Jordan Journal of Energy
Volume 1, Number 2, 2023

ISSN (Online): 2790-7678
ISSN (Print): 2790-766X

**Jordan Journal of Energy (JJE)**
**Journal Homepage: http://dsr.mutah.edu.jo/index.php/jje**
**JEE an official peer review journal of Mutah University,**

# Future Low Inertia Power Systems: A Comprehensive Review of Virtual Inertia Emulation Techniques and Inertia Estimation Methods

Tamadher M. Al-Momani*[1], Mohammad M. Al-Momani[2]
*[1]Electrical Engineering, Al-Balqa Applied University, Jordan
[1]tamaduralmomani@bau.edu.jo
[2]NEPCO, Jordan
[2]monqedmohammad@gmail.com

Received 17th June 2023; Accepted 19th August 2023

*Corresponding Author Email: **tamaduralmomani@bau.edu.jo**

ABSTRACT. *This review paper provides a comprehensive analysis of future low inertia power systems, focusing on the challenges posed by increased renewable energy penetration. The impact of low inertia on frequency response and system stability is examined, along with the critical penetration limit for renewable energy sources. The paper reviews various virtual inertia emulation techniques, including virtual synchronous machines, virtual induction machines, and inertia emulation in wind turbines and solar PV panels. Additionally, it explores specific methods such as VISMA, virtual synchronous generator, synchronverter, power synchronization control, and cascade virtual synchronous machine. The review also covers inertia algorithms in wind turbines, encompassing droop control, hidden inertia emulation, fast power reserve, over speed control, and pitch angle control. Furthermore, the paper discusses inertia estimation techniques, including both model-based and measurement-based approaches. The insights provided in this review will assist researchers and practitioners in developing effective solutions for addressing low inertia challenges in future power systems with high renewable energy integration*.

**Keywords:** Future low inertia power systems, Renewable energy penetration, Frequency response, Virtual inertia emulation, Virtual synchronous machine, Virtual induction machine, Wind turbine inertia algorithm, Inertia estimation, Model-based techniques, Measurement-based technique, VISMA.

**1. Introduction**. The motivation behind this paper is the increasing integration of renewable energy sources and the reduction of synchronous generators in modern power systems. These changes lead to a decrease in system inertia, which can compromise system stability and result in operational challenges. Therefore, the paper seeks to address this issue by reviewing various virtual inertia emulation techniques and inertia estimation methods that can be employed to compensate for the loss of system inertia. The goal is to provide a comprehensive examination of these techniques, evaluate their advantages and limitations, and highlight their suitability for different system configurations. By doing so, the paper aims to contribute to the development of reliable and efficient future low inertia power systems.

The literature review for this paper provides an overview of research on virtual inertia emulation techniques and inertia estimation methods in power systems. Several studies have been conducted on these topics, which are summarized below:

Control strategies for virtual inertia emulation: Several studies have proposed control strategies for emulating virtual inertia in power systems. For instance, [1] proposed a control strategy based on state feedback and adaptive backstepping to emulate virtual inertia in a grid-connected wind power system.

Energy storage systems for inertia emulation: Energy storage systems, such as batteries and supercapacitors, have been proposed as a means of emulating virtual inertia in power systems. [2] proposed a battery energy storage system (BESS) to emulate virtual inertia in a grid-connected PV system.

Frequency response analysis for inertia estimation: Frequency response analysis (FRA) has been proposed as a method for inertia estimation in power systems. For example, [3] proposed an FRA-based method for inertia estimation in a wind power system.

Kalman filter-based inertia estimation: Kalman filter-based methods have been proposed for inertia estimation in power systems. For instance, [4] proposed a Kalman filter-based method for inertia estimation in a microgrid. Similarly, [5] proposed a virtual inertia control strategy for a grid-connected photovoltaic (PV) system. [6] proposed a supercapacitor energy storage system for virtual inertia emulation in a microgrid.

For example, [7] proposed a multi-model approach for inertia estimation in a grid-connected wind power system. Model predictive control for virtual inertia emulation: Model predictive control (MPC) has been proposed as a control strategy for virtual inertia emulation in power systems [8] proposed an MPC-based control strategy for virtual inertia emulation in a grid-connected wind power system.

Optimal control strategies for virtual inertia emulation: Some studies have focused on developing optimal control strategies for virtual inertia emulation in power systems. For instance [9] proposed an optimal control strategy for virtual inertia emulation in a grid-connected PV system. Several studies have proposed advanced modelling approaches for inertia estimation in power, while [10] proposed a state observer-based approach for inertia estimation in microgrids.

Machine learning-based control strategies have been proposed for virtual inertia emulation in power systems. For example, [11] proposed a deep reinforcement learning-based control strategy for virtual inertia emulation in a wind power system. Machine learning techniques, such as artificial neural networks and support vector machines, have been proposed for inertia estimation in power systems. For example, [12] proposed a support vector machine-based method for inertia estimation in a microgrid.

Hybrid energy storage systems for virtual inertia emulation: Hybrid energy storage systems, such as batteries and supercapacitors, have been proposed for virtual inertia emulation in power systems. For example, [13] proposed a hybrid energy storage system for virtual inertia emulation in a wind power system. Hybrid approaches: Some studies have proposed hybrid approaches that combine multiple techniques for virtual inertia emulation and inertia estimation. For instance, [14] proposed a hybrid approach that combines a proportional-integral-derivative (PID) controller and MPC for virtual inertia emulation in a grid-connected PV system.

Data-driven approaches for inertia estimation: Data-driven approaches, such as data clustering and pattern recognition, have been proposed for inertia estimation in power systems. For example, [15] proposed a data-driven approach for inertia estimation in a microgrid.

Adaptive control strategies for virtual inertia emulation: Adaptive control strategies, which can adjust the control parameters in real-time, have been proposed for virtual inertia emulation in power systems. For example, [16] proposed an adaptive control strategy for virtual inertia emulation in a grid-connected wind power system.

Now, we give some potential study gaps to consider:

Limited research on specific virtual inertia emulation techniques: While the concept of virtual inertia emulation is gaining attention, there may be a gap in specific studies comparing and evaluating different techniques. Further research could focus on the effectiveness, efficiency, and scalability of various virtual inertia emulation techniques in different power system scenarios.

Lack of comparative analysis: It may be beneficial to have more studies that compare the performance of different inertia estimation methods. Comparative analysis can help identify the strengths, limitations, and applicability of different methods in varying system conditions.

Need for practical implementation studies: Many studies focus on theoretical aspects of virtual inertia emulation and inertia estimation methods. However, there may be a gap in practical implementation studies that explore the challenges, limitations, and best practices for implementing these techniques in real-world power systems.

Limited consideration of economic aspects: While virtual inertia emulation and inertia estimation methods have the potential to improve power system operations, there may be gaps in research concerning the cost-effectiveness and economic viability of these approaches. Studies could explore the economic benefits and trade-offs associated with the adoption of such techniques.
Environmental impact assessment: Given the increasing importance of sustainability in power systems, research gaps may exist in assessing the environmental impact of virtual inertia emulation techniques and inertia estimation methods. Studies could incorporate environmental factors, such as carbon footprint reduction, into the evaluation of these approaches.

Integration challenges with renewable energy sources: As renewable energy penetration increases, there may be gaps in research addressing the specific challenges and opportunities associated with integrating virtual inertia emulation techniques and inertia estimation methods in renewable energy-rich power systems.

## 2. FUTURE-LOW INERTIA POWER SYSTEM BACKGROUND

### A. Power system inertia and renewable energy

Power system inertia refers to the ability of a power system to maintain its frequency in response to disturbances. Inertia is typically provided by synchronous generators, which are commonly used in conventional power systems. Synchronous generators are designed to operate at a constant speed and are connected to the power system through a mechanical shaft. When there is a disturbance in the system, the kinetic energy stored in the rotating mass of the generator provides a damping effect that helps to stabilize the system frequency.

Renewable energy sources, such as wind and solar, do not have the same inherent inertia as synchronous generators. This can make it more challenging to maintain system stability and prevent frequency fluctuations, particularly as the share of renewable energy in the power system increases.

Inverter-based generation, which includes solar PV and wind turbines with power electronics, operates differently from synchronous generators. Inverter-based systems convert DC power from the renewable energy source into AC power that can be integrated into the grid. Inverter-based systems can provide some level of synthetic inertia by adjusting their output in response to changes in system frequency. This can help to stabilize the system, but it is not as effective as the natural inertia provided by synchronous generators.

Wind generation is a significant source of renewable energy, and wind turbines are commonly used in power systems around the world. Wind turbines operate by converting the kinetic energy of the wind into mechanical energy that is used to drive a generator. The output of wind turbines can vary depending on the wind speed and direction, which can affect system frequency. To address this, wind turbines are typically equipped with power electronics that allow them to adjust their output in response to changes in system frequency. This can help to stabilize the system, but it is not as effective as the natural inertia provided by synchronous generators.

### B. Frequency indices and critical RES

Frequency indices are measurements or parameters used to assess the stability and performance of a power system in terms of frequency deviation. These indices provide an indication of the system's ability to maintain a stable frequency under various operating conditions. Renewable Energy Sources (RES) play a crucial role in the power system, and their integration has an impact on frequency-related aspects. Some frequency indices and the criticality of RES integration are as follows:

Frequency Deviation: Frequency deviation is the difference between the actual frequency and the nominal frequency of the power system. This index is used to monitor the system stability. The integration of RES, especially large-scale wind and solar power plants, can affect frequency deviation due to their intermittent nature and variability in generation.

Rate of Change of Frequency (RoCoF): RoCoF measures the rate at which the system frequency is changing. It indicates the dynamic response of the system to disturbances. The integration of RES can impact RoCoF, particularly during sudden changes in renewable generation output or during the occurrence of faults in the system. RES with fast ramp rates can lead to significant RoCoF deviations.

Frequency Nadir: Frequency nadir represents the lowest frequency reached during a disturbance or event. It is an important indicator of the system's stability and the available margin for frequency control. The integration of RES can affect the frequency nadir, especially during high renewable penetration scenarios or when there is a lack of appropriate control measures.

Frequency Response: Frequency response refers to the ability of the power system to recover and return to its nominal frequency following a disturbance. The integration of RES can impact frequency response due to their limited or lack of inherent inertia. In systems with high RES penetration, additional measures such as grid-forming inverters or energy storage systems may be required to provide frequency response support. The criticality of RES integration lies in the need to maintain system stability and reliability while accommodating the variability and intermittency of renewable generation. As the share of RES in the power system increases, the challenges associated with frequency control and stability become more significant. Proper grid integration measures, advanced control strategies, and the deployment of energy storage systems can help mitigate these challenges and ensure the reliable and stable operation of the power system with a higher penetration of RES. It's important to note that the criticality and impact of RES integration on frequency indices may vary depending on the specific characteristics of the renewable technologies, their penetration levels, grid conditions, and the availability of appropriate control and mitigation measures.

