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Virtual Inertia Control Topology Addressing Indonesia's Low-Inertia Renewable Grid Resilience Challenge

Fikri Waskito[1], Fransisco Danang Wijaya[1], Eka Firmansyah[1], Juan C. Vasques[2]

[1] Department of Information and Electrical Engineering, Faculty of Engineering, Universitas Gadjah Mada, Sleman, D.I. Yogyakarta 55281, Indonesia
[2] Center for Research on Microgrids (CROM), AAU Energy, Aalborg University, 9220 Aalborg, Denmark

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Corresponding Author: Fransisco Danang Wijaya (email: danangwijaya@ugm.ac.id)

ABSTRACT — The increasing penetration of renewable energy sources in Indonesia, particularly photovoltaic (PV) systems, into electric power grids has led to a reduction in system inertia, potentially compromising frequency stability during disturbances. This paper proposes a virtual inertia control method for single-phase rooftop PV inverters to enhance frequency response in low-inertia microgrids. A single-phase synchronverter model based on the swing equation was developed and tested on the IEEE 13-bus system. Three scenarios were evaluated: a solar-only microgrid, a wind-integrated microgrid, and a microgrid combining renewable sources with a synchronous generator. Simulation results demonstrated that the proposed virtual inertia method improved frequency and voltage stability, closely mimicking the response of traditional synchronous generators. Within the first 10 s following a disturbance, the system failed to restore its frequency to the nominal value due to insufficient inertia in the inertial response time range. This indicates that the initial 10 s are a critical period for frequency recovery. The poorest frequency response was observed in scenario 1 (solar-only configuration), where system inertia was the lowest among the three scenarios, while the hybrid configuration with a synchronous generator (scenario 3) provided the most stable and robust frequency performance. The findings support the recommendation to implement policies requiring rooftop PV systems to incorporate virtual inertia functionalities, ensuring greater system resilience as renewable energy penetration increases.

KEYWORDS — Distributed Generation, Virtual Inertia, Voltage Source Inverter, Single Phase Control, Renewable Energy.

I. INTRODUCTION

Nowadays, the development of renewable energy in electric power generation systems has become one of the problems that have drawn the attention of the researchers in the field of electric power system over the last few decades. Electricity generation in electric power systems is currently still dominated by fossil fuel oil and gas power plants. This type of fuel is considered as limited in availability, not cost effective, and has a high environmental carbon footprint [1].

This condition encourages research and application of technology in the field of power generation systems using renewable energy to develop rapidly to combat greenhouse gases and air pollution. Multiple energy and sustainability programs and events are supporting the realization of net zero emissions (NZE) globally to achieve environmental sustainability, such as Kyoto protocol 2005 and Paris agreement 2015. The United Nations, with Sustainable Development Goal (SDG) 7 targets to ensure that everyone has access to reasonable, dependable, clean, renewable and maintainable vitality [2]. The renewable vitality is the key to the feasible green vitality for human day-today living and normal environment with nonpolluting gas outflows to decrease climate alter.

However, the penetration of renewable energy generation systems will change the conventional electric generation system, which tends to transmit in one direction from generation to load, into a distributed generation system with the ability to inject electric power to the grid so that consumers will become prosumers [3]–[4]. This condition causes a shift in the electric power system, which is dominated by synchronous generator-based systems towards systems connected to inverters [1].

The high penetration rate of renewable energy in the electric power system can disrupt system stability due to decreased inertia in the electric power system [5]. The involvement of photovoltaic (PV) systems in the distribution network can also influence the voltage profile across the electricity grid. The high solar PV penetration will increase the voltage on the power distribution line, which can lead to overvoltage. On the other side, if a group of PV systems experiences a sudden drop in power output, it could lead to a voltage drop, which might activate the protective relays [6]. In a weak power distribution system, sudden change in power generation will drop the power frequency. This encourages researchers to control the voltage source inverter (VSI) to mimic the characteristics of an electric engine to enhance power system stability [7].

This condition encourages the development of research to apply electric engine simulations by performing VSI control to improve system stability in the future. Some countries, such as Indonesia, set the regulations for distributed generations connection to main utility grid so that the electrical parameters, such as frequency and voltage, are within the allowable limits and thresholds [8].

In general, research literature related to virtual inertia concepts to improve power system stability is a topic that has been running in recent years. The majority of generators connected to the electric power system are synchronous generators which use a lot of fossil energy fuels. Therefore, technology which controls the VSI at the initial stage intends to mimic the characteristics of synchronous generators [9]–[11]

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Imitation of synchronous generator characteristics applied to VSI have several challenges. One of them is the slow VSI response to changes in system frequency. In addition, because synchronization of generators highly depends on phase-locked loops (PLL) [10], dome VSI controls can mimic synchronous generator without the dependency to the PLL [12]–[14]. However, the VSI control mimicking the induction generator can provide give better response to the system frequency drift [15]-[17]. Current research has not considered control frequency involving systems with different renewable energy sources, giving an opportunity for the development of further research [18]. In addition, there are high harmonic problems in the system due to the massive penetration of power electronic equipment [19].

The application of inverter-based resources is also growing in recent years in Indonesia. As an archipelagic country with almost 17,000 islands spread near the equator, Indonesia has enormous potential to generate PV solar power. However, the provision of electricity on several islands still depends on diesel power plants, which have low investment costs but incur high operating costs and are not environmentally friendly because they emit CO_2. Based on the 2021–2030 Electricity Supply Business Plan (Rencana Usaha Penyediaan Tenaga Listrik, RUPTL), the Indonesian government through National Electricity Company as a state-owned electricity company is replacing diesel power plant in rural area or isolated area such as small islands with photovoltaic solar power or microgrid systems based on renewable energy such as wind, biomass and micro hydro [20].

