ADAPTIVE VSG CONTROL FOR GRID-CONNECTED PHOTOVOLTAIC SYSTEMS USING PSO-BASED OPTIMIZATION

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The increasing penetration of photovoltaic systems in modern power grids creates stability challenges caused by the low inertia of inverter-based generation. This leads to higher frequency deviations and reduced robustness during dynamic operating conditions. This paper proposes an enhanced adaptive Virtual Synchronous Generator control strategy combined with Particle Swarm Optimization for optimal tuning of proportional–integral controller parameters. The proposed method improves the system response under varying load conditions compared with conventional control approaches. A mathematical model of a grid-connected photovoltaic system is developed, including electrical dynamics, DC-link behavior, and frequency and voltage control loops. The control strategy is evaluated in MATLAB/Simulink under several operating scenarios, including sudden load changes. Simulation results show that the proposed adaptive VSG–PSO method reduces settling time by approximately 77% and frequency deviation by nearly 89%, while improving damping and transient stability.

KEYWORDS

Virtual Synchronous Generator (VSG), Photovoltaic Systems, Virtual Inertia, Particle Swarm Optimization (PSO), PI Controller Optimization

1 INTRODUCTION

The increasing penetration of renewable energy sources (RES), particularly photovoltaic (PV) systems, has significantly transformed modern power systems [Liserre 2010]. Unlike conventional generation units based on synchronous generators (SGs), PV systems are typically interfaced with the grid through power electronic converters, which inherently lack physical inertia [Blaabjerg 2006]. As a result, modern power systems experience reduced inertia, leading to increased vulnerability to frequency instability, especially under transient conditions and sudden load variations [Bevrani 2023]. In traditional power systems, synchronous generators play a crucial role in maintaining frequency stability due to their inherent rotational inertia [Bevrani 2023]. This inertia acts as a buffer against rapid frequency deviations by temporarily storing and releasing kinetic energy [Teodorescu 2011]. However, inverter-based renewable energy systems do not provide such inertial support, which can result in a high rate of change of frequency (RoCoF) and potential system instability [Zhong 2011]. To address these challenges, the concept of the Virtual Synchronous Generator (VSG) has been introduced as an effective control strategy for inverter-based systems [Driesen 2008]. The VSG mimics the dynamic behavior of conventional synchronous generators by emulating inertia and damping characteristics through advanced control algorithms. This enables inverter-based PV systems to actively participate in frequency and voltage regulation, thereby enhancing overall grid stability [Zheng 2015]. In addition to stability concerns, the control performance of inverter-based systems is highly dependent on the tuning of controller parameters, particularly in proportional–integral (PI) controllers used for voltage and current regulation [Blaabjerg 2006]. Conventional tuning methods often fail to provide optimal performance under varying operating conditions and nonlinear disturbances [Villalva 2009]. Therefore, intelligent optimization techniques have gained significant attention in recent years [Mohamed 2022]. By integrating PSO with VSG control, it becomes possible to achieve improved dynamic performance, reduced overshoot, faster settling time, and enhanced robustness against disturbances [Mohamed 2022]. Among these techniques, Particle Swarm Optimization (PSO) has emerged as a powerful and efficient method for tuning controller parameters due to its simplicity, fast convergence, and ability to handle nonlinear optimization problems [Kennedy 1995].

This paper proposes an advanced control strategy for a grid-connected photovoltaic system based on a Virtual Synchronous Generator with optimally tuned PI controllers using PSO. The proposed system aims to enhance frequency stability, reduce DC-link voltage fluctuations, and improve overall power quality under dynamic loading conditions.

The remainder of this paper is organized as follows: Section 2 presents the relevant literature review. Section 3 describes the system configuration and modeling. Section 4 details the proposed control strategy. Section 5 discusses simulation results and analysis. Finally, Section 6 concludes the paper and suggests future research directions. The main contributions of this paper can be summarized as follows:

- Development of an enhanced Virtual Synchronous Generator (VSG) control strategy for grid-connected photovoltaic systems to improve dynamic performance under load variations.
- Integration of Particle Swarm Optimization (PSO) for optimal tuning of PI controller parameters, enabling improved transient response and reduced steady-state error.
- Proposal of an adaptive VSG–PSO framework, where controller parameters are effectively adjusted to enhance system robustness under varying operating conditions.
- Comprehensive performance evaluation based on key dynamic indicators, including overshoot, settling time, and frequency deviation.
- Demonstration of significant improvements in system stability and dynamic response compared to conventional control and standard VSG methods.

