International Journal of Applied Power Engineering (IJAPE)
Vol. 14, No. 3, September 2025, pp. 701~711
ISSN: 2252-8792, DOI: 10.11591/ijape.v14.i3.pp701-711

Enhanced multi-mode control of Z-source virtual synchronous generator for photovoltaic systems using fuzzy logic controller

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Article Info

Article history:

Received Mar 30, 2024
Revised May 14, 2025
Accepted Jun 23, 2025

Keywords:

Fuzzy logic controller
Photovoltaic systems
Standalone
Total harmonic distortion
Z-source virtual synchronous generator

ABSTRACT

An enhanced multi-mode control solution for a Z-source virtual synchronous generator (ZVSG) that makes use of a fuzzy logic controller (FLC) is proposed by this study for use in photovoltaic (PV) systems. As a potential grid integration option for PV systems, the ZVSG has great potential due to its steady and adjustable power production. A stable voltage and frequency output can be maintained by the ZVSG when it is running in a variety of modes, such as grid-connected, standalone, and islanding, according to the control approach that has been provided. The FLC is used for the purpose of controlling the switching frequency of the ZVSG as well as the DC-link voltage. The performance of the ZVSG is improved by the FLC-based control approach that has been proposed. This technique reduces the steady-state error and offers a rapid dynamic response. The results of the simulation show that the recommendation for a control approach improves the performance of the ZVSG across a wide variety of operating modes and load conditions.

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1. INTRODUCTION

Since power demand is rising, thermal and other energy sources may be depleted in the coming decades. Traditional power plant carbon emissions harm the environment. Nuclear energy is dangerous. Experts have recently concentrated on renewable energy sources to solve these issues. Solar is free and abundant, making it the most popular renewable energy. PV technology uses solar energy. Solar photovoltaic (PV), electric-power conversion devices, and a PV electricity monitoring device comprise the solar energy conversion system. Nonlinear PV cells generate DC power inefficiently from solar light and temperature.

This letter shows how rotor inertia, damping factor, integral coefficient, and low-pass filter time constant relate to demonstrate a practical secondary frequency control (SFC) method for virtual synchronous generators (VSGs) that simplifies parameter design and predicts rotor frequency response. Simulation results support the theory [1]. VSG-SG microgrids' transient performance is examined here. A novel pre-synchronization control approach minimizes phase jumps and meets generating unit closure and re-closure requirements. The capacity ratio of VSG and SG units and a small-signal dynamic model may create VSG inertia and damping. Power angle stability research suggests an active power supply to reduce inertia-induced power oscillation [2]. Analysis of converter and line dynamics shows that stability limits virtual inertia and damping. Basic transfer function analysis is used to study stability circumstances. Damping-to-virtual inertia ratio is critical for VSG stability and second-order system approximation [3]. Transient stability differences in paralleled systems may affect steady operation, especially in fault circumstances. This study examines the transient angle stability of paralleled VSG and SG-VSG systems using paralleled synchronous and virtual generators. Different speed governors create temporary instability in paralleled SG-VSG systems [4]. The enhanced VSG management's fade time constant, voltage, current limiting authority, and variable modification are examined. VSG regulation works in conventional and fault grid testing and simulations [5]. Unlike bulk power facilities, distributed generators (DG) lack dampening and spinning mass. As DG penetration increases, low inertia and damping degrade grid stability and dynamic performance [6]. This article analyzes virtual inertia literature and future research. Analyze and classify key virtual inertia topologies. Theoretical and numerical simulations of specified topologies show that time and inertia constants may create similar inertial responses but different frequency dynamics [7]. This study recommends using state-space research to change virtual stator reactance to share transient active power and reduce oscillations for improved VSG management. Common AC bus voltage estimation and inverse voltage droop control allow reactive power sharing without communication. In simulations and testing, updated VSG control works better [8]. However, the three-phase inverter's current amplitude limitation control can fulfill varied low voltage ride through (LVRT) requirements and deliver the highest reactive power within the rated current amplitude when voltage drops [9]. This study uses a one-stage, three-phase grid-connected PV system. By changing incremental conductance maximum power point tracking (MPPT), the recommended control may meet control targets and improve MPPT stability. Reactive power adjustment for local load cuts grid use [10]. A power electronics interface (PEI) with many auxiliary services for photovoltaic (PV) applications is available. To enable distributed producing systems, renewable energy PEIs should feature reactive power adjustment and LVRT. This work proposes a dependable model predictive-based control technique for grid-tied Z-source inverters (ZSIs) in LVRT PV systems [11]. To maximize HRES energy inertia, this control approach blends the insufficient grid's power imbalance with renewable producers. Maximizing renewable energy while satisfying operational and environmental restrictions is an optimization challenge [12]. Sliding-mode control-based feedback linearization increases PV system response speed under LVRT in this investigation. This article makes the control system parameter-resistant using feedback linearization and sliding-mode control. PV system linearization is achievable over its operation [13]-[18]. Enhanced PV installation capacity is assessed in steady-state and dynamic Taiwan. A charged system search (CSS) technique first finds the optimal PV installed capacity at chosen buses to limit gearbox loss and voltage volatility [19]-[22]. For three-phase grid-connected solar systems, the inverter controls output current and keeps it under the maximum limit during grid disruptions. Also satisfies low-voltage ride-through needs. The proposed intelligent controller sets reactive power to fulfill LVRT grid failure conditions [23]-[25]. Before, ZSI grid auxiliary service effectiveness studies neglected virtual inertia emulation. An inertia-mimicking Z-source virtual synchronous generator (ZVSG) delivers grid ancillary services in this research.