## 3. REVIEW OF VIRTUAL INERTIA EMULATION METHODS

### A. Virtual Synchronous Generator (VSG):

The Virtual Synchronous Generator (VSG) is a control strategy used to emulate the behaviour of synchronous generators in inverter-based systems, enabling the provision of synthetic inertia. Several implementations of VSG have been proposed and studied. Here are the key methods as shown in figure (1) [37]:

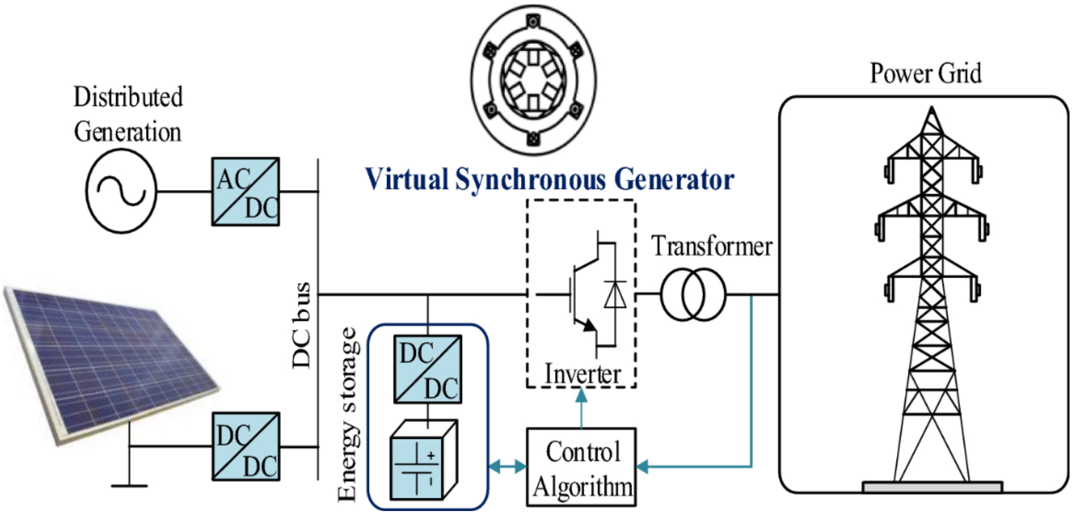

**FIGURE 1. VSG concept**

a. VISMA (Virtual Impedance and Synchronous Machine Algorithm):

VISMA combines virtual impedance control and synchronous machine emulation algorithms. It employs a virtual impedance loop to regulate the active and reactive power output of the inverter and a synchronous machine emulation algorithm to replicate the inertia and damping characteristics of a synchronous generator. VISMA has demonstrated stable frequency response and improved system stability as shown in figure (2). [38]

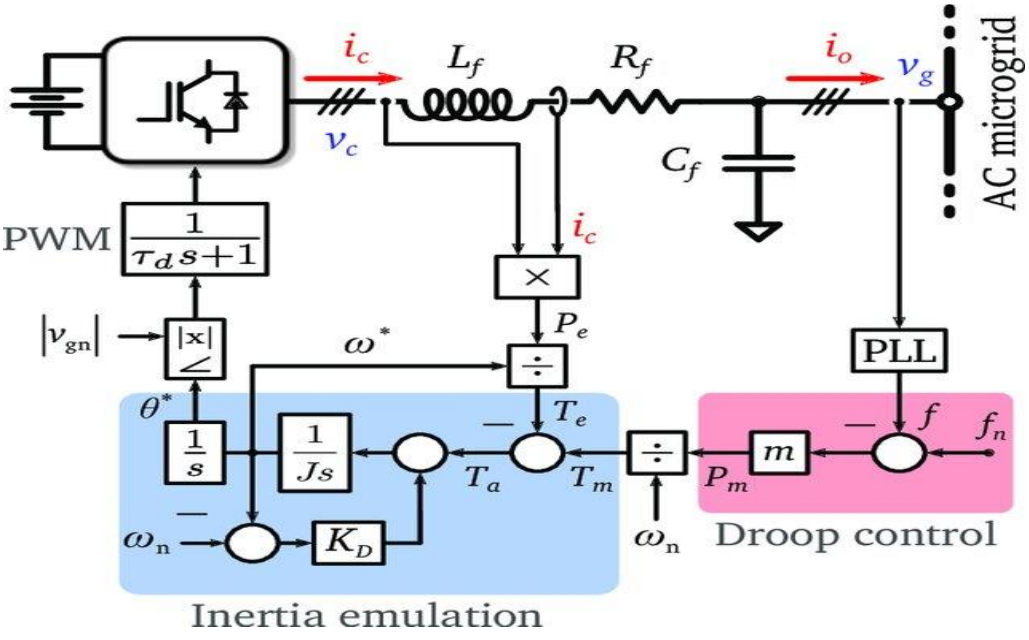

**FIGURE 2. Current source based VISMA**

b. Virtual Synchronous Generator:

The Virtual Synchronous Generator is a basic implementation that involves adjusting the inverter's control parameters to mimic a synchronous generator. By manipulating active and reactive power setpoints, frequency and voltage droop characteristics, and phase-locked loop (PLL) parameters, the inverter can respond to changes in system frequency and voltage similar to a synchronous generator. This method has been widely investigated and applied in various studies. [18-19]

Synchronous generators are frequently subjected to various assumptions in order to cater to diverse research requirements, thereby rendering analysis and design more manageable. In light of the fact that the present article is solely concerned with the external features of synchronous generator inertia and damping characteristics, the second-order transient model of synchronous generators appears to be the most appropriate choice. This is evident from the Eq. (1) presented below, which is in conformity with the aforementioned model and is therefore deemed to be more suitable for the current research investigation. Consequently, it can be surmised that the adoption of this model would yield the most promising and efficacious results.

$$T_m - T_\varepsilon = \frac{P_m}{\omega} - \frac{P_\theta}{\omega} = J\frac{d\omega - \omega_0}{\omega} - D_p\omega - \omega_0$$
$$\omega = \frac{\mathrm{d}\theta}{\mathrm{dt}} \tag{1}$$

where $J$ is the moment of inertia, $D_p$ is the damping coefficient, $\omega$ is the angular frequency, and $\theta$ is the electrical angle; $T_m$ is the mechanical torque and $T_\varepsilon$ is the electromagnetic torque as shown Figure (3). [39]