Indonesia has set ambitious targets for renewable energy in its energy mix, aiming for 23% by 2025 and 31% by 2050. Rooftop solar panels play a key role in achieving these goals. The government has implemented several strategies to boost the adoption of rooftop solar energy. The regulation set by Ministry of Energy and Mineral Resources (MEMR) mandates net metering, allowing residential and commercial users to sell excess electricity generated from rooftop solar panels back to the grid. This encourages adoption by lowering electricity bills and providing a return on investment [21]. The government has streamlined licensing and permitting processes, fostering new business models and prosumers to install rooftop solar panels. In this sense, there are economic incentives for households' owners and industries to install rooftop solar panels, e.g. low-interest loans and subsidies provided by MEMR. The government offers tax holidays and reductions for companies investing in renewable energy, which can help reduce upfront costs for solar installations.

In some regions, pilot projects are currently implemented to encourage solar panel usage, particularly in areas with high energy demand, like Jakarta, West Java, and Bali. These energy projects also target remote and island communities with limited access to the grid. Indonesia's strategy aims to address its significant renewable energy potential while gradually reducing its dependency on fossil fuels, especially coal. However, challenges such as financing, grid stability, and policy enforcement remain crucial to scaling rooftop solar energy deployment nationwide.

Indonesia aims to install 3.61 gigawatts (GW) of rooftop solar capacity by 2025. This is part of the overall target for renewable energy to make up 23% of the total energy mix by the same year. The target for rooftop solar installation is projected to increase to 9.3 GW by 2030. This is a step toward achieving a larger goal of 31% renewable energy in the energy mix by 2050 [21].

This paper proposes system frequency response enhancement to inertia reduction due to the reduced role of synchronous generators by providing a virtual inertia simulation using inverters. The proposed method considers controlling a single-phase PV rooftop to represent the effect of a low-inertia rooftop system to the electrical power system. The proposed method was validated via an IEEE 13 bus system with three scenarios, which represent a PV/wind microgrid, and a battery as an energy storage system. The contribution of this work is a novel control architecture to provide virtual inertia of inverter-based power generation to maintain the quality of the frequency and amplitude of the voltage in the system.

The control scheme introduced in this work is specifically developed for single-phase PV inverter architectures. By omitting the need for a phase-locked loop (PLL), the method inherently supports standalone operation and enables direct regulation of voltage and frequency in isolated or islanded environments. This makes it highly applicable to small-scale, renewable-based single-phase microgrids, which are commonly implemented in rural and remote regions. Further investigation into broader applications and detailed performance analysis in practical microgrid scenarios is identified as a subject for future research.

Recent advances in commercial inverter technology have made single-phase units with virtual inertia and grid-forming capabilities widely available, especially for residential PV and small off-grid systems. These inverters are engineered to perform autonomous voltage and frequency regulation without relying on PLL-based synchronization, enabling stable operation directly in isolated and islanded microgrid environments. The control approach proposed in this study aligns with these existing technologies, demonstrating practical relevance beyond laboratory prototypes and responding to the needs of modern renewable energy applications.

II. RELATED WORKS

A. EFFECT OF HIGH RENEWABLE ENERGY PENETRATION TO SYSTEM STABILITY

The high penetration of renewable energy in the electric power system results in the tendency of the electric power system to shift towards a VSI-connected system, resulting in reduced system inertia [19]. This trend results in reduced system stability because the system frequency can be affected by a reduction in system inertia [20]. This encourages system inertia control to overcome the stability problem because additional virtual inertia is proven to help improve system stability as depicted in Figure 1.

VSI in the electric power system is dominated by wind farms connected to the grid [7]. This is because the majority of wind generator utilize variable speed wind turbines (VSWT), which uses a back-to-back converter as a link between the generator and the grid. This condition affects the stability of the system connected to VSWT. At the initial stage, VSI control is performed by simulating a synchronous generator called a synchronverter [10].

Synchronous generators are carried out as the basis for the simulation applied at VSI because the majority of generators connected to the electric power system are synchronous generators driven by fossil fuels. This makes the synchronization process carried out at the grid level simpler because the grid system only sees all power generation systems

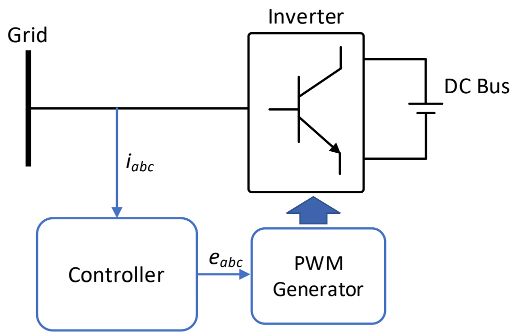

Figure 1. Inducverter for virtual inertia [5].

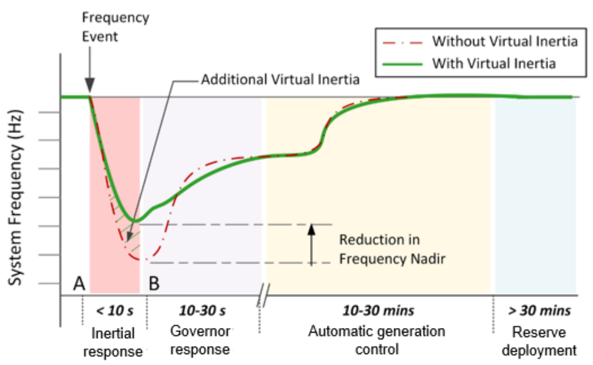

Figure 2. Effect of virtual inertia to the system stability [5].

as synchronous generators. In general, an overview of the synchronverter performance can be seen in Figure 2. Synchronverter consists of a power part, which is an inverter, and an electronic part as a controller.

A synchronverter, also known as a virtual synchronous generator, is an inverter that mimics the operation of a conventional synchronous generator. This makes it useful in integrating renewable energy sources like solar or wind power into the grid, while improving grid stability and compatibility with existing grid systems [22]. The core concept of a synchronverter is to employ control algorithms that replicate the behavior of a rotating synchronous machine.

A synchronverter mimics the voltage, current, and frequency characteristics of a conventional synchronous generator, which typically consists of a rotating mass (rotor) with inertia, producing AC power [23]. This behavior is achieved through control algorithms that simulate the physical characteristics of such machines.

Conventional synchronous generators inherently provide inertia due to their mechanical mass, which helps stabilize the grid during frequency fluctuations [24]. A synchronverter simulates this mechanical inertia electronically, responding to changes in grid frequency much like a physical generator. This capability is especially useful for grids with a high penetration of renewable energy, which generally lacks inertia.

A synchronverter continuously monitors the grid's voltage, frequency, and phase angle. It adjusts its output to match these parameters, just like a synchronous generator would when connected to the grid. This ensures smooth power delivery without causing disturbances or imbalances in the grid. Like a synchronous generator, a synchronverter uses droop control to regulate its active and reactive power output. Droop control adjusts power output based on changes in frequency (for active power) and voltage (for reactive power), maintaining balance between supply and demand in the grid.

The synchronverter adjusts its internal power angle, simulating the angular difference between the generator's rotor and the grid's frequency. This enables it to regulate the real power exchanged with the grid, simulating how a conventional generator responds to changes in load. By emulating the damping characteristics of a synchronous generator, the synchronverter helps in stabilizing oscillations in the grid. This feature is particularly useful in scenarios of sudden load changes or disturbances, as it can absorb or supply power accordingly.

A synchronverter can interface directly with renewable energy sources like PV (solar) systems or wind turbines. It converts DC power from these sources into AC and delivers it to the grid while ensuring that it behaves like a synchronous generator, enhancing grid stability [5].

Another advantage of the synchronverter is that it is easy to synchronize with terminal voltages. Synchronverter topology generally involves PLL so that the wave synchronization process can run well [25]. The basic form of synchronverter generally involves the use of PLL, however in its application the synchronverter can affect system stability [26]. Another development of this virtual synchronous generator implements VSI control using the swing equation which estimates the characteristics of a synchronous generator that responds to changes in frequency in the system [14].

Further development of this VSI control takes an induction generator as the basis which is called an inducverter [27]. The main feature of this control is using the characteristics of an induction machine as the basis for VSI control without involving the use of PLL in the algorithm. An overview of the inducverter performance can be seen in Figure 3. The inducverter has the ability to mimic the characteristics of an induction generator that can synchronize with the system without any information from the grid. In addition, the inducverter also has the ability to improve system frequency and also power regulation because the grid detects the DC-link as a virtual rotor.

An inducverter is a specialized inverter that operates based on the principles of an induction generator [28]. While the term "inducverter" is not widely used in traditional literature, it can be understood as an inverter that mimics the behavior of an induction generator, just as a synchronverter mimics a synchronous generator. Induction generators are typically used in wind turbines and other renewable energy systems.

An inducverter simulates the behavior of an induction generator, which operates by converting mechanical energy into electrical energy without needing an external excitation source, as in synchronous generators. It does this by adjusting its control algorithms to produce the output characteristics of an induction generator.

Unlike synchronverters, which simulate the inertia of synchronous generators, inducverters do not inherently provide virtual inertia. This is because induction generators do not provide inertia in the same way that synchronous generators do. However, this can be compensated for using external control mechanisms if needed.

Induction generators rely on reactive power from the grid to operate. In the case of an inducverter, the system must manage the reactive power, similarly, ensuring proper voltage regulation and stability. This is achieved by controlling the reactive power exchange between the inverter and the grid.

The inducverter controls both active and reactive power to maintain grid stability. Active power is controlled by adjusting

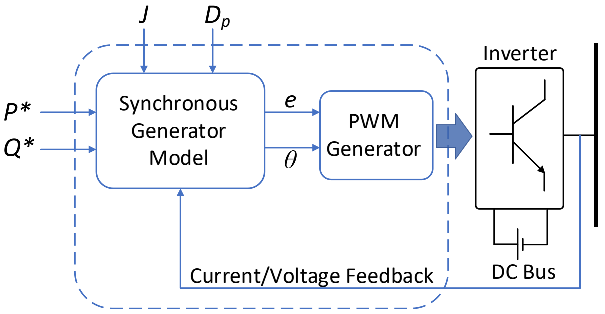

Figure 3. Synchronverter for virtual inertia [5].

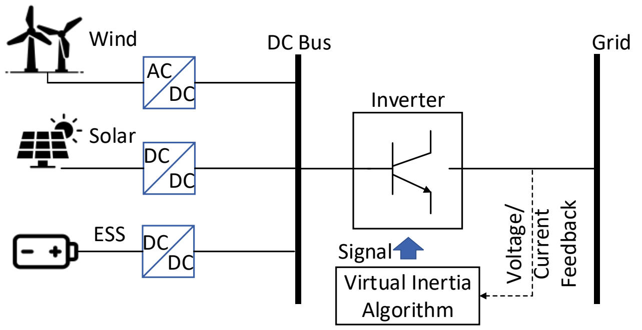

Figure 4. Energy conversion system with virtual inertia connected to a microgrid.

the real power output, while reactive power is managed to regulate voltage levels. This is particularly important in grids with a high penetration of renewable energy sources, such as wind and solar.