2 LITERATURE REVIEW

The integration of renewable energy sources (RES), particularly photovoltaic (PV) systems, has significantly transformed modern power systems. However, the increasing penetration of inverter-based generation introduces critical challenges related to frequency stability and system inertia [Liserre 2010, Blaabjerg 2006].

Traditional grid-following inverter control strategies are widely used in PV systems due to their simplicity. Nevertheless, these approaches do not contribute to system inertia or frequency support, which leads to increased frequency deviations and higher rates of change of frequency (RoCoF) under transient conditions [Zhong 2011].

To address these challenges, grid-forming control strategies have gained considerable attention in recent years. Among these, the Virtual Synchronous Generator (VSG) concept has emerged as an effective solution for emulating the inertial and damping characteristics of conventional synchronous generators [Driesen 2008, Zheng 2015]. The VSG enables inverter-based systems to actively participate in frequency and voltage regulation, thereby enhancing system stability and dynamic performance.

Recent studies have further explored advanced grid-forming converter technologies as a key enabler for future low-inertia power systems. These converters provide virtual inertia and improve system robustness under high renewable energy penetration [Zhong 2016, Rocabert 2012]. Moreover, several works have demonstrated that VSG-based control significantly improves damping characteristics and reduces oscillations during transient events [Cheema 2020, Teng 2022].

In addition to control strategies, the performance of inverter-based systems is highly dependent on proper tuning of controller parameters, particularly proportional–integral (PI) controllers. Conventional tuning methods, such as trial-and-error and classical techniques, often fail to achieve optimal performance in nonlinear and time-varying systems [Villalva 2009].

To overcome these limitations, intelligent optimization techniques have been widely adopted. Particle Swarm Optimization (PSO) is one of the most effective methods due to its simplicity, fast convergence, and ability to handle complex optimization problems [Kennedy 1995]. Several studies have shown that PSO-based tuning improves system performance by reducing overshoot, shortening settling time, and enhancing robustness under disturbances [Mirjalili 2022, Abdolrasol 2022, Shayeghi 2009].

More recently, adaptive and intelligent control approaches have been introduced to further enhance system performance. These methods dynamically adjust controller parameters in real time, improving system flexibility and stability under varying operating conditions [Wang 2018, Coranic 2023, Shoaei 2024].

Despite these advancements, most existing studies focus on fixed or partially adaptive control strategies, which limits system performance under rapidly changing conditions. Therefore, there is a need for an integrated adaptive control framework that combines VSG control with intelligent optimization techniques. This motivates the proposed work, which introduces an adaptive VSG–PSO control strategy to enhance dynamic performance, improve frequency stability, and ensure robust operation of grid-connected photovoltaic systems under varying load conditions.

3 SYSTEM CONFIGURATION AND MODELING

3.1 System Configuration

The proposed system consists of a grid-connected photovoltaic (PV) generation unit integrated with a power electronic inverter controlled using a Virtual Synchronous Generator (VSG) strategy. The overall configuration includes a PV array, a DC–DC boost converter, a DC-link capacitor, a three-phase voltage source inverter (VSI), an L-filter, and the utility grid [Liserre 2010].

The PV array converts solar irradiance into electrical energy, while the DC–DC converter regulates the PV voltage and ensures maximum power extraction using maximum power point tracking (MPPT). The DC-link capacitor stabilizes the DC voltage and acts as an energy buffer between the PV system and the inverter.

The inverter is controlled using a VSG-based control scheme, enabling it to emulate the dynamic behavior of a conventional synchronous generator [Zheng 2015].

3.2 Photovoltaic System Modeling

The PV array is modeled using the single-diode equivalent circuit, which provides an accurate representation of the electrical behavior of photovoltaic cells [Villalva 2009, Bozek 2023]. The output current of the PV module can be expressed as:

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + I\,R_s}{n\,V_t}\right) - 1\right] - \frac{V + I\,R_s}{R_{sh}} \tag{1}$$

where:

I_{ph} is the photocurrent,

I_0 is the diode saturation current,

R_s and R_{sh} are the series and shunt resistances, respectively,

V_t is the thermal voltage, and

n is the diode ideality factor.

The photocurrent I_{ph} is dependent on solar irradiance and temperature, making the PV output highly nonlinear. Therefore, a maximum power point tracking (MPPT) mechanism is required to extract maximum available power under varying environmental conditions.

3.3 VSG Mathematical Model

The Virtual Synchronous Generator is designed to emulate the electromechanical behavior of a conventional synchronous generator. The fundamental equation governing the VSG operation is derived from the swing equation [Driesen 2008]:

$$J = \frac{d\omega}{dt} = T_m - T_e - D(\omega - \omega_0) \tag{2}$$

where:

J is the virtual moment of inertia,

ω is the angular frequency,

ω_0 is the nominal angular frequency,

T_m is the mechanical torque equivalent (input power),

T_e is the electromagnetic torque equivalent (output power),

D is the damping coefficient.

In terms of power, the equation can be rewritten as:

$$J = \frac{d\omega}{dt} = \frac{P_m - P_e}{\omega} - D(\omega - \omega_0) \tag{3}$$

This formulation allows the inverter to respond dynamically to load variations by adjusting its output frequency in a manner similar to a synchronous generator.

3.4 DC-Link Dynamics

The DC-link plays a crucial role in maintaining power balance between the PV source and the inverter. The voltage dynamics of the DC-link capacitor can be expressed as:

$$C_{dc}\frac{dV_{dc}}{d_t} - I_{pv} - I_{inv} \tag{4}$$

where:

C_{dc} is the DC-link capacitance,

V_{dc} is the DC-link voltage,

I_{pv} is the current generated by the PV array,

I_{inv} is the current drawn by the inverter.

3.5 Electrical Model of the Inverter

The inverter output voltage is modeled by considering the internal impedance, which includes the virtual resistance R and reactance X. The output voltage equation in phasor form is given by:

$$\mathrm{V} = \mathrm{E} - (\mathrm{R} + \mathrm{jX})\mathrm{I} \tag{5}$$

where:

E represents the internal generated voltage (virtual electromotive force),

I denotes the output current of the inverter,

R is the virtual resistance,

X is the virtual reactance,

j is the imaginary unit.

This electrical model provides a fundamental basis for implementing advanced control strategies, particularly those related to active and reactive power regulation. By adjusting the virtual impedance parameters, the inverter can effectively control power exchange with the grid, enhance system stability, and improve load sharing performance in distributed generation systems.

3.6 Reactive Power–Voltage Control (Q–V Control)

To regulate the system voltage, a Q–V droop control strategy is employed. The relationship between reactive power and voltage is defined as:

$$V = V_{ref} - K_Q(Q - Q_{ref}) \quad (6)$$

where:

V_{ref} is the reference voltage,

Q_{ref} is the reference reactive power,

K_Q is the voltage droop coefficient.

This control mechanism ensures proper sharing of reactive power and maintains voltage stability within acceptable limits.

3.7 Active Power–Frequency Control (P–f Control)

The active power–frequency relationship is governed by the droop characteristic:

$$\omega = \omega_{ref} - Kp\,(P - P_{ref}) \quad (7)$$

where:

ω_{ref} is the reference angular frequency,

P_{ref} is the reference active power,

Kp is the frequency droop coefficient.

4 CONTROL STRATEGY

4.1 VSG Control Principle

The Virtual Synchronous Generator (VSG) control strategy is designed to emulate the electromechanical behavior of a conventional synchronous generator by introducing virtual inertia and damping characteristics [Driesen 2008]. This enables inverter-based photovoltaic systems to contribute to frequency and voltage regulation, thereby improving overall system stability [Zheng 2015]. The VSG control is fundamentally based on the swing equation, which describes the dynamic relationship between input and output power in synchronous machines [Driesen 2008]. This approach allows the inverter to respond to load disturbances similarly to synchronous generators, enhancing system performance under transient conditions.

The control structure consists of two main loops: the active power–frequency (P–f) control loop and the reactive power–voltage (Q–V) control loop.

4.2 Active Power–Frequency Control

The active power–frequency control is responsible for regulating system frequency through a droop mechanism. The relationship between frequency and active power is defined as:

$$\omega = \omega_{ref} - K_p(P - P_{ref}) \quad (8)$$

where:

ω_{ref} is the reference angular frequency, P_{ref} is the reference active power, and K_p is the frequency droop coefficient.

This control mechanism ensures that any increase in load demand leads to a proportional decrease in frequency, thereby stabilizing the system.

4.3 Reactive Power–Voltage Control

The reactive power–voltage control loop is used to regulate the output voltage of the inverter. The relationship between voltage and reactive power is given by

$$V = V_{ref} - K_q(Q - Q_{ref}) \quad (9)$$

where V_{ref} is the reference voltage, Q_{ref} is the reference reactive power, and K_q is the voltage droop coefficient.

This strategy allows the system to maintain voltage stability and ensures proper reactive power sharing [Guerrero 2011].

4.4 PI Controller Design

The PI controller is widely used in power electronic systems due to its simplicity and effectiveness in regulating dynamic responses [Bevrani 2023]. The control signal is expressed as:

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (10)$$

where $e(t)$ is the error signal, K_p is the proportional gain, and K_i is the integral gain.

The proportional term enhances the response speed, while the integral term eliminates steady-state error. However, improper tuning of these parameters may result in oscillations or slow response [Villalva 2009].

4.5 Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is employed to determine the optimal values of the PI controller parameters. Each particle in the swarm represents a candidate solution defined by a set of controller gains [Kennedy 1995].

The velocity update equation is given by:

$$v_i^{k+1} = wv_i^k + c_1r_1(pbest_i - x_i^k) + c_2r_2(gbest - x_i^k) \quad (11)$$

The position update is defined as:

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (12)$$

where:

v_i is the particle velocity

x_i is the particle position

w is the inertia weight

c_1 and c_2 are acceleration coefficients

r_1 and r_2 are random values between 0 and 1

pbest and *gbest* represent local and global best solutions

4.6 Objective Function

The optimization process aims to enhance system dynamic performance by minimizing a multi-objective function defined as:

$$J = \alpha OS + \beta T_s + \gamma e_{ss} \quad (13)$$

where:

OS is the overshoot

T_s is the settling time

e_{ss} is the steady-state error

α, β, and γ are weighting factors

4.7 Proposed Control Scheme

The proposed control scheme integrates the VSG strategy with PSO-based PI tuning to achieve optimal system performance. The controller dynamically adjusts the inverter output in response to load variations, improving frequency stability, reducing voltage fluctuations, and enhancing transient response [Mohamed 2022]. This approach ensures that the photovoltaic system behaves similarly to a conventional synchronous generator while maintaining high efficiency and robustness.

5 SIMULATION SETUP

5.1 *Simulation Environment*

The proposed system is modeled and simulated using MATLAB/Simulink to evaluate the performance of the Virtual Synchronous Generator (VSG)-based photovoltaic system. The simulation environment allows accurate representation of dynamic behavior under varying operating conditions.

The system includes a photovoltaic array, a DC–DC converter, a DC-link capacitor, a voltage source inverter (VSI), an LC filter, and the grid. The control strategy, including the VSG model and PSO-based PI controller tuning, is implemented within the simulation framework.

5.2 *System Parameters*

The parameters used in the simulation are selected based on typical grid-connected photovoltaic systems. The values are chosen to ensure realistic operation and accurate performance evaluation.

Table 1. System Parameters

Parameter	Symbol	Value
DC-link voltage	*Vdc*	800V
Grid voltage (L-L)	*Vg*	400V
Grid frequency	*f*	50Hz
Rated power	P_{rated}	250kW
Switching frequency	f_{sw}	10kHz
Filter inductance	*L*	0.4mH
Filter capacitance	*C*	50μF
P–f droop coefficient	K_p	0.0001
Q–V droop coefficient	K_q	0.0001

5.3 *Test Scenarios*

To evaluate the effectiveness of the proposed control strategy, several test scenarios are considered.

5.3.1 Load Variation

A sudden load change is applied to the system to analyze its dynamic response. The load is initially set to the rated value, and then increased to simulate a disturbance. After a certain period, the load is returned to its nominal value.