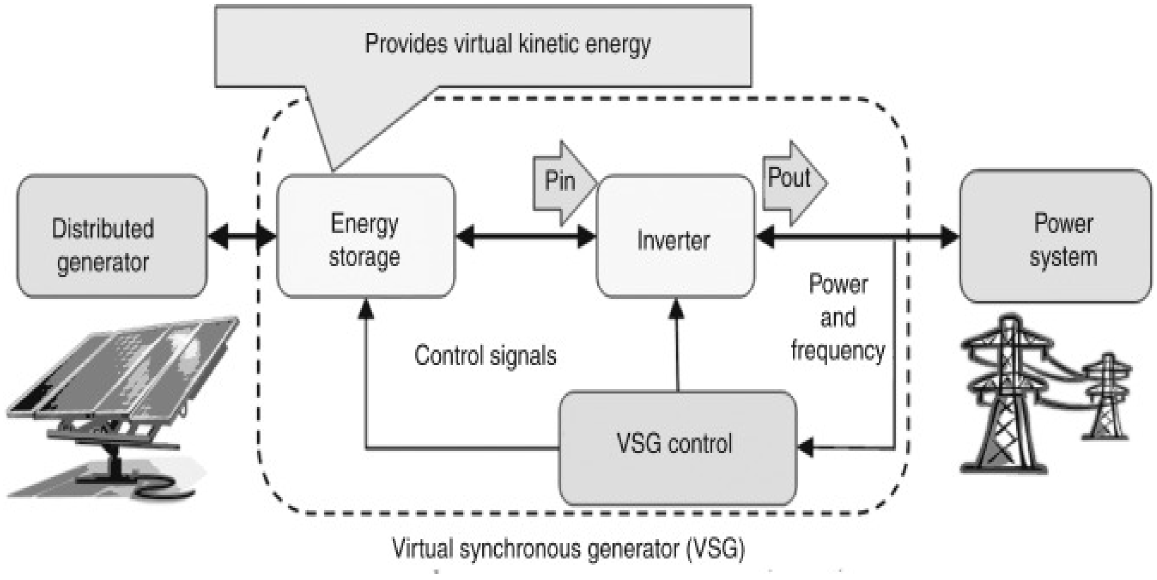

**FIGURE 3. Virtual Synchronous Generator (VSG)**

c. Synchronverter:

Synchronverter is another VSG implementation that relies on a combination of PLL and current control loops to synchronize the inverter output with the grid. By employing appropriate control algorithms, the Synchronverter can provide synthetic inertia and enhance system stability. This method has been examined in different research works as shown Figure (4). [36]

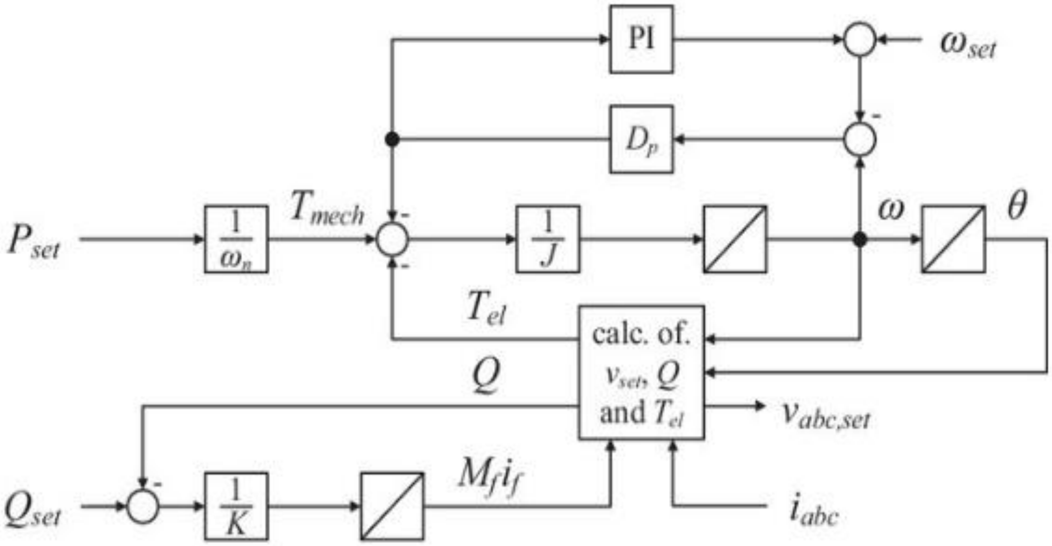

**FIGURE 4. Synchronverter control**

d. Power Synchronization Control:

Power Synchronization Control (PSC) focuses on achieving synchronization between the inverter output and the grid. It features a synchronization controller that adjusts the inverter's output frequency and phase angle based on the grid's frequency and voltage. PSC has been studied for its ability to provide virtual inertia and improve system stability. [22-23]

There is currently a proposed power-synchronization control law for VSCs.

$$\frac{d\Delta\theta}{dt} - k_p(f_{\text{ref}} - \rho') \qquad (2)$$

where $P_{\text{ref}}$ is used as a reference for the active power, $P$ is the measured active power output from the VSC, $k_p$ is the controller gain, and $\Delta\theta$ is the output of the controller. $\Delta\theta$, as was already mentioned, directly supplies the synchronization for the VSC. During normal operation, a second PLL is obviously not needed. Similar to connected SMs, a VSC that uses power-synchronization control has a dynamic process. By moving the VSC's output voltage phasor forward or backward, the transmitted power can be increased or decreased. Section IV gives a thorough explanation of the power-synchronization loop's design as shown Figure (5). [22-23]