Following is the paper's outline. Section 2 explains the ZSI's principal purpose. Section 3 describes the recommended control methods. Section 4 describes fault control. Section 5 shows experimental data that proves the system works, and section 6 concludes the investigation.

2. Z-SOURCE VIRTUAL SYNCHRONOUS GENERATOR

ZSI may short-circuit load terminals via either phase leg's lower and upper switches using shoot-through states. Traditional voltage source inverters cannot operate in these circumstances because the converter and DC connection would be damaged. Since ZSI switches may employ all switching combination states, dead time is not needed. This should reduce current harmonic distortion and current itself. ZSI performance may be improved by adjusting the inverter's modulation index m and shoot-through time duration. Figure 1 depicts the Z-source virtual synchronous generator block diagram. The (1) determines ZSI output voltage u_{abc}.

$$B = \frac{V_{pn}}{V_{pv}} \tag{1}$$

$$u_{abc} = m * B \frac{V_{pv}}{2} \tag{2}$$

The input DC voltage is denoted as VPV, the boosting factor is B, and the impedance network output voltage is Vpn. Since (3) is true for symmetrical topologies, where L1 = L2 and C1 = C2, we may write it as (3).

$$VC_1 = VC_2 = VC_3$$
$$iL_1 = iL_2 = iL \quad (3)$$

Where V_c is the voltage across the impedance network's capacitors and iL is the current through the inductor. Applying volt-second and capacitor-charge mean values for L_v and C_i, the (4) and (5) show ZSI input/output links.

$$V_{pn} = \frac{V_{pv}}{1-2D_0} = \frac{V_c}{1-D_0} \quad (4)$$

$$V_c = \frac{1-D_0}{1-2D_0} V_{pv} \quad (5)$$

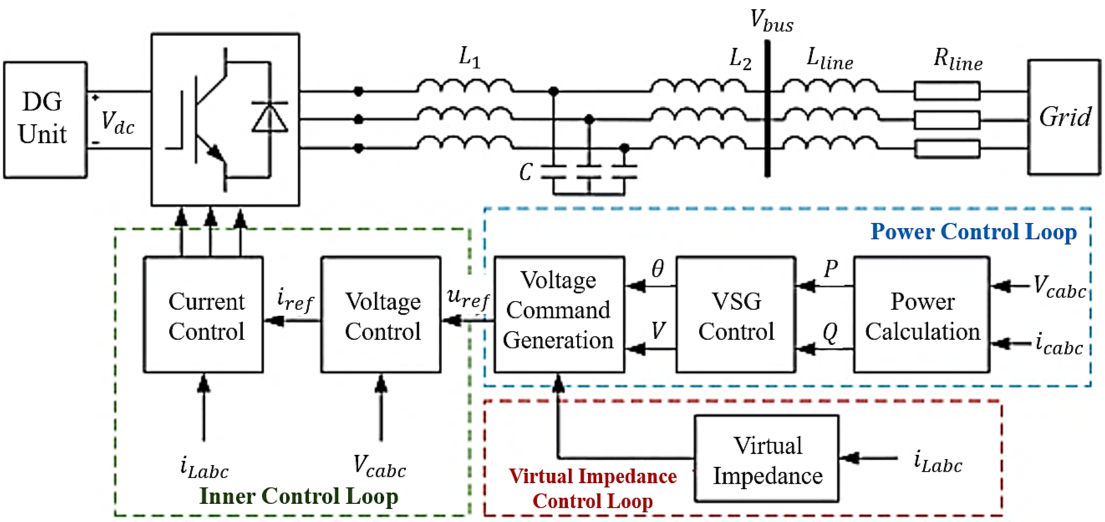

Figure 1. Block diagram of Z-source virtual synchronous generator

3. WAYS OF FUNCTIONING

The recommended ZVSG changer is flexible. The PV system employs conventional MPPT (rated voltage and frequency). The AC inverter's VSG regulates the rated frequency. The converter has a power factor of one, and the VSG control algorithm utilizes PV panels' PMMPT power as its active power reference. After low-voltage fault detection, MPPT switches to LVRT. Reactive power injection restores grid voltage. Thus, the control system must boost reactive power and lower active power. System demands and grid codes should establish new active and reactive power references.

3.1. Normal DC and AC side operation

The perturb and observe approach employs MPPT in Figure 2. A PI governor calculates the shoot-with duty D0 to control the impedance network result voltage, Vpn, by comparing the PV array voltage, VPV, to the cite voltage at the larger power point, VMPP.

The SG swing equation is evaluated digitally at every calculation series to obtain a cite angle. Second, angle evaluation produces 3-ph cite voltage. The SG is indicated in (6) and (7).

$$\frac{d\theta}{dt} = \omega \quad (6)$$

$$2H\frac{d\omega}{dt} = T_m - T_e - D_p\Delta\omega \quad (7)$$

Te and Tm are the mechanical and electromagnetic output torques in (8).

$$T_m = K_f(f_0 - f) + \frac{P_{ref}}{\omega} \quad (8)$$

Active power droop coefficient (kf), assessed and cite PV result watt power (Pe and Pref, respectively), and rated and measured frequencies (f0, f) of the system are also involved. The cite voltage, Eref, used by the VSG method, is determined using (9).

$$E_{ref} = E_0 + E_Q \tag{9}$$

The amplitude of the grid voltage is denoted by E0 and the reactive power component adjustment is denoted as EQ in section IV-B. Since the grid does not receive reactive power while operating normally, there is no EQ. Employ the cite voltage scope Eref and the projected cite angle Θ from (6) and (7), get the ZVSG 3-ph cite voltage in (10).

$$E_{ref} = \begin{bmatrix} e_{ar} \\ e_{br} \\ e_{cr} \end{bmatrix} = \begin{bