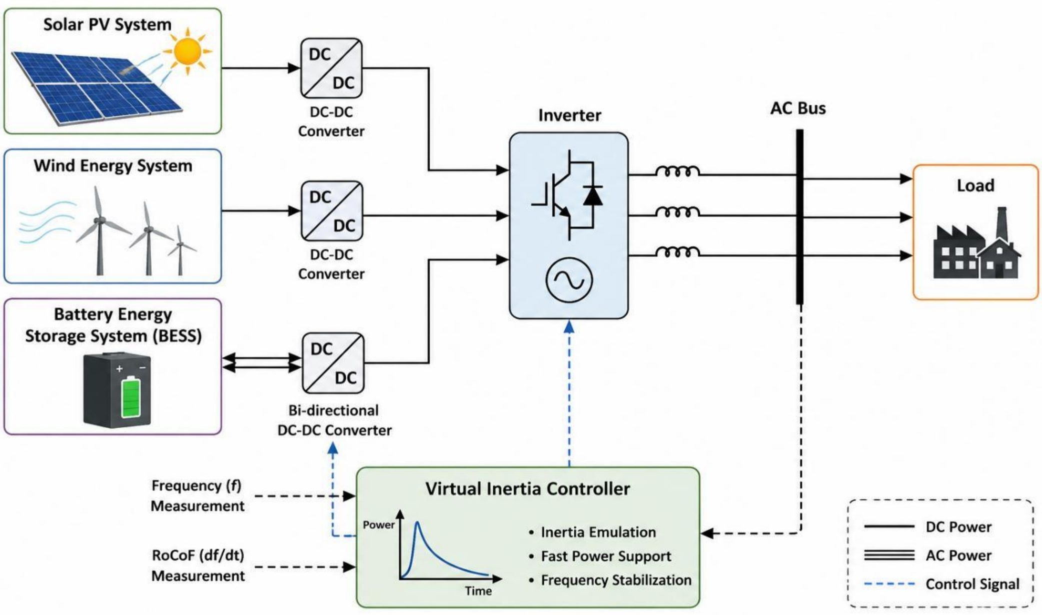


Figure 1. Proposed renewable energy-based microgrid with virtual inertia support.

3.2 Frequency Stability Analysis

The stability of the frequency response is analyzed to assess the dynamic response of the microgrid when subjected to disturbances like sudden load variations and fluctuation in renewables. The frequency dynamics of power system is described by the swing equation which relates power imbalance and power system frequency.

Swing equation is written as:

$2H(d\omega/dt) = Pm - Pe - D(\omega - \omega 0)$ where,

(H) = Inertia constant (s)

(\omega) = Angular frequency (rad/s)

The mechanical input power (P_m) is given by:Mechanical input power (P_m) is: (P_e) = Electrical output power (pu)

(D) = Damping coefficient

(\omega_0) = Nominal angular frequency

Another key parameter able to measure how fast the frequency changes after a disturbance is the Rate of Change of Frequency (RoCoF). RoCoF is given by:

RoCoF = df/dt

A lower Inertia constant gives a higher value of RoCoF and a quick deviation in frequency. For the stable operation of a micro-grid, therefore, it is required to ensure the adequate inertia.

3.3 Virtual Inertia Controller

A virtual inertia controller is added to the inverter based microgrid for increasing frequency stability. The virtual inertia controller acts as the inertial response seen with traditional synchronous generators and rapidly injects or absorbs active power during frequency perturbations.

The equation to support the virtual inertia is:

$PVI = Kv\ (df/dt) + Kd\ (f - f0)$

where,

P_{VI} (P-band 6) = Virtual inertia support power (K_v) = Virtual inertia gain

(K_d) = Damping gain

(f) = System frequency (f_0) = Nominal frequency

The control strategy is to continuously check the system frequency, and calculate the frequency deviation and RoCoF. Depending on these parameters, the controller decides what the BESS needs to supply the required power support and instructs the inverter to absorb or supply power as necessary. This quick response helps achieve better frequency regulation, lower RoCoF and better transient stability.