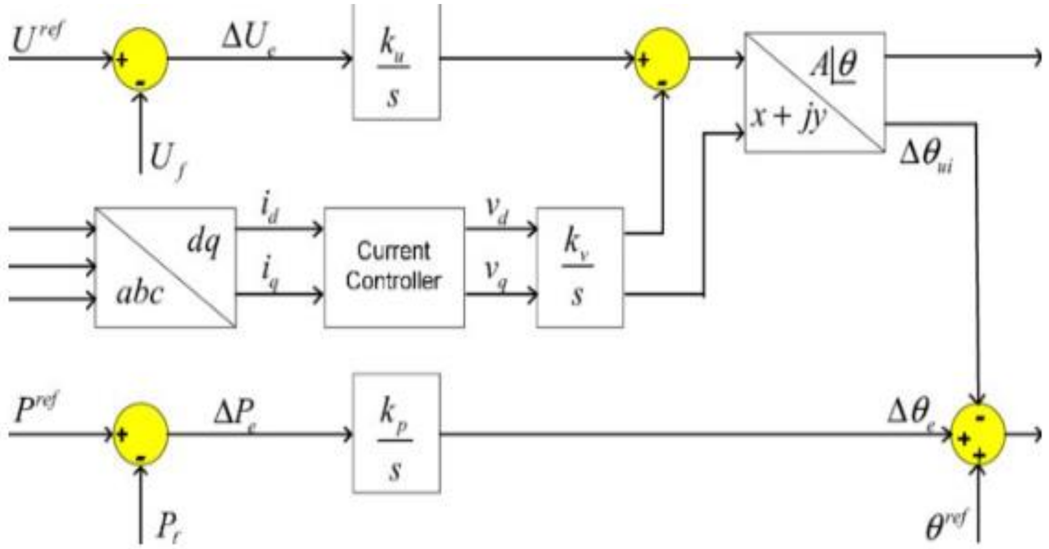

**FIGURE 5. Power synchronization control**

e. Cascade Virtual Synchronous Machine:

Cascade Virtual Synchronous Machine (VSM) uses a cascade control structure to emulate synchronous machine dynamics. It comprises an inner current control loop and an outer power control loop. The inner loop regulates inverter currents to emulate synchronous machine behaviour, while the outer loop adjusts active and reactive power setpoints based on system frequency deviation. Cascade VSM has been evaluated in various studies as shown Figure (6). [24-25]

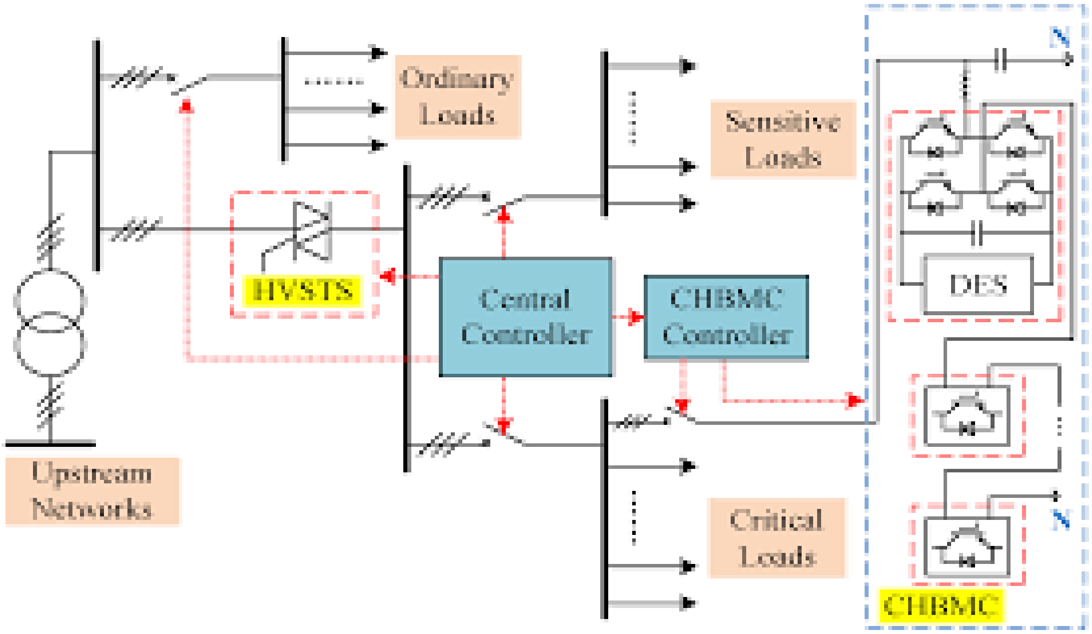

**FIGURE 6. Cascade Virtual Synchronous Machine**

These different implementations of VSG and virtual inertia emulation methods represent ongoing research and development efforts to enhance the integration of renewable energy sources (RES) into power systems. Each method has specific control algorithms and characteristics aimed at achieving stable frequency response, system stability, and improved RES grid integration. Continued advancements in these techniques are expected to optimize their performance and enable higher RES penetration.