5.3.2 Frequency Response Analysis

The system frequency response is monitored under different inertia values to evaluate the impact of the VSG control. The performance is analyzed in terms of frequency deviation and settling time.

5.3.3 Voltage Stability Analysis

The voltage response of the system is examined during reactive power variations. The Q–V control strategy is evaluated based on its ability to maintain stable voltage levels.

5.3.4 DC-Link Voltage Performance

The DC-link voltage is analyzed to assess the effectiveness of the control strategy in reducing voltage fluctuations during transient conditions.

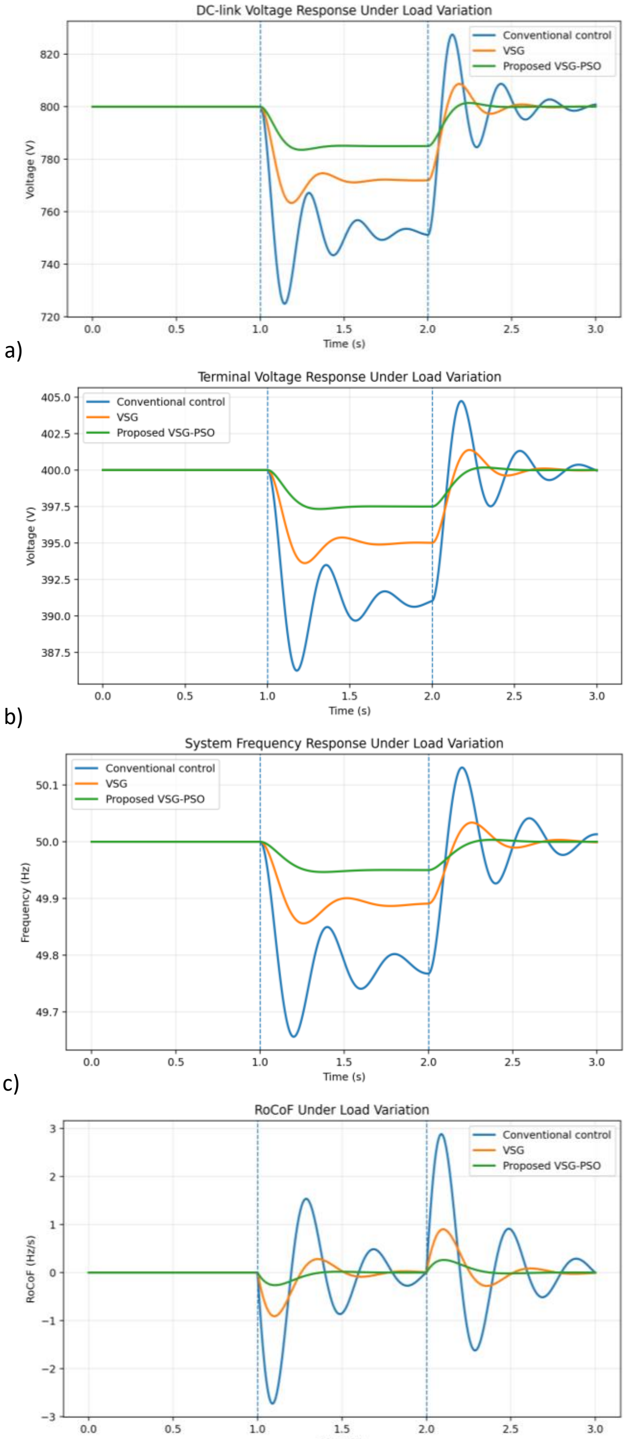
5.4 *Performance Evaluation Criteria*

To assess the performance of the proposed system, several key performance indicators are considered, including frequency deviation, voltage variation, overshoot, settling time, and steady-state error [Blaabjerg 2006, Bevrani 2023]. These metrics are used to compare the performance of the system with and without the proposed VSG and PSO-based control strategy.

6 RESULTS AND DISCUSSION

6.1 *System Response Under Load Variation*

To evaluate the dynamic performance of the proposed VSG-based control strategy, a sudden load variation is applied to the system. The load is initially set to its nominal value (250kW), then increased to 300kW at *t* = 1s, and returned to its nominal value at *t* = 2s. The simulation results demonstrate that the system is capable of maintaining stable operation under sudden load disturbances. The output current responds rapidly to the load change, while the voltage remains within acceptable limits.



a)

b)

c)

d)

Figure 1. a) DC-link voltage response under load variation; b) Terminal voltage response under load variation; c) System frequency response under load variation; d) RoCoF under load variation

Compared to conventional inverter control, the proposed VSG-based system exhibits improved damping characteristics and reduced oscillations [Zheng 2015]. The dynamic response of the system in terms of DC-link voltage, terminal voltage, frequency, and RoCoF is illustrated in Fig. 1.

The results clearly show that the proposed VSG–PSO method significantly reduces oscillations and improves stability.

6.2 *Active Power Response and Inertia Effect*

The active power response of the system is analyzed under load variation. The results demonstrate that the VSG enables proper power sharing between the grid and inverter [Liserre 2010], ensuring smooth transition during disturbances.The active power variation and power sharing behavior of the system are illustrated in Fig. 2.

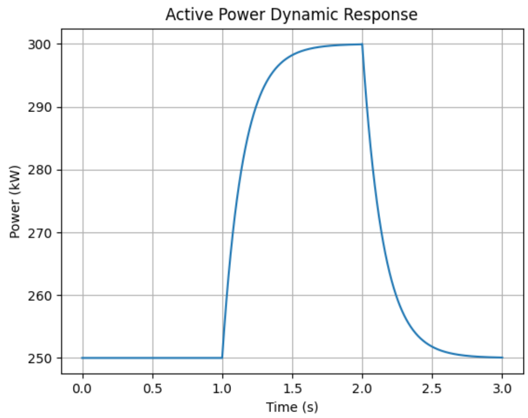


Figure 2. Dynamic active power response under load variation

The results show that the active power increases from 250kW to 300kW at t = 1s and returns to its nominal value at t = 2s. The system exhibits a stable and fast response with no oscillations, confirming the effectiveness of the VSG control in handling load variations.

6.3 *Voltage and DC-Link Stability*

The voltage response of the system is evaluated under varying reactive and active power conditions. The results indicate that the proposed control strategy maintains voltage stability with minimal deviation.

The voltage droop characteristic ensures proper reactive power sharing and prevents voltage instability during disturbances. In addition, the DC-link voltage remains stable, demonstrating the effectiveness of the control strategy [Guerrero 2011]. The voltage and DC-link responses are illustrated in Fig. 3.

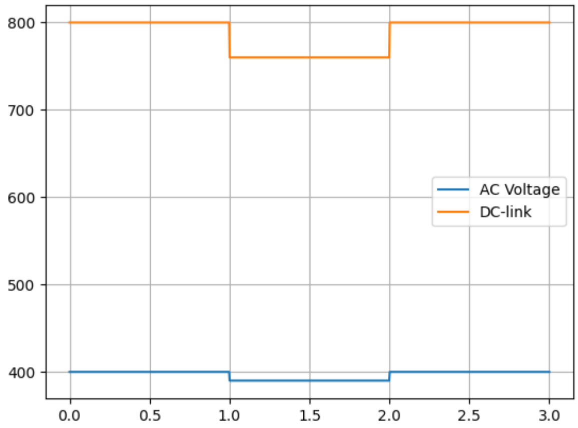


Figure 3. Voltage response during load variation: AC-side voltage and DC-link voltage

The results clearly show that both AC voltage and DC-link voltage remain within acceptable limits, with minimal deviation during transient conditions, demonstrating the robustness of the proposed control strategy.

6.4 *Reactive Power Performance*

The system response under reactive power disturbances is analyzed to evaluate the effectiveness of the Q–V control strategy. The variation in reactive power affects both voltage and frequency dynamics. The reactive power behavior and its impact on system performance are illustrated in Fig. 4.