3.4 Simulation Setup

The proposed microgrid model is hybridized and simulated in MATLAB/Simulink platform for determination of the effectiveness of virtual inertia towards frequency stability enhancement. The simulation does include Solar PV, Wind Energy System, Battery Energy Storage System, Variable load and interfaces to PV or Wind.

Two simulation "cases" are examined:

Case 1 – No Virtual Inertia

In this situation, the microgrid is operated with no virtual inertia support. Sudden load disturbances are considered in the frequency response, RoCoF and transient characteristics. This case will be used as the reference case to compare performance.

In this case, Virtual Inertia is fully active.In this case, Virtual Inertia is fully enabled.

In the above case, the virtual inertia controller is integrated with the inverter and BESS. A controller actively controls what the artificial inertia is during disturbance by controlling the injection of the active power. Frequency deviation, RoCoF, damping characteristics & settling time are used to assess the system performance.

The simulation results from both the cases are compared to evaluate the performance of virtual inertia for the dynamic stability and frequency regulation performance of inverter dominated microgrids.

4. RESULTS AND DISCUSSION

4.1 frequency response without using Virtual Inertia. Then, remove the 4.1 frequency response without Virtual Inertia.

The microgrid frequency response was first examined without the presence of the virtual inertia. To investigate the dynamic behavior of the system, a sudden load disturbance was applied to the system at (t = 2) s. The obtained results showed that the operational frequency was 49.35 Hz, which is 0.65 Hz deviation from the nominal frequency of 50 Hz. Moreover, the Rate of Change of Frequency (RoCoF) was as high as 1.25 Hz/s, which is very high in the absence of adequate inertia of the system. The system was slightly under-damped and would take about 4.8 seconds to reach its steady state value. The results show that the absence of inertia support on these inverter-dominated microgrids is very unstable.

4.2 Frequency Response

In the latter scenario, virtual inertia controller has been embedded in the inverter and Battery

Energy Storage System (BESS). With the same disturbance, the frequency response was much improved. The maximum frequency deviation was 0.22 Hz in which the minimum frequency was

49.78 Hz. With a reduced value of RoCoF, energy production was reduced to 0.42 Hz/s, clearly representing a smooth and lower-frequency frequency behaviour. In addition, the settling time has been shortened to 2.1 s because of the better damping of the virtual inertia controller. The results show the effectiveness of the implemented "virtual inertia" to closely simulate the inertia response of a synchronous generator and to enhance the microgrid dynamic stability.

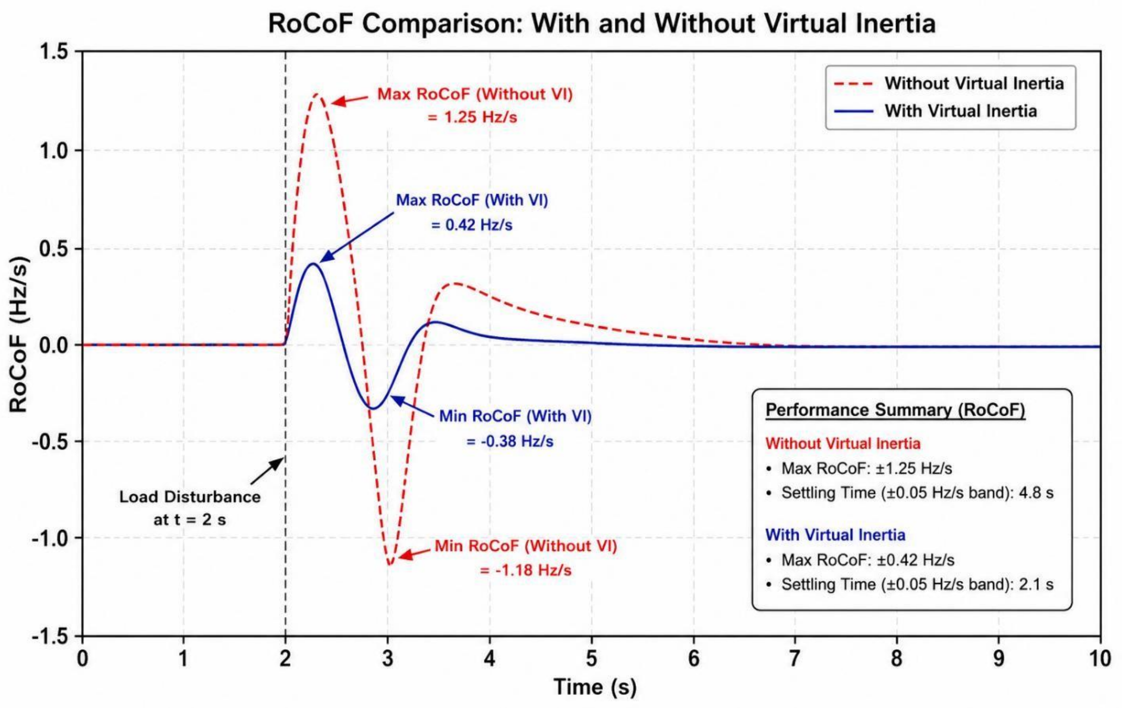
4.3 Comparison of Results

Table 1 presents a comparison of the system performance with and without virtual inertia support.

Table 1. Comparison of Frequency Stability Performance.

Parameter	Without Virtual Inertia	With Virtual Inertia	Improvement
Nominal Frequency	50 Hz	50 Hz	-
Maximum Frequency Deviation	0.65 Hz	0.22 Hz	66.15%
Minimum Frequency	49.35 Hz	49.78 Hz	Improved
RoCoF	1.25 Hz/s	0.42 Hz/s	66.40%
Settling Time	4.8 s	2.1 s	56.25%
Damping Characteristics	Weak	Improved	Significant

The comparison clearly shows that the incorporation of virtual inertia substantially improves the frequency stability of the microgrid. The frequency deviation is reduced by more than 66%, while RoCoF decreases from 1.25 Hz/s to 0.42 Hz/s. In addition, the settling time is shortened by approximately 56%, indicating faster recovery following disturbances.

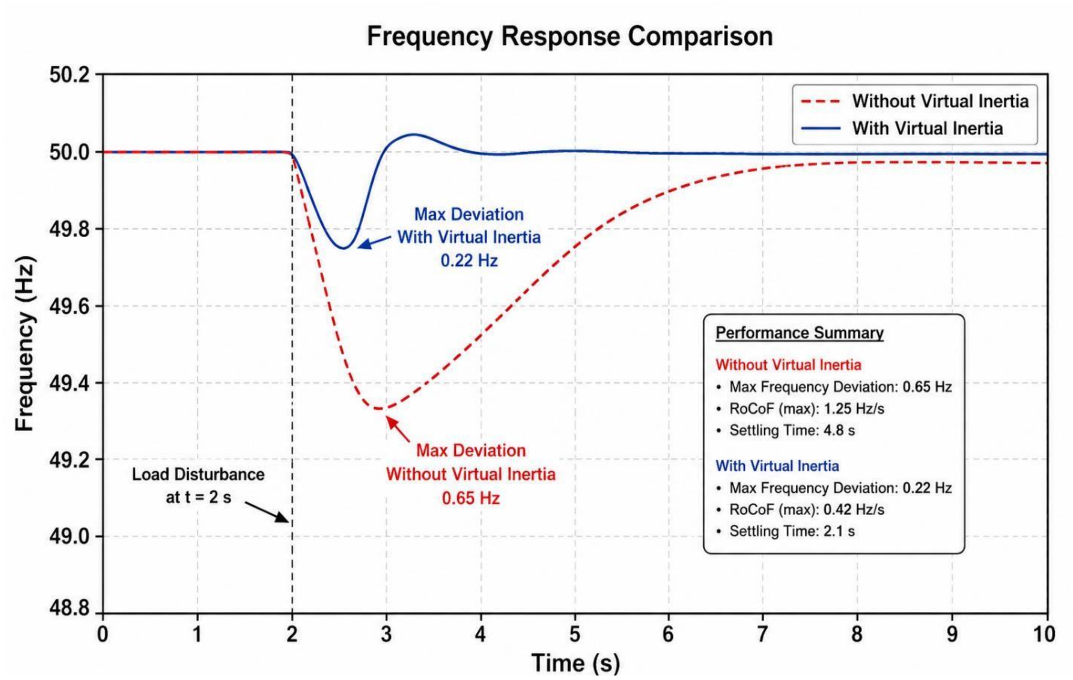


Graph: 1 (Comparison of RoCoF for the microgrid with and without virtual inertia)

4.4 Discussion of Performance Improvement

The active power support is provided by the virtual inertia controller and the improvement of the system performance can be credited to the virtual inertia controller active power support, which is provided in a very fast time frame. When the disturbance occurs, the controller constantly observes the system frequency and RoCoF and injects or absorbs power in an amplified and timely way through the Battery Energy Storage System. Generating this synthetic inertia will offset the fact that inverter-based systems have no inherent inertia, thus preventing sudden variations in frequency.

The simulation results show the improvement in damping characteristics, decrease in frequency overshoot and improvement in transient stability performance of the virtual inertia. The result is a more resilient micro-grid that can withstand variable renewable energy load fluctuations and sudden loads. The finding proves that the virtual inertia is an effective and practical method to ensure the frequency stability in contemporary microgrids that are dominated by high share of inverter connected loads.



Graph: 2 (Frequency response of the microgrid with and without virtual inertia.)

5. CONCLUSION

In this work, the stability analysis of microgrids with high percentage of inverter penetration is studied and the influence of virtual inertia on frequency stability of the grid is investigated. In recent years, the conventional power systems have evolved into inverter-dominated power systems. Inverter-based renewable energy systems offer significant benefits such as cleaner generation, higher degree of control and higher flexibility of operation; however, they lack the physical rotational inertia of conventional synchronous generators. Modern microgrids, however, have low-inertia and hence small frequency deviations, high Rate of Change of Frequency (RoCoF), poor damping behavior, and poor transient stability.

The above-mentioned challenges would be addressed by incorporating a virtual inertia controller in the proposed microgrid model. virtual Inertia controller runs an emulation of the inertia response of a synchronous generator, and quickly injecting or absorbing active power to the system during any event of disturbance in frequency. A MATLAB/Simulink model of Solar PV system, Wind Energy system, BESS, Inverter and Electrical load system was set up to test the system performance in various operating conditions.

Simulations showed a substantial improvement of the dynamic performance of the microgrid when the virtual inertia was used. In the absence of virtual inertia support, the system had a maximum frequency deviation of 0.65 Hz, a RoCoF of 1.25 Hz/s, and a settling time of 4.8 s in response to a load disturbance. On the other hand, by using virtual inertia support, the frequency deviation was reduced to 0.22 Hz, the rate of change of frequency was 0.42 Hz/s and the settling time was reduced to 2.1 s. Further, the performance of damping was significantly enhanced and the microgrid now recovered frequency more quickly and exhibited improved transient stability.

Based on this comparative analysis, it is concluded that using virtual inertia in an inverter dominated microgrid is an effective and practical solution to enhance frequency stability. Virtual inertia, which brings synthetic inertia and quick frequency response types will decrease the negative impact of low inertia operation and make the operation of renewable power systems reliable and resilient. Thus, virtual inertia-based control methods can be helpful for integrating more renewable energy resources in the future smart grid and help maintain its stability operation.

The future studies along this line can be directed towards the development of adaptive virtual inertia controllers, various optimization techniques like Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) as well as artificial intelligence applications for further enhancing stability, flexibility and efficiency of an inverter dominated power system.

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