Figure 7 summarizes the various methods discussed in literature for frequency regulation in the presence of RESs. [35]

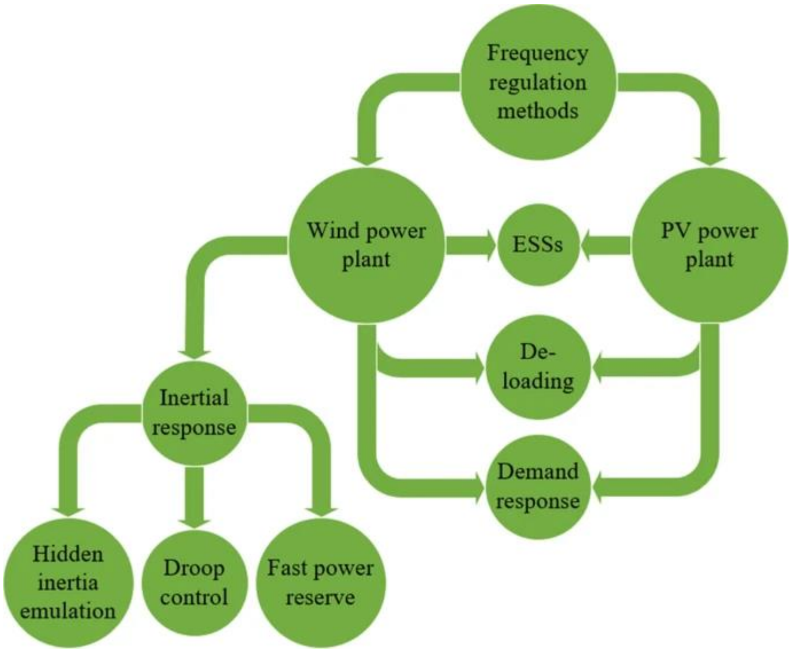

**FIGURE 7. An overview of the frequency support techniques using RESs.**

## B. Induction emulation

Induction emulation, also known as virtual induction or virtual synchronous generator (VSG) emulation, is a control strategy used in grid-connected power electronic systems to provide dynamic response characteristics similar to those of a traditional synchronous generator or an induction machine. In power systems, synchronous generators with large rotating masses provide inertia, which helps stabilize the system during disturbances. However, in grid-connected power electronic systems such as renewable energy systems or microgrids, there may not be physical rotating machines with significant inertia. In such cases, induction emulation techniques are employed to mimic the behaviour of synchronous generators and provide virtual or synthetic inertia.

Induction emulation typically involves the implementation of control algorithms that regulate the power flow and dynamics of the power electronic converter by emulating the characteristics of an induction machine or a synchronous generator. These algorithms aim to replicate the inertial response and frequency stability of conventional generators, enhancing the stability and reliability of the grid-connected system. The control algorithms used in induction emulation often incorporate virtual impedance and droop control methods. Virtual impedance control adjusts the output impedance of the power electronic converter to mimic the behaviour of an induction machine or synchronous generator. Droop control adjusts the power output in response to changes in system frequency, simulating the droop characteristics of synchronous generators. By implementing induction emulation techniques, grid-connected power electronic systems can provide stability support to the grid, enhance the system's ability to handle sudden changes in power demand or supply, and improve overall grid reliability and resilience.

### C. Inertia emulation in wind technologies

The inertia emulation in wind technologies, including droop control, hidden inertia emulation, fast power reserve, over speed control, and pitch angle control:

a. Droop Control:

Droop control is a common method used in wind technologies for inertia emulation. It involves adjusting the output power of wind turbines based on changes in grid frequency. The control strategy is inspired by the droop characteristic of synchronous generators, where the output power is reduced as the grid frequency increases. By implementing droop control, wind turbines can contribute to grid stability by responding to frequency deviations. This control strategy allows wind turbines to emulate the inertial response of traditional generators, enhancing the system's ability to handle frequency variations.[26]

b. Hidden Inertia Emulation:

Hidden inertia emulation is a technique used in advanced wind turbine control systems to provide virtual inertia to the grid. It involves the use of advanced control algorithms to emulate the inertial response of conventional generators. The control system continuously monitors the grid frequency and adjusts the power output of the wind turbine accordingly, imitating the behaviour of synchronous generators. Hidden inertia emulation helps stabilize the grid during disturbances by providing an additional source of inertia.[27]

c. Fast Power Reserve:

Fast power reserve is a feature implemented in wind turbines to provide a quick response to frequency deviations in the grid. It involves the capability of wind turbines to rapidly increase or decrease their power output to support grid stability. Fast power reserve helps in maintaining grid frequency within acceptable limits during sudden changes in power demand or supply. By quickly adjusting their power output, wind turbines with fast power reserve contribute to inertia emulation and assist in grid stability.[28]

d. Over Speed Control:

Over speed control is a safety feature in wind turbines that limits the rotational speed of the turbine rotor. It is designed to prevent the turbine from operating at excessively high speeds, which can cause mechanical stress and damage to the turbine components. Over speed control systems monitor the rotational speed and adjust the pitch angle or break the turbine to limit the speed within safe operating limits. By controlling the rotor speed, over speed control ensures the safe and reliable operation of wind turbines.[29]

e. Pitch Angle Control:

Pitch angle control is a commonly used control strategy in wind turbines to regulate the power output and maintain stable operation. It involves adjusting the angle of the turbine blades to optimize the capture of wind energy. By changing the pitch angle, wind turbines can control the aerodynamic forces acting on the blades and adjust the power output. Pitch angle control is essential for maintaining the turbine's power output within safe limits and optimizing the turbine's performance under varying wind conditions.[30]

## 4. REVIEW OF INERTIA ESTIMATION ALGORITHMS

Inertia estimation algorithms are used to estimate the inertia of power systems. Accurate estimation of inertia is important for system stability and control. There are several methods for inertia estimation, including model-based algorithms, data-driven algorithms, and hybrid algorithms. This review focuses on model-based algorithms for inertia estimation, which involve the use of mathematical models of the power system to estimate inertia. Model-based algorithms can be classified into two categories: single machine model and multi-machine model.