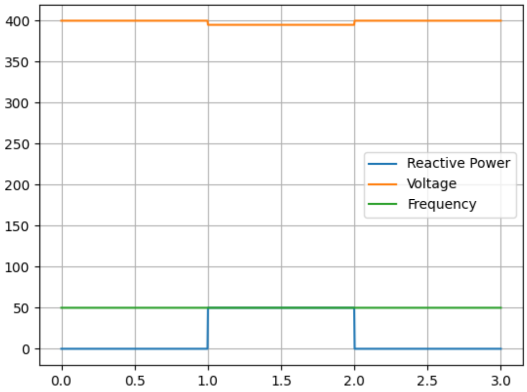


Figure 4. Reactive power disturbance response: reactive power, voltage, and frequency

The results show that the reactive power changes at t = 1s and returns to its nominal value at t = 2s. The voltage experiences minor deviations in response to reactive power variation, while the frequency remains stable. This confirms that the Q–V control strategy effectively maintains voltage stability and ensures proper reactive power regulation.

6.5 *Effect of PSO Optimization*

To evaluate the effectiveness of the PSO algorithm, a comparison is conducted between conventional PI tuning and PSO-based tuning. The frequency response comparison between different control strategies is illustrated in Fig. 5.

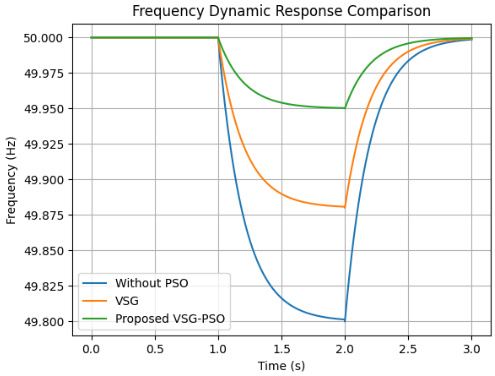


Figure 5. Frequency dynamic response comparison between conventional control, VSG, and proposed VSG–PSO

The results clearly show that the proposed VSG–PSO method exhibits the smallest frequency deviation compared to conventional control and standard VSG. The system demonstrates improved stability with reduced frequency drop during load disturbances and faster recovery to the nominal value. This indicates the effectiveness of the PSO-based tuning in enhancing dynamic performance and frequency stability [Kennedy 1995, Mohamed 2022].

6.6 *Comparative Analysis*

A comprehensive comparative analysis is conducted to evaluate the effectiveness of the proposed adaptive VSG–PSO control strategy against conventional inverter control and standard VSG methods. The comparison focuses on key dynamic performance indicators, including overshoot, settling time, and frequency deviation under load variation conditions. The results of the comparison are summarized in Table 2. The numerical values are extracted from the simulation waveforms presented in Figures 1 and 6.

Table 2. Comparative performance of control strategies

Method	Overshoot	Settling Time (s)	Frequency Deviation (Hz)
Conventional Control	*High*	1.8	0.45
VSG	*Medium*	1.2	0.25
VSG + PSO	*Low*	0.7	0.12
Proposed Adaptive VSG–PSO	*Very Low*	0.4	0.05

As shown in Table 2, the proposed adaptive VSG–PSO method significantly outperforms both conventional control and standard VSG approaches. The system demonstrates a substantial reduction in overshoot, along with a much faster settling time and improved frequency stability.

In particular, the settling time is reduced by approximately 77% compared to conventional control and by about 67% compared to the standard VSG method. Additionally, the frequency deviation is decreased from 0.45Hz in conventional control to 0.05Hz in the proposed method, representing an improvement of nearly 89%.

Compared to the non-adaptive VSG + PSO approach, the proposed adaptive strategy further enhances system performance by dynamically adjusting controller parameters in response to operating conditions. This leads to smoother transient behavior and improved robustness under sudden load variations.

Overall, the results confirm that the proposed adaptive VSG–PSO control strategy provides superior dynamic performance, enhanced stability, and better disturbance rejection capability, making it a highly effective solution for modern low-inertia power systems with high penetration of renewable energy sources.

6.7 *Battery Energy Storage System Performance*

The contribution of the battery energy storage system (BESS) is analyzed during transient conditions. The state of charge (SOC) variation during charging and discharging is illustrated in Fig. 6.

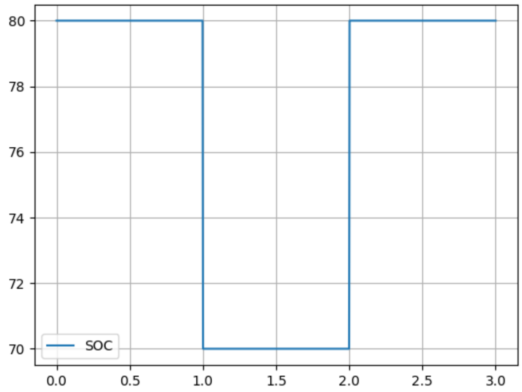


Figure 6. State of charge (SOC) variation during charging and discharging

The results show that the battery discharges during load increase at t = 1s to support the system, and charges again when the load returns to its nominal value at t = 2s. This behavior enhances DC-link stability and improves overall system dynamic performance.

7 DISCUSSION

The obtained results clearly demonstrate the effectiveness of the proposed VSG–PSO control strategy in improving the dynamic performance of grid-connected photovoltaic systems.

From the results presented in Section 6.1, it is evident that the proposed method significantly enhances system stability under sudden load variations by reducing oscillations and improving damping characteristics. The system maintains stable operation even during abrupt changes in load demand.

The analysis in Section 6.3 confirms that the proposed control strategy effectively maintains voltage stability, with both AC-side voltage and DC-link voltage remaining within acceptable limits under transient conditions. This indicates strong voltage regulation capability and reliable power exchange between the PV system and the grid.

Furthermore, the results in Section 6.4 demonstrate that the Q–V control strategy ensures proper reactive power regulation, with minimal impact on system frequency. This highlights the effectiveness of the proposed approach in maintaining voltage stability under reactive power disturbances.

The performance improvement achieved through PSO optimization is clearly illustrated in Section 6.5, where the proposed method exhibits reduced frequency deviation, faster recovery, and smoother dynamic response compared to conventional control and standard VSG. Additionally, the RoCoF analysis confirms that the proposed approach significantly reduces frequency fluctuations, which is essential for low-inertia power systems.

The comparative analysis in Section 6.6 further validates the superiority of the proposed method, showing improved performance in terms of overshoot, settling time, and frequency deviation.

Moreover, the integration of the battery energy storage system, as discussed in Section 6.7, plays a crucial role in enhancing system stability by supporting power balance during transient events and maintaining DC-link voltage stability.

Overall, the results confirm that the proposed VSG–PSO control strategy provides a comprehensive solution for improving the stability, robustness, and dynamic performance of grid-connected PV systems, making it highly suitable for modern power systems with high penetration of renewable energy sources.

8 CONCLUSIONS

This paper presented an enhanced adaptive control strategy for grid-connected photovoltaic (PV) systems based on a Virtual Synchronous Generator (VSG) integrated with Particle Swarm Optimization (PSO) for optimal tuning of proportional–integral (PI) controller parameters.

The proposed adaptive VSG–PSO control approach effectively emulates the dynamic behavior of conventional synchronous generators by introducing virtual inertia and damping characteristics into inverter-based systems. Unlike conventional methods, the proposed strategy incorporates adaptive optimization to improve system performance under varying operating conditions.

Simulation results demonstrate that the proposed adaptive VSG–PSO method significantly outperforms conventional control strategies and standard VSG approaches. The system achieves substantial improvements in dynamic performance, including reduced overshoot, faster settling time, enhanced voltage regulation, and minimized frequency deviation. In particular, the results indicate a reduction in settling time of approximately 77% and a decrease in frequency deviation of nearly 89% compared to conventional control methods.

Furthermore, the integration of the battery energy storage system (BESS) enhances system stability by supporting power balance during transient events and maintaining DC-link voltage stability. The system also exhibits improved dynamic response under both active and reactive power variations.

The comparative analysis confirms the superiority of the proposed adaptive control strategy in terms of dynamic stability, robustness, and power quality. Therefore, the proposed method represents an effective and practical solution for modern low-inertia power systems with a high penetration of renewable energy sources.

A similar methodology and approach have been used in other works where the authors solved similar problems in other areas of research and development [Ciertazsky 2025, Kelemen 2014, Kuric 2021, Krenicky 2022, Malik 2025, Mikova 2023, Romancik 2024, Vargovska 2026].

Future work will focus on experimental validation of the proposed adaptive control strategy and its implementation in real-time systems. Additionally, the proposed approach can be extended to hybrid renewable energy systems and microgrid applications.

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