Like other types of inverters, an inducverter must remain synchronized with the grid's voltage and frequency. It continuously monitors grid parameters and adjusts its output to ensure that it remains in sync with the grid, thereby ensuring smooth power delivery and avoiding instability.

Induction generators are known for their ability to share loads dynamically, and inducverters emulate this behavior. When load or grid conditions change, the inducverter can adjust its output to match the required power without causing disturbances in the grid.

The development of the inducverter in a further stage uses a control scheme that observes an induction engine that has a rotor speed close to synchronous speed, which has its own starting capability [13]. This algorithm allows the amplitude and frequency of the voltage to be maintained without amplitude and frequency feedback from the system.

Research on this topic still has ample room for development because there are still opportunities to work on this VSI control, because the initial research carried out still experiences problems with other power quality (PQ) problems besides the frequency and voltage amplitude [29]–[31]. In future PQ problem, the spread generation power system will not only be limited to the frequency and voltage amplitude.

Recent advancements in virtual inertia control, single-phase inverter technology, and microgrid applications have been comprehensively documented in the literature. Robust overviews of virtual inertia support strategies, topologies, and practical implementations relevant to both single-phase and multi-bus networks have been reported, emphasizing their critical role in renewable energy integration [32]. The influence of virtual synchronous generators (VSGs) on frequency stability in contemporary power systems, especially with adaptive control designs under dynamic grid scenarios, has been comprehensively analyzed [33]. Additionally, ongoing innovations in virtual inertia—including configurable virtual impedance and enhanced resource modeling for isolated microgrids—have been discussed in detail [5]. These recent works underscore the continued evolution and deployment of inverter-based virtual inertia systems in alignment with current power system demands.

B. VIRTUAL INERTIA

Theoretically, virtual inertia is a combination of a control algorithm, a renewable energy source, and a battery system that simulates the inertia of a conventional generation system [5]. This virtual inertia system can be described simply as a group of renewable energy-based generation combined with a battery connected to the grid via a power electronics device as shown in Figure 4 [5]. This group of renewable-based generators is considered a microgrid. Microgrids, which are small-scale local networks with a high integration of distributed generation units and renewable energy technologies, can operate either connected to the main grid or independently in islanded mode [34].

The use of converters from AC to DC and DC to AC is a common thing in electricity generation that uses renewable energy [35]. This resulted in a large number of VSIs connected to the grid. VSI connection to the grid can result in decreased system inertia [19]. One solution to overcome this problem is to simulate the characteristics of the electric engine at VSI to obtain the characteristics of the electric machine on the system.

The first basic electric engine simulation at VSI is to simulate an induction generator at VSI. The selection of an induction generator was made because the induction generator is a generator that is mostly connected to the grid because of the large portion of the generator that uses fossil fuels [34].

III. PROPOSED METHOD

The proposed method in this research comprised a swing equation based three-phase synchronous generator to control a single-phase rooftop PV. Therefore, the three-phase synchronverter should be first modified into a single-phase synchronverter, as can be seen at Figure 5. As it can be seen, each phase is connected to the same amount of battery with controlled inverter. The performance of mechanical part of a synchronous generator can be stated in the commonly known swing equation, namely:

$$T_{mech} - T_{em} = 2H\frac{d\omega_r}{dt} + \Delta\omega_r \tag{1}$$

where T_{mech} is mechanical torque, Tem is load torque, ω_r is synchronous speed, D is damping and H is the inertia coefficient, which is represented by (2).

$$H = \frac{E_{kinetic}}{VA_{rated}} = \frac{J\omega_{ref^2}}{2VA''_{rated}}. \tag{2}$$

$E_{kinetic}$ is the kinetic energy produced by the generator, while J is a combination of the moment of inertia that is owned by the generator and turbine. By adjusting the coefficients using (2), the inverter produces different virtual inertia. As understood that power = torque x angular velocity, then the equation should be based on that basic. The angular velocity is obtained using the input from grid frequency and PLL algorithm.

The simplicity for this transformation is based on the a dq-transformation as in (3), where S represents any variable being transformed. The torque can be given in per unit as in (4). Therefore, both flux and current in three-phase system should be brought to the d-q area.

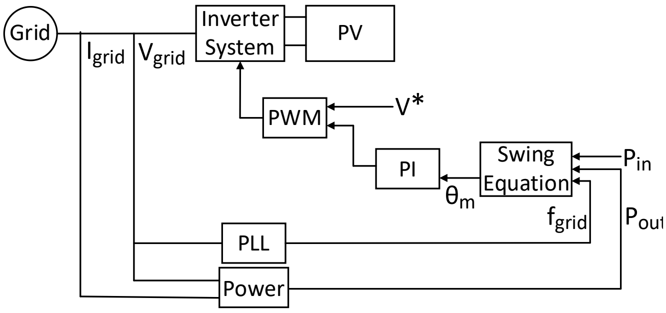

Figure 5. Single-phase swing equation.

$$\begin{bmatrix} S_d \\ S_q \\ S_0 \end{bmatrix} = \beta \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3} & -\sin(\theta + \frac{2\pi}{3} \\ \beta_0 & \beta_0 & \beta_0 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \quad (3)$$

$$T_e = (\Psi_d i_q - \Psi_q i_d). \quad (4)$$

In general, the single-phase model is derived by initially treating the single-phase machine as a two-phase machine, utilizing two of its stator windings. This is achieved by asymmetrically loading the three-phase machine, where load is applied to two of the three phases, leaving the third phase unloaded. A single-phase system is then created by grounding one of the two active phases. With one of the armature windings left unloaded, the three-phase currents are defined as:

$$i_a = 0, i_b = i, i_c = -i. \quad (5)$$

Then, the single-phase voltage will be: $u = u_b - u_c$. Using the dq-transformation, where β is notated as 2/3 to have d and q axis armature to have the same turns with single-phase winding, the currents of direct and quadrature axis can be obtained as:

$$i_d = \frac{2}{3} i \left[\cos\left(\omega t - \frac{2\pi}{3}\right) - \cos\left(\omega t - \frac{4\pi}{3}\right)\right] \quad (6)$$

$$i_q = -\frac{2}{3} i \left[\sin\left(\omega t - \frac{2\pi}{3}\right) - \sin\left(\omega t - \frac{4\pi}{3}\right)\right]. \quad (7)$$

The trigonometric equation can be simplified using identity method, where:

$$\begin{aligned} \cos\left(\omega t - \frac{2\pi}{3}\right) - \cos\left(\omega t - \frac{4\pi}{3}\right) &= \left[\cos(\omega t)\cos\left(\frac{2\pi}{3}\right)\right. \\ &\quad \left. + \sin(\omega t)\sin\left(\frac{2\pi}{3}\right)\right] \\ &\quad - \left[\cos(\omega t)\cos\left(\frac{4\pi}{3}\right)\right. \\ &\quad \left. + \sin(\omega t)\sin\left(\frac{4\pi}{3}\right)\right] \end{aligned} \quad (8)$$

The current of direct quadrature axis can be notated as:

$$i_d = \frac{2}{\sqrt{3}} i \sin\omega t \quad (9)$$

$$i_d = \frac{2}{\sqrt{3}} i \cos\omega t. \quad (10)$$

Another variable that is used to support (1) is flux linkage, where it is associated with the voltage equation. Equation (11) is a stator voltage equation of a single-phase machine.

$$u = R.i + L_l \frac{di}{dt} + \frac{d\psi}{dt} \quad (11)$$

where $\psi = N_{1\,phase} \phi \cos\left(\theta t - \frac{\pi}{2}\right)$.

As stated, single-phase machine equation can be obtained using two single-phase machines, then stator voltage for those two phases will be:

$$u_b = R_{a(3\,phase)} i_b + L_{l(3\,phase)} \frac{di_b}{dt} + \frac{d\psi_b}{dt} \quad (12)$$

$$u_c = R_{a(3\,phase)} i_c + L_{l(3\,phase)} \frac{di_c}{dt} + \frac{d\psi_c}{dt}. \quad (13)$$

Knowing that $i = i_b = -i_c$ and $u = u_b - u_c$, the single-phase voltage can be stated as in (14).

$$u = 2R_{a(3\,phase)} i + L_{l(3\,phase)} \frac{di}{dt} + \frac{d(\psi_b - \psi_c)}{dt}. \quad (14)$$

The flux linkage can between those two phases can be expressed as:

$$\psi_b = N_{3\,phase} \phi_a \cos\left(\theta(t) - \frac{2\pi}{3}\right) \quad (15)$$

$$\psi_c = N_{3\,phase} \phi_a \cos\left(\theta(t) + \frac{2\pi}{3}\right). \quad (16)$$

From (15) and (16), $(\psi_b - \psi_c)$ can be written as:

$$\psi_c = N_{3\,phase} \phi_a \cos\left(\theta(t) + \frac{2\pi}{3}\right). \quad (17)$$

Then, the voltage equation of single-phase machine will be:

$$\begin{aligned} u = 2R_{a(3\,phase)} i + 2L_{l(3\,phase)} \frac{di}{dt} + \\ \sqrt{3} N_{3\,phase} \frac{d}{dt}\left(\phi_a \cos\left(\theta(t) - \frac{\pi}{2}\right)\right). \end{aligned} \quad (18)$$

Using the characteristic of 90° alignment from the mentioned two phases, the equation is stated as:

$$\begin{aligned} u = 2R_{a(3\,phase)} i + 2L_{l(3\,phase)} \frac{di}{dt} \\ + \sqrt{3} \frac{d}{dt}\left(\psi_a\left(\theta(t) - \frac{\pi}{2}\right)\right) \end{aligned} \quad (19)$$

It can be confirmed that the resistance of single-phase armature winding is two times of the three-phase armature winding, while the flux linkage of single-phase winding can be stated as:

$$\psi = \sqrt{3}\psi_a. \quad (20)$$

The proposed method was tested in a simple test system to see the effect of the virtual inertia algorithm generated by the single-phase swing equation system. The test system can be seen at Figure 6. The test system was used to compare synchronverter, VSG, and without virtual inertia performance when 2 kW load switch was closed. The selection of a 2-kW energy storage system (ESS) and an 18 kVA inverter was based on the need to represent a realistic small-to-medium-scale distributed energy resource typically used in low-voltage distribution systems. The 18 kVA inverter was chosen to ensure adequate power conversion capability to handle both the ESS and variable renewable sources like PV and wind under different operating scenarios.