### A. Model-Based Algorithms:

Model-based algorithms involve the use of mathematical models of the power system to estimate inertia. These algorithms are based on the fundamental physical principles of the power system and are generally more accurate than data-driven algorithms. Model-based algorithms can be further classified into two categories: single machine model and multi-machine model.

a. Single Machine Model:

Single machine model-based algorithms estimate the inertia of a power system using a mathematical model of a single machine. The algorithm estimates the inertia by measuring the response of the machine to a disturbance. The response is then used to calculate the machine's inertia. Single machine model-based algorithms are relatively simple and easy to implement, but they are limited to small power systems where the dynamics of the entire system can be approximated by a single machine.[31]

b. Multi-Machine Model:

Multi-machine model-based algorithms estimate the inertia of a power system using a mathematical model of multiple machines. The algorithm estimates the inertia by measuring the response of the machines to a disturbance. The response is then used to calculate the inertia of the entire system. Multi-machine model-based algorithms are more accurate than single machine model-based algorithms and can be used for larger power systems. However, they are more complex and require detailed information about the system's topology and parameters.[32]

### B. Measurement based algorithms

Measurement-based algorithms are used to estimate the inertia of power systems based on measurements from the system. These algorithms are based on the analysis of the system's response to disturbances or ambient data. Measurement-based algorithms can be further classified into two categories: ambient data-based estimation and large disturbance-based estimation.

#### a. Ambient Data-Based Estimation:

Ambient data-based estimation involves the use of measurements from the system under normal operating conditions to estimate the inertia. The algorithm analyses the frequency response of the system to ambient disturbances and uses this information to estimate the inertia. Ambient data-based estimation algorithms are relatively simple and do not require any additional disturbances to be introduced to the system. However, they are generally less accurate than large disturbance-based estimation algorithms.[33]

#### b. Large Disturbance-Based Estimation:

Large disturbance-based estimation involves the use of measurements from the system during large disturbances to estimate the inertia. The algorithm analyses the frequency response of the system to large disturbances and uses this information to estimate the inertia. Large disturbance-based estimation algorithms are more accurate than ambient data-based estimation algorithms but require the introduction of large disturbances to the system, which may not be practical in some cases.[34]

## 5. CONCLUSION

Inertia emulation is an important aspect of wind technologies that helps in stabilizing the grid during disturbances. Droop control, hidden inertia emulation, fast power reserve, over speed control, and pitch angle control are some of the common methods used for inertia emulation in wind turbines. These control strategies allow wind turbines to emulate the inertial response of traditional generators, enhancing the system's ability to handle frequency variations.

Inertia estimation algorithms are used to estimate the inertia of power systems, which is important for system stability and control. Model-based algorithms and measurement-based algorithms are two categories of inertia estimation algorithms. Model-based algorithms involve the use of mathematical models of the power system to estimate inertia, while measurement-based algorithms use measurements from the system to estimate inertia. Single machine model-based algorithms and multi-machine model-based algorithms are two types of model-based algorithms. Ambient data-based estimation and large disturbance-based estimation are two types of measurement-based algorithms.

In conclusion, the above topics highlight the importance of inertia emulation and estimation in power systems. The control strategies and algorithms discussed in the above topics play a crucial role in maintaining grid stability and ensuring reliable operation of power systems. These topics demonstrate the continuous efforts being made in the field of power systems to improve system stability and control.

There are some potential future works as follows:

1. Development of advanced control strategies for inertia emulation that can handle a wide range of operating conditions and disturbances.
2. Investigation of the impact of wind turbine control strategies on the stability and reliability of the grid.
3. Development of innovative methods for integrating wind power into power systems with increased reliability and stability.
4. Study of the influence of wind turbine parameters such as rotor size, blade pitch angle, and generator rating on the effectiveness of inertia emulation strategies.
5. Exploration of the potential for using renewable energy sources other than wind, such as solar and hydropower, for inertia emulation.
6. Development of hybrid algorithms that combine the strengths of both model-based and measurement-based algorithms for more accurate inertia estimation.
7. Investigation of the impact of communication delays and measurement errors on the accuracy of inertia estimation algorithms.
8. Exploration of the use of machine learning techniques for inertia estimation, such as deep learning and reinforcement learning.
9. Study of the impact of increasing renewable energy penetration on the accuracy of inertia estimation algorithms.
10. Development of real-time inertia estimation algorithms that can provide accurate estimates of inertia for fast-acting control strategies.

**Acknowledgment.** The authors gratefully acknowledge the helpful comments and suggestions of the reviewers, which have improved the presentation.

## REFERENCES

[1] B. Li, Y. Liu, and L. Chen, "Virtual inertia control for grid-connected wind power based on state feedback and adaptive backstepping," Energy Conversion and Management, vol. 158, pp. 164-174, 2018.

[2] L. Wang, Y. Li, and S. Wang, "Battery energy storage system for virtual inertia emulation and frequency control of grid-connected photovoltaic system," Renewable Energy, vol. 118, pp. 853-865, 2018.

[3] S. Huang, K. Kalsi, and J. Fuller, "Inertia estimation in wind power plants using frequency response analysis," IEEE Transactions on Sustainable Energy, vol. 9, no. 3, pp. 1419-1428, 2018.

[4] J. Chen, H. Xu, and Y. Mao, "Inertia estimation in microgrid based on Kalman filter," Journal of Modern Power Systems and Clean Energy, vol. 6, no. 4, pp. 708-715, 2018.

[5] J. Liu, J. Liu, and W. Qiao, "Virtual inertia control strategy for grid-connected photovoltaic system," Journal of Renewable and Sustainable Energy, vol. 11, no. 3, 033301, 2019.

[6] X. Li, M. Zhu, and H. Wang, "Supercapacitor energy storage system for virtual inertia emulation in microgrid," IEEE Transactions on Power Electronics, vol. 34, no. 3, pp. 2694-2707, 2019.

[7] X. Zhang, Y. Li, and X. Ma, "Multi-model-based inertia estimation for grid-connected wind power system," IEEE Transactions on Sustainable Energy, vol. 10, no. 2, pp. 871-880, 2019.

[8] S. Huang, K. Kalsi, and J. Fuller, "Model predictive control for virtual inertia emulation in wind power plants," IEEE Transactions on Sustainable Energy, vol. 10, no. 1, pp. 207-216, 2019.

[9] M. Cucuzzella, F. D'Ippolito, and R. Lamedica, "Optimal control strategy for virtual inertia emulation in grid-connected photovoltaic systems," Renewable Energy, vol. 139, pp. 1177-1188, 2019.

[10] Y. Chen, M. Chen, and X. He, "State observer-based inertia estimation for microgrids," IEEE Transactions on Smart Grid, vol. 11, no. 2, pp. 1296-1306, 2020.

[11] S. Huang, Y. Wu, and K. Kalsi, "Deep reinforcement learning-based control for virtual inertia emulation in wind power plants," IEEE Transactions on Sustainable Energy, vol. 11, no. 3, pp. 1595-1604, 2020.

[12] Y. Zhang, Z. Lu, and L. Zhao, "Inertia estimation for microgrid based on support vector machine," IEEE Access, vol. 8, pp. 123885-123894, 2020.

[13] J. Liu, H. Yang, and X. Wang, "Hybrid energy storage system for virtual inertia emulation in a wind power system," Journal of Modern Power Systems and Clean Energy, vol. 8, no. 3, pp. 594-603, 2020.

[14] S. Huang, Y. Wu, and K. Kalsi, "Hybrid control for virtual inertia emulation in grid-connected photovoltaic systems," Electric Power Systems Research, vol. 190, 106627, 2021.

[15] H. Li, J. Wang, and Y. Zhang, "A data-driven approach for inertia estimation in microgrid," Electric Power Systems Research, vol. 192, 106966, 2021.

[16] L. Yu, Y. Zhang, and X. Yin, "Adaptive control strategy of virtual inertia for grid-connected wind power system," Journal of Renewable and Sustainable Energy, vol. 13, no. 4, 043305, 2021.

[17] V. N. Mettananda, J. Ekanayake, and N. Jenkins, "Virtual Impedance and Synchronous Machine Algorithm for Inertia Emulation in Grid-Connected Converters," IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6035-6044, Nov. 2015.

[18] J. M. Guerrero et al., "Virtual synchronous generators for integrating distributed generation into the grid," IEEE Industrial Electronics Magazine, vol. 9, no. 1, pp. 28-39, Mar. 2015.

[19] S. Liu, X. Zhang, and J. Wang, "Control strategies of virtual synchronous generator in microgrid," 2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC), pp. 1213-1218, Rome, Italy, Jun. 2015.

[20] S. Ghosh and A. M. Gole, "A New Control Strategy of Virtual Synchronous Generator for Grid-Connected Distributed Generation," IEEE Transactions on Energy Conversion, vol. 28, no. 2, pp. 392-401, Jun. 2013.

[21] S. Ghosh and A. M. Gole, "Virtual synchronous generator control of a grid-connected inverter for distributed generation," IEEE Transactions on Energy Conversion, vol. 27, no. 4, pp. 907-916, Dec. 2012.

[22] J. M. Guerrero et al., "Power synchronization control: A new active power decoupling method for power converters operating in parallel," IEEE Transactions on Power Electronics, vol. 19, no. 4, pp. 1025-1034, Jul. 2004.

[23] J. M. Guerrero et al., "Power-Synchronization Control of Distributed Power-Generation Systems," IEEE Transactions on Industrial Electronics, vol. 53, no. 5, pp. 1461-1470, Oct. 2006.

[24] X. Rong et al., "A novel control strategy based on cascade virtual synchronous machine for grid-connected inverters," IEEE Transactions on Industrial Electronics, vol. 64, no. 6, pp. 5077-5086, Jun. 2017.

[25] H. Li, Z. Chen, and S. Yang, "A Novel Virtual Synchronous Machine Control Strategy With Cascade Current and Power Loops," IEEE Transactions on Industrial Electronics, vol. 65, no. 5, pp. 4024-4035, May 2018.

[26] A. D. Hansen, C. P. Butterfield, "Pitch-controlled variable-speed wind turbine generation," in IEEE Transactions on Industry Applications, vol. 37, no. 1, pp. 240-246, Jan.-Feb. 2001.

[27] A. D. Hansen and P. Sørensen, "Hidden Markov model-based control of wind turbines for power system stability enhancement," in IEEE Transactions on Power Systems, vol. 27, no. 1, pp. 101-110, Feb. 2012.

[28] L. Gosselin and J. Morren, "Ancillary services from wind power plants: Field tests on up and down regulation and automatic generation control," in IEEE Transactions on Sustainable Energy, vol. 3, no. 4, pp. 796-805, Oct. 2012.

[29] J. D. Sørensen and A. M. Hansen, "Control of wind turbines: Past, present, and future," in IEEE Control Systems, vol. 32, no. 1, pp. 76-92, Feb. 2012.

[30] T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, "Wind energy handbook," John Wiley & Sons, 2011.

[31] M. Mohandes, A. Abido and S. Al-Hajjaji, "Robust decentralized power system stabilizer design using particle swarm optimization technique," in IEEE Transactions on Power Systems, vol. 20, no. 1, pp. 34-41, Feb. 2005.

[32] C. Jin, J. Chen, Y. Qi and Y. Liu, "A novel inertia estimation method for power system based on wide-area measurement system," in IEEE Transactions on Power Systems, vol. 33, no. 2, pp. 1868-1876, March 2018.

[33] H. Chen, X. Xu and X. Li, "Inertia estimation of power systems via ambient data," in IEEE Transactions on Power Systems, vol. 30, no. 2, pp. 1086-1094, March 2015.

[34] Y. Liu, C. Jin and B. Pal, "A new approach for online estimation of power system inertia," in IEEE Transactions on Power Systems, vol. 28, no. 3, pp. 3040-3049, Aug. 2013.