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Control Approach for Photovoltaic Inverters Enhancing the Primary Grid Using the Virtual Synchronous Generator Concept

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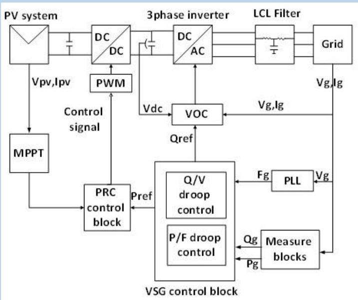
Abstract: This paper presents a control scheme for virtual synchronous generators (VSGs) in PV inverters, designed to enhance grid frequency and voltage. Through the skillful management of active and reactive power, this control scheme enables PV inverters to interact seamlessly with the main grid in response to grid events, including voltage and frequency fluctuations. The VSG controller is implemented using Matlab Simulink, and its effectiveness is rigorously assessed under various scenarios in a case study involves a 50 kVA rated PV inverter, a 50 kW rated PV system, and a 220 V grid phase voltage. In conditions of low power generation from the PV system (solar radiation of 200 W/m²) and high load power (120 kW and 37.5 kVAr), the load voltage drops to 202.4 V. The VSG controller successfully raises the grid voltage by 17.6 V, stabilizing it at 220 V. Conversely, in scenarios of high PV power generation (solar radiation of 1000 W/m²) and low load power (20 kW and 7.5 kVAr), the grid voltage surges by 10 V, reaching 230 V. The proposed control strategy adeptly fine-tunes the voltage, ultimately stabilizing at 220 V. Additionally, when the frequency deviates within ±0.4 Hz from the nominal frequency of 50 Hz, the proposed control effectively restores the frequency to its nominal value.



Keywords: Virtual synchronous generator (VSG), PV inverter. frequency regulation, voltage regulation, power system stability.

Introduction

Photovoltaic (PV) systems offer a sustainable energy solution with numerous advantages, including zero greenhouse gas emissions, lower operational costs, and reduced reliance on fossil fuels (1). The surge in PV system deployment on the utility grid is driven by these benefits and the escalating demand for clean energy. However, integrating PV systems with high penetration levels into the grid presents challenges, notably voltage and frequency fluctuations that impacts grid stability and potentially harm electrical devices (2). One promising solution to address these issues involves the utilization of PV inverters in the form of virtual synchronous generators (VSGs) (3). VSGs introduce an innovative method to manage the variability inherent in PV systems and ensure grid stability by emulating the synchronous behavior of conventional generators (4). Extensive studies have demonstrated the effectiveness of VSGs in supporting the grid against voltage and frequency fluctuations stemming from power variations in PV systems. For instance, researchers successfully employed a VSG to govern the reactive power and voltage of a PV system, showcasing its prowess in sustaining grid stability (5). Similarly, another study harnessed a comparable approach to regulate voltage and frequency variations induced by a high-penetration PV system (6). The integration of VSGs within PV systems yields several advantages. Firstly, VSGs offer swifter response times and superior control over power flow (7). Secondly, VSGs can also reduce the need for expensive grid infrastructure upgrades (7). Finally, they facilitate a more substantial integration of PV systems onto the grid without compromising its stability (8).

Research Methodology

The research begins with a comprehensive literature review to identify the state-of-the-art techniques employed in virtual synchronous generator (VSG) systems. Following this, the objectives of the study are distinctly outlined, primarily focusing

on leveraging the PV inverter as a synchronous generator to provide ancillary services for the grid, and to enhance grid support through voltage and frequency improvements. Subsequently, a detailed mathematical model of the PV system and the inverter is developed. The VSG concept is then seamlessly integrated into the inverter control scheme, involving the emulation of synchronous generator behavior, inclusive of voltage and frequency control. An intricately designed control algorithm, rooted in the VSG principle, is formulated. The control algorithm is further implemented using the Simulink Matlab software for software-based simulation. Rigorous simulations are conducted to evaluate the performance of the proposed control approach. These evaluations encompass critical parameters such as voltage and frequency regulation. The simulation results are then meticulously analyzed to ascertain the effectiveness of the control strategy.

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Proposed VSG of PV Inverter

The integration of virtual synchronous generator (VSG) technology in photovoltaic (PV) systems has received significant attention in recent years (6). The VSG controls both active and reactive power to support voltage and frequency stability (9), (10). To support voltage stability, the VSG control adjusts the reactive power output of the inverter. When the grid voltage is low, the inverter increases its reactive power output to supply the required reactive power and raise the voltage. Conversely, when the grid voltage is high, the inverter absorbs reactive power output to maintain the voltage within acceptable limits (7). To support frequency stability, the VSG control adjusts the active power output of the inverter. When the grid frequency is low, the inverter increases its active power output to supply the required power and raise the frequency. Similarly, when the grid frequency is high, the inverter reduces its active power output to maintain the frequency within acceptable limits. In the case of a PV inverter, it may be necessary to deliver or absorb reactive power even when operating under rated power due to low solar radiation. The VSG control can be used to deliver or absorb the required reactive power to maintain voltage stability. For active power control, a battery can be used to absorb or deliver power depending on the measured frequency. However, the cost of a battery is high, and so operating the inverter in reserve power mode may be required. The concept of reserve power is applicable in the smart grid context since some power inverters are smart and controlled by a central unit. The grid operator can reduce the output active power from these inverters if it exceeds the load requirement, and in normal situation the operator can restore the inverter to maximum active power.

In reserve power mode, the inverter controller maintains a certain amount of power reserve to quickly respond to changes in power demand. When required to deliver active power, the inverter works in maximum power no reserve mode. Conversely, when required to reduce active power, the inverter increases the reserve power to reduce the active power output. The VSG topology without energy storage systems, known as power reserve control (PRC), depends on the concept of power reserve control to stabilize system frequency. This method allows the PV system to regulate its real power output in real-time and preserve a certain amount of up or down-regulation capability. The topology used and discussed in this paper, along with its control scheme, is depicted in Figure 1.

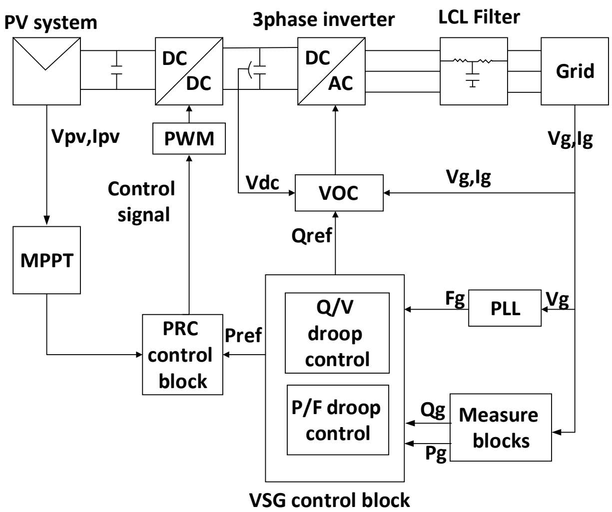


Figure (1): Block diagram of PV with power reserve control.

In this control approach, the voltage and current in three phases on the grid side undergo measurement and transformation from the ABC reference frame to the DQ reference frame using Park's transformation. This process simplifies computations and allows for independent regulation of the D and Q axes. The next step involves the computation of active power, reactive power, and grid frequency. These values serve as input signals in both the Virtual Synchronous Generator (VSG) and Power Resonant Controller (PRC) blocks, facilitating the precise delivery of active and reactive power to support the grid. The reference current, Id_ref, is determined by the DC-voltage control in accordance with PRC regulations, while Iq_ref is determined based on the proposed Q-V droop control.

A. Reactive power control

When the measured voltage is higher than the reference voltage, the inverter absorbs Q. On the other hand, when the measured voltage is lower than the reference voltage, the inverter injects Q into the system. This helps to increase the system's reactive power and raise the voltage level.

The synchronous generator's output voltage is directly linked to the reactive power it supplies. Illustrated in Figure 2 is the curve depicting the relationship between reactive power and voltage, which serves as a reference for computing the necessary reactive power corresponding to the measured grid voltage. By utilizing both Figure 2 and Equation (1), we ascertain the reactive power needed to maintain the load voltage at 220 V. This computed value is subsequently compared against the inverter's capability to either supply or absorb reactive power, as indicated in the flow chart presented in Figure 3.

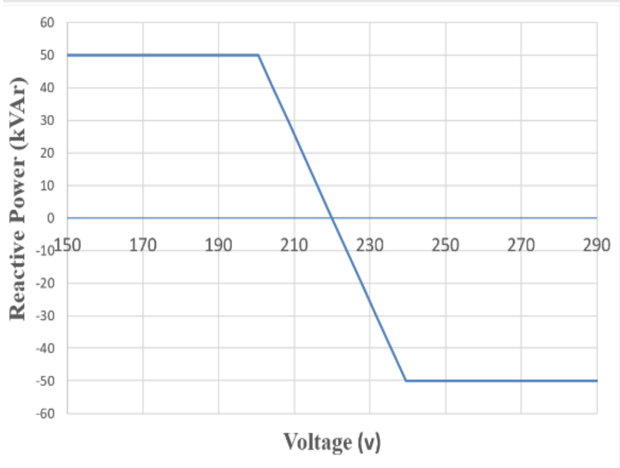


Figure (2): Output voltage/output reactive power curve.

$$Q_{req} = \frac{Q_{max}}{0.08 * V_{nom}} * (v_{nom} - v_g) \qquad (1)$$

where

Q_{req}: the required reactive power that is needed to regulate the voltage.

V_{nom}: is the nominal AC voltage.

V_g: is the voltage measured on the grid side.

The reactive power output of a VSG is limited by the available capacity of the inverter. The calculation of the reference reactive power is based on the flow chart shown in Figure 3, where Q_{av} is the available reactive power the inverter can supply or absorbed.

B. Active power control

In a PV inverter, it is important to deliver the active power generated from PV panels to the grid in order to avoid losses. However, in certain situations, it may be necessary to reduce the active power output even if the PV panels are generating power. For example, during times of high PV generation and low demand, the utility may request that the VSG reduce its active power output in order to prevent over generation and grid instability. In this situation, the VSG would operate in reserve power mode, where it maintains a certain amount of power reserve to quickly respond to changes in power demand. In reserve power mode, the VSG controller increases the VSG adjusts its active power output accurately, which helps to stabilize grid by maintaining grid frequency within permissible limits.

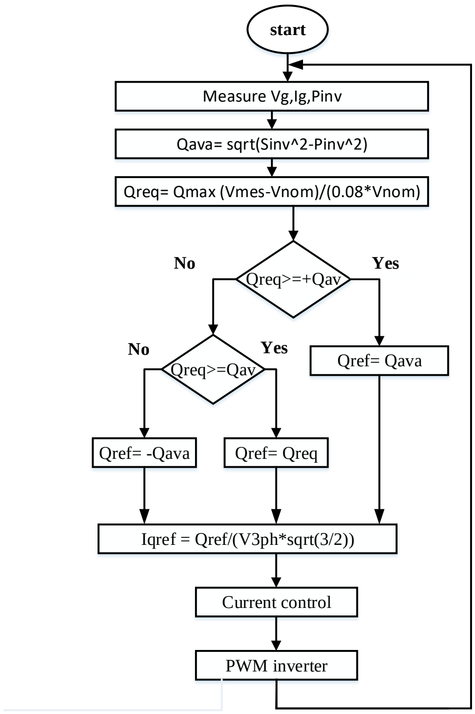


Figure (3): Flowchart of reactive power control.

The regulating frequency achieved by injection or absorption of active power to counteract deviations. In case the measured frequency exceeds the nominal value, it indicates an excess of power in the grid. Therefore, the VSG reducing active output power and increasing the reserve power of the PV inverter, thereby restoring the frequency to its nominal value. Meanwhile, if the measured frequency falls below the nominal value, signifying a power deficit in the grid, the VSG controller responds by increasing the active power output of the inverter to maintain the desired frequency. Consequently, it may be necessary to reduce the reserve power to ensure the inverter delivers the maximum power generated by the PV panels.

The widely employed PRC mode proves effective in managing both reactive power and active power output in VSGs. This approach enhances grid stability and reduces reliance on costly energy storage systems (ESSs), resulting in overall cost reduction. The integration of VSGs with PRC mode facilitates the seamless assimilation of photovoltaic (PV) energy into the power grid. Nevertheless, meticulous management of reserve power is crucial in ensuring system stability and reliability. Compliance with relevant regulations and standards, coupled with consideration of external factors such as solar radiation and frequency deviation, enables the achievement of efficient and effective power support for the grid.

The reserve power of PV systems is a critical parameter that necessitates meticulous management. Regulations and standards, such as the 10% reserve power limit in China (11), impose specific constraints on the reserve power. Additionally, external factors like solar radiation and frequency deviation also impact the reserve power. Proper management of the reserve power through VSG control ensures stable and reliable grid operation.

Adjusting the reserve power is contingent upon the measured grid frequency. In the case of high frequency, increasing the reserve power allows for a reduction in the output power of the PV system. Conversely, during periods of low frequency, reducing the reserve power or setting it to zero enables the maximum power generated by the PV system to be supplied to the grid.

If the system frequency experiences an increase, there will be a corresponding rise in ΔP, capped at a maximum increment of 30% of Pmpp. Conversely, in the event of a decrease in system frequency below the nominal level, ΔP will decrease, limited to a maximum reduction of 10% of Pmpp as indicated in Equation (2).

$$\Delta P_{ref} = \begin{cases} 30\%\ \mathrm{Pmpp}\,, & P_{fs} < -20\%\ \mathrm{Pmpp} \\ \Delta P - P_{fs}\,, & -20\%\ \mathrm{Pmpp} \le P_{fs} \le \Delta P \\ 0\,, & P_{fs} \ge \Delta P \end{cases} \quad (2)$$

where

ΔP_{ref}: is the reference reserve power

P_{fs}: is the reference power for frequency support.

The flowchart of the grid frequency support is shown in Figure 4, where F_{mes} is the measured frequency and F_{nom} is the nominal grid frequency.

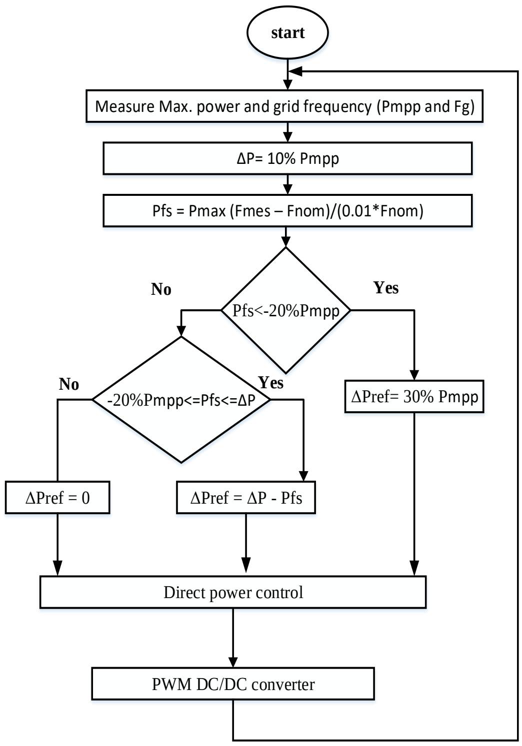


Figure (4): Flowchart of active power control.

Case Study Description

The inverter used in this paper is a three-phase grid inverter with a capacity of 50 kVA is used to connect the PV system to the grid. The LCL filter was used to connect the inverter to the grid and eliminate current ripples from the pulse width modulation (PWM). The inverter was equipped with a maximum power point tracking (MPPT) controller to regulate the DC side of the inverter by using a DC-DC boost converter. The duty ratio of the boost converter changes according to the MPPT Perturb and Observe (P&O) technique to obtain the maximum power from the PV panels and maintain a constant DC voltage input to the inverter of 800 V which is suitable for 400V line to line voltage of PV three phase inverter (12). The control of active power in a photovoltaic (PV) inverter is a complex process that involves several components and techniques as shown in Figure 5, the DC link controller, which regulates the DC voltage to remain constant around 800 volts. To achieve this, a PI controller is used to compare the actual DC voltage to the reference voltage and adjust the duty cycle of the DC-DC boost converter accordingly. Another crucial component is the current controller, which uses id and iq references to control the output current of the inverter. The control of active power is managed by the id reference, while the reactive power is managed by the iq reference. To minimize distortion and ripple in the current waveform, the current controller guarantees that the output current closely tracks the reference current.

Moreover, an important aspect of PV inverter control is vector-oriented control (VOC), which allows the inverter to control both the amplitude and phase of the output voltage. This is essential for grid-connected applications where the inverter synchronize with the grid by using phase locked loop (PLL) (13). In VOC, the inverter output voltage is transformed into a rotating reference frame represented by two components: a quadrature component Iq and an in-phase component Id. The id component controls the active power of the inverter, while the iq component controls the reactive power. Typically, the Iq reference is typically set to zero in grid connected inverter, while the Id reference is adjusted to control the output active power. However, in the case of a VSG the active and reactive power of the inverters controlled by Iq and Id references according to voltage and frequency, respectively.

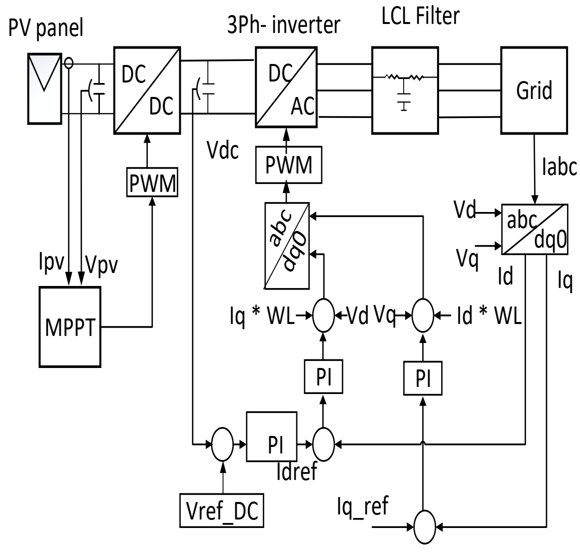


Figure (5): PV inverter control based on VSG.

Table 1. shows the parameters of transmission line, filter, the PI controllers, and VSG control.

Table (1): Simulation parameters.

V nominal (line to line)	380 V
F nominal	50 Hz
R (transmission line)	0.015 ohm/km
L (transmission line)	(4.32/1000) H/km
Distance	0.2 km
DC voltage	800 V
Rated power of the inverter	50 kVA
L filter	540e-6 H
C filter	54.8 μF
Q-V droop coefficient	0.08
kp & ki of the current controller	kp = 0.005 , ki = 1
kp & ki of DC-link voltage control	kp = 0.15 , ki = 80

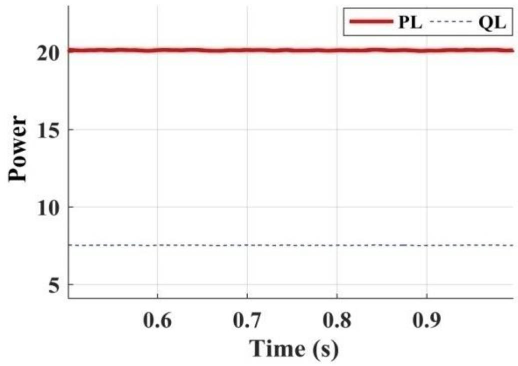
Simulation Results and Discussion

In order to validate the proposed control strategy, it is important to test it under various scenarios and conditions that can occur in a real power grids. These scenarios include voltage rise, voltage drop, and frequency deviation due to changes in the power demand and the variability of PV generated power. Therefore, simulating these scenarios the performance of the control strategy can be evaluated to ensure reliable and efficient operation of the PV inverter system.

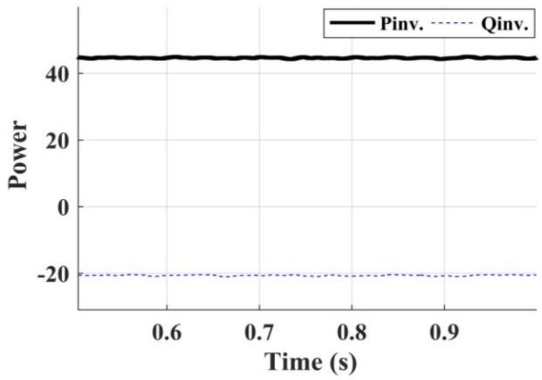
A. Reactive power control mode

Reactive power control is used to support the grid voltage, in the case the PV generated power exceeds the load demand, the grid voltage can rise due to reverse power flow. This increase in voltage affects the system stability. In this scenario, the VSG can take action to absorb reactive power and regulate the voltage. The suggested control approach aims to mitigate the impact of reverse power flow in the grid. This is achieved by configuring the inverter to emulate the behavior of a synchronous generator, enabling it to absorb a specific portion of reactive power from the grid. This action is taken to maintain the load voltage at its designated nominal level. Figure 6 illustrates that the active power generated by the PV system, amounting to 45 kW, surpasses the actual load power of 20 kW. This surplus results in a reverse power flow and subsequently leads to a voltage elevation up to 230 V.

To counteract this, the control strategy makes the inverter absorb 20 kVAr of reactive power, resulting in the voltage returning to its nominal value 220V as shown in Figure 7.



a- Active and reactive load power.



b-Inverter output power.

Figure (6): Load and inverter active (kW) and reactive (kVAr) power (reactive power absorb).

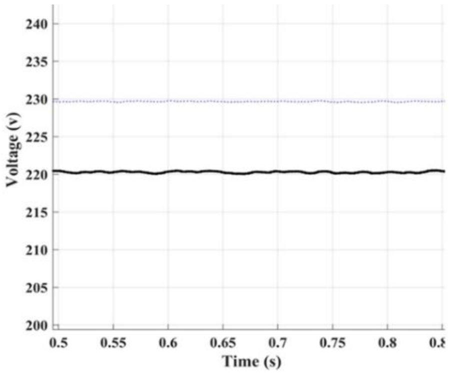
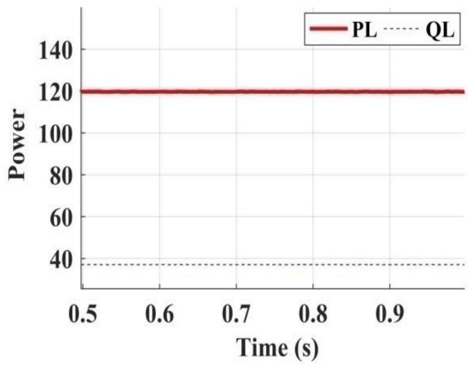
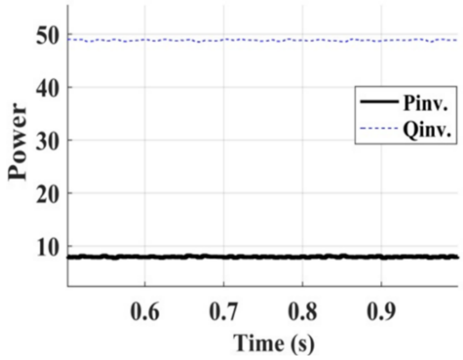


Figure (7): Voltage rise improvement.

During periods of low solar radiation, the power generated by the PV system might not be enough to meet the load demand, which can result in a drop in voltage near the load. To counter this, the VSG steps in to provide reactive power. This enhances the grid's voltage and ensures stability for the connected loads. Achieving this involves injecting reactive power into the grid to compensate for the voltage drops, a process demonstrated in Figure 8. For instance, when the active power of the load and PV system stood at 120 kW and 8 kW respectively, the proposed control strategy called for the PV inverter to deliver 49 kVAr of reactive power. This successfully raised the voltage from 202V back to 220V, as depicted in Figure 9.



a- Load power, P (kW), Q (kVar)



b-Inverter output power P (kW), Q (kVar)

Figure (8): Load and inverter active (kW) and reactive (kVAr) power (reactive power support).

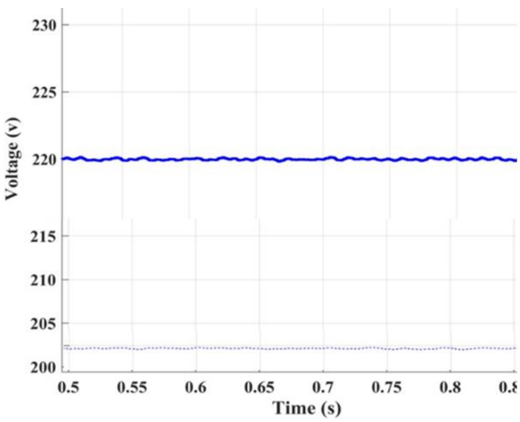


Figure (9): Voltage drop improvement.

B. Active power control mode

The VSG improves the frequency by controlling the active power based on RPC, in case frequency drop the reserve is zero and the inverter delivers the maximum active power generated from PV panels. However, in case of voltage rise

The reserve power becomes max not exceeds the defined threshold value. In the case that the frequency increases the control strategy increases the reserve power and make reduction of the inverter active power and ultimately as shown in Figure 10 and 11 respectively. As a result, this leads to restore the frequency to its nominal value from 50.4Hz to 50Hz.

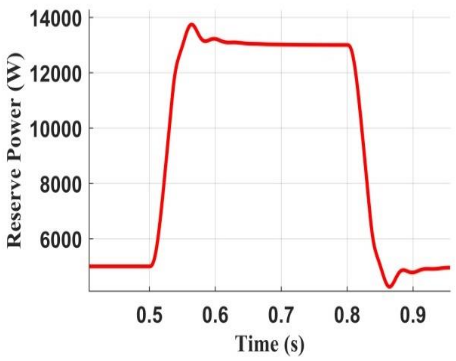


Figure (10): Reserve power (kW).

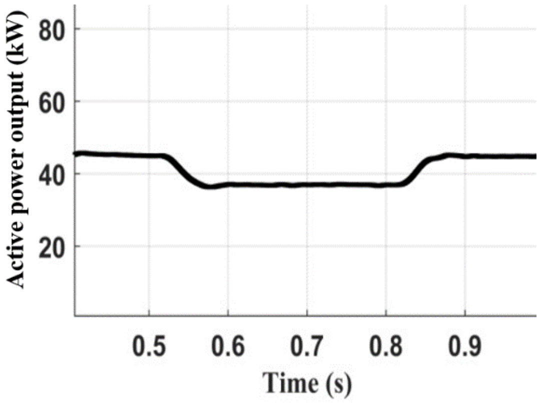


Figure (11): Inverter output with PRC control.

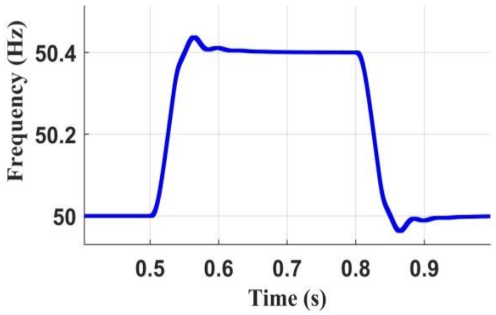


Figure (12): Frequency restoration by RPC.

c. conclusions and future work

This study proposes a PV inverter control strategy using VSG to enhance power grid voltage and frequency profiles without costly energy storage systems. The approach involves a DC/DC converter, power electronics inverter, and PRC technique for effective power conversion and reactive power regulation, adaptable to both MPPT and PRC modes. The method significantly improves grid voltage 220 V and frequency 50 Hz, proving more cost-effective than existing solutions. The findings advance VSG control, holding practical significance in the power industry. The case study encompassed a 50 kVA rated PV inverter, a 50 kW rated PV system, and a 220 V grid phase voltage. In conditions of low PV power generation with a solar radiation of 200 W/m² and a high load power of 120 kW and 37.5 kVAr, the load voltage experienced a drop to 202.4 V. The VSG controller adeptly elevated the voltage by 17.6 V, effectively restoring it to its nominal value of 220 V. Conversely, with high solar radiation of 1000 W/m², leading to high PV power generation and a low load power of 20 kW and 7.5 kVAr, the load voltage rose to 230 V. Nevertheless, the VSG controller effectively fine-tuned the voltage by 10 V, ultimately stabilizing at 220 V. Additionally, when the frequency deviated within ±0.4 Hz from the nominal frequency of 50 Hz, the VSG controller efficiently corrected the frequency by ±0.4 Hz, successfully restoring it to its nominal value. In future works, an extended investigation could focus on the real-world deployment and validation of the proposed control strategy. This practical implementation would serve to empirically demonstrate its potential in enhancing power system stability.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The raw data required to reproduce these findings are available in the body and illustrations of this manuscript.

Author's contribution

The authors confirm contribution to the paper as follows: manuscript writing and structuring: Moien Omar; modeling and simulation results: Noor Aldeen Ghazzawi; revising of draft manuscript: Marwan M. Mahmoud.

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Conflicts of interest: None

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