Inverter-based resources (IBRs), which are widely deployed as interfaces for renewable energy systems, typically employ insulated gate bipolar transistors (IGBTs) due to their superior performance characteristics. The advantages of IGBTs include minimal harmonic distortion, high-speed switching, and efficient control capabilities, making them well-suited for enhancing the reliability and effectiveness of modern power electronic converters in renewable energy applications [36]

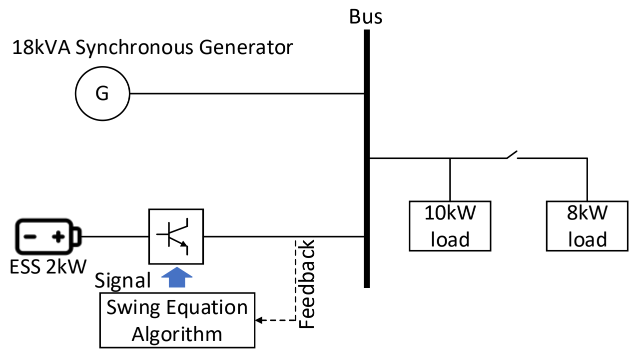

Figure 6. Comparison between virtual inertia system and real generator.

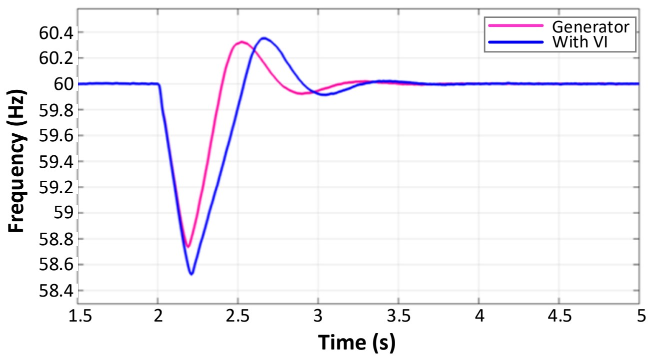

Figure 7. Frequency response between virtual inertia system and real generator.

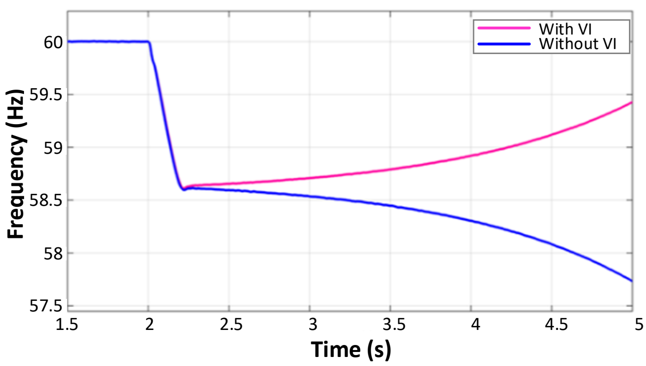

Figure 8. Frequency response with virtual inertia and without virtual inertia.

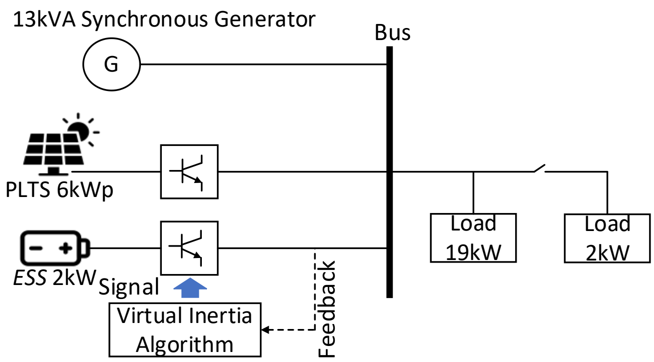

Figure 9. Experimental verification for proposed method.

It can be seen at Figure 7 that the proposed virtual inertia method gives a similar response compared to the real generator, with a bit late response to the real one. At 2 s, the 8kW load at the load side was connected to the system. Therefore, the system frequency dropped because of the change of load. When the generator was connected to the system, it was easier for the system to maintain the frequency because of the inertia of the generator.

However, when the inverter was connected to the system, the inverter did not have any inertia. The system faced difficulty in maintaining the frequency. When virtual inertia was introduced into the system, the response would mimic that of the generator. Nonetheless, the real inertia would give a better response than virtual inertia. The contribution of virtual inertia became more apparent when a critical point of load shedding was found, when the system barely fell after the event. As can be seen in Figure 8, a slight virtual inertia injected to the system may help to maintain the frequency to return to normal state. The performance of the proposed method was validated using a test system proposed at [37], as can be seen in Figure 9.

The test system was used to compare the synchronverter, VSG, and without virtual inertia performance when the 2 kW load switch was closed. The experimental verification compared the minimum frequency when an event occurred, the maximum rate of change of frequency (RoCoF), settling time, peak power delivered, as well as energy exchanged with the system. In the proposed method, (1) was compared to the previous method, as can be seen at Table I.

From the comparison, (1) has a similar performance compared to another method mentioned in the experiment. The proposed method also fulfilled International Organization for Standardization (ISO) standard 8528-5 for generators islanded/isolated, where frequency should be kept between

TABLE I
TECHNICAL SPECIFICATIONS

Parameters	No Virtual Inertia	Synchronverter	VSG
Minimum frequency	57.3 Hz	58.1 Hz	58.3 Hz
Maximum RoCoF	1.9 Hz/s	1.5 Hz/s	1.7 Hz/s
Settling time	11.3 s	13.2 s	17.9 s
Peak power delivered	0 W	1,825 W	1,929 W
Energy exchanged	0 W	0.8 W	4.9 W

±1.5 Hz. However, it could not satisfy the standard at the settling time, where the frequency should return to normal within 10 s. The standard also requires maximum RoCof to be 0.6 Hz/s. The proposed method still satisfied North American Electric Reliability Corporation (NERC) recommendation for control, where the recommendation states that the generator should be disconnected when the frequency falls below 57 Hz.

IV. SYSTEM CONFIGURATION

The proposed method was implemented on the IEEE 13 bus test system, featuring a total connected load of 11 MW and 3 MVar. In this system, a wind turbine with an output capacity of 7.5 MW and a PV installation generating 3 MW were integrated. The battery and inverter capacities were varied in the simulation, as illustrated in Figure 10. The IEEE 13 bus system was chosen because it contains various distribution network components, including single-phase and unbalanced loads, making it suitable for testing smart grid algorithms and renewable integration.

Based on [38], the simulation of a single-phase synchronverter integrates specific electrical and control

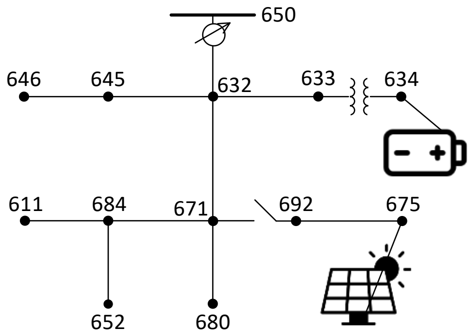

Figure 10. Scenario 1.

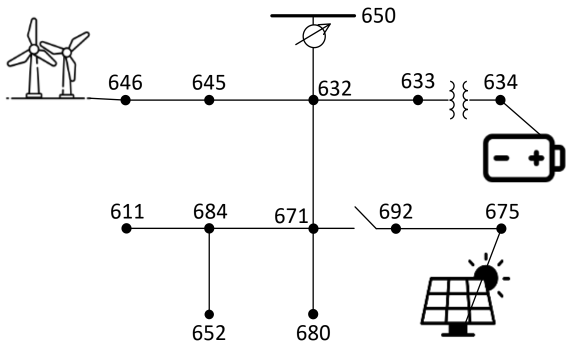

Figure 11. Scenario 2.

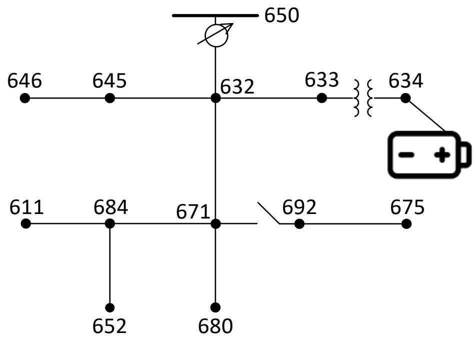

Figure 12. Modified IEEE 13 Bus System.

parameters to accurately emulate synchronous generator dynamics. The parameters include a grid voltage of 230 V, filter inductance of 2 mH, filter capacitance of 4.7 μF, and a virtual inertia constant ranging from 0.1 to 1 s. The damping and droop control parameters were chosen to ensure an underdamped response and appropriate power sharing, aligned with typical synchronous generator behavior. For this study, the synchronverter system was further tailored to operate in conjunction with the IEEE 13 bus distribution system, with parameter values and control settings adjusted to ensure compatibility and reliable grid integration within this benchmark network.

By changing the different virtual inertia with the same energy source, it can be seen that the frequency reached the same point when it reached a steady-state point. The distinct virtual inertia determined the nadir, which occurred right after the system disconnected from the main bus. Virtual inertia was obtained by controlling the inverter to simulate synchronous machine characteristics. Synchronous machines were chosen because the VSG is the most commonly used characteristic for controlling inverters generating virtual inertia. The resulting virtual inertia could be adjusted using two ways, namely by changing the control method, which had different characteristics, and by changing the inertia parameter in the control. When the IEEE 13 bus system was disconnected from the main bus, the inertia compensated for changes in system frequency.

The energy source installed at point 634 was adjusted to a different magnitude to match the load on the IEEE 13 bus. The IEEE 13 buses had a total installed load of 11 MW and 3 MVar. Three scenarios were developed to determine the effect of low inertia.

Scenario 1 is suitable for Indonesia, as Indonesia's vast archipelago, consisting of over 17,000 islands, presents both a challenge and an opportunity when it comes to energy generation. Many of the smaller, remote islands are still heavily reliant on diesel-powered generators, which are costly to operate, environmentally damaging, and dependent on imported fuel. Solar power, especially rooftop solar panels and microgrids, offers a promising alternative that could transform energy access across these islands.

Solar power is a critical solution for Indonesia's energy challenges, particularly for the remote and isolated islands that still rely on diesel generators. By investing in solar energy—especially decentralized rooftop solar systems and microgrids—Indonesia can reduce fuel dependency, lower carbon emissions, and provide clean, reliable, and cost-effective electricity to its people.

Scenario 2 can be efficient for coastal and island country. Many island countries, particularly those located near the equator (like Indonesia), receive abundant sunlight throughout the year, making them ideal for solar energy generation. Regions like Southeast Asia, the Caribbean, and the Pacific islands experience high levels of solar irradiance. Many island countries are surrounded by oceans, which provide excellent opportunities for wind energy due to strong and consistent coastal winds. Offshore wind farms, in particular, have significant potential for generating electricity in island nations.

Both solar and wind can be complementary energy sources, helping island nations reduce costs, improve energy security, and transition to a more sustainable future. However, this transition will require investments in infrastructure, policy support, and capacity-building to overcome the challenges and fully harness the potential of renewable energy.

However, in most island countries, the electrical power system is still dominated by diesel energy.

Finally, scenario 3 is used to illustrate the combination of renewable energies and synchronous generator.

A. SCENARIO 1

In this scenario, another renewable energy source, which was PV, was connected to bus 675, as can be seen at Figure 11. Solar panel was modeled as battery, to supply the reactive power needed by system. In the time of event, node 650 was cut from the main grid. Sources from nodes 634 and 675 were sufficient to supply the loads.

B. SCENARIO 2

In this scenario, the renewable sources were added at node 646 and 675, as can be seen at Figure 12. Solar panel was modeled as battery, to supply the reactive power needed by system. In the time of event, node 650 was cut from the main grid. Sources from nodes 646, 634, and 675 were sufficient to supply the loads.

C. SCENARIO 3

In the 3rd scenario, the solar panel was added at node 675, synchronous generator was connected to node 646, as can be

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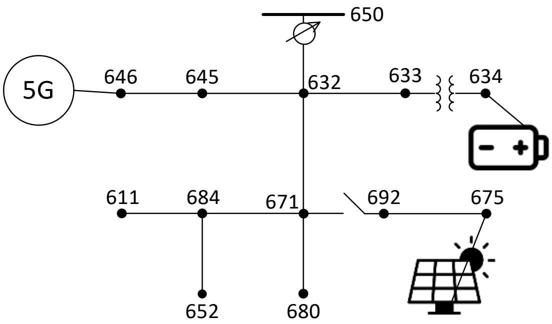

Figure 13. Scenario 3.

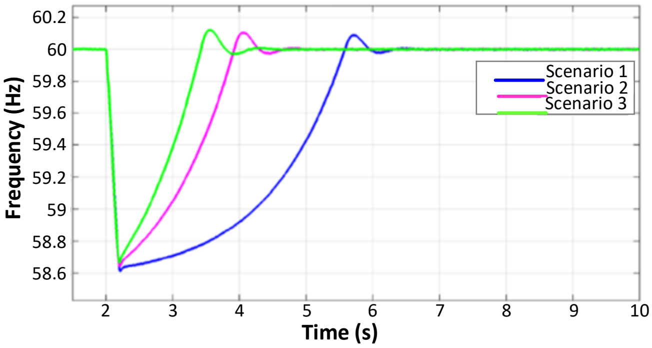

Figure 14. Frequency response between scenarios.

seen at Figure 13. Solar panel was modeled as battery, to supply the reactive power needed by system. In the time of event, node 650 was cut from the main grid. Sources from nodes 646, 634, and 675 were sufficient to supply the loads.

As comparison, these three scenarios are possible cases that may occur when a microgrid system is connected to main grid. The microgrid may connected to solar farm, wind farm, or synchronous generator. Therefore, the frequency response between those sources may be compared.

D. RESULTS

Each scenario was modeled using MATLAB/Simulink model. Scenario 1 is the representation of a distributed generation with connected solar panel in the microgrid system. This scenario represents the lack of inertia in the microgrid system. Scenario 2, where a wind farm is connected in bus 646, represent a microgrid system with better inertia than the 1st scenario. Wind turbines, especially type 3 (doubly fed induction generators, DFIG) or type 1/2 (squirrel cage induction generators), can contribute electromechanical inertia to the grid. At the scenario 3, a synchronous generator is connected to the bus 646 to represent better inertia at system which provides mechanical inertia to the electrical system.

As shown in Figure 14, without enough inertia at inertial response time range, the frequency failed to return to the stable frequency. This indicates that the initial 10 s are a critical period for the system to restore its frequency to the nominal value. The poorest frequency response was observed at scenario 1, where the system inertia was the smallest out of three scenarios. Meanwhile, the best frequency response was achieved in scenario 3, where synchronous generator was connected to the microgrid system.

V. RECOMMENDATION

In the future, as rooftop PV penetration continues to grow, especially in microgrid systems, the overall system inertia will decrease. This reduction in inertia can negatively impact the system's ability to maintain frequency stability during disturbances. In particular, microgrids with a high share of single-phase rooftop PV installations are more vulnerable to instability due to their limited inherent inertia.

To address this challenge, it is recommended that a regulatory policy be implemented requiring all grid-connected rooftop PV systems to incorporate virtual inertia mechanisms within their inverters. Specifically, inverters should be equipped with VSG functionalities, which can be implemented through cost-effective control systems. This approach will enable PV inverters to provide fast frequency support and mitigate the severity of frequency drops following disturbances.

Such a policy will not only enhance system stability and resilience but also support the safe and reliable integration of distributed renewable energy sources in both microgrids and larger distribution networks. Over time, this measure will help maintain grid performance as renewable energy penetration increases.

VI. CONCLUSIONS

The simulation results demonstrate that incorporating virtual inertia in inverter systems connected to a load network effectively provides the necessary inertia to stabilize the system during load variations. The implemented control strategy successfully maintains frequency quality and voltage amplitude, ensuring stable system operation under dynamic conditions. These findings highlight the critical role of virtual inertia in supporting grid stability, especially in renewable energy-dominated systems. Therefore, this study can serve as a foundation for developing policies that mandate the integration of virtual inertia mechanisms in all renewable energy systems connected to the grid, enhancing overall power system stability and resilience.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS'CONTRIBUTIONS

Conceptualization, Fikri Waskito and Fransisco Danang Wijaya; methodology, Fikri Waskito and Fransisco Danang Wijaya; software, Fikri Waskito and Eka Firmansyah; validation, Fransisco Danang Wijaya; formal analysis, Fikri Waskito; investigation, Fikri Waskito; resources, Fransisco Danang Wijaya and Juan C. vasques; data curation, Fikri Waskito; writing—original draft preparation, Fikri Waskito; writing—review and editing, Fransisco Danang Wijaya, and Eka Firmansyah; visualization, Fikri Waskito; supervision, Fransisco Danang Wijaya and Eka Firmansyah; project administration, Fransisco Danang Wijaya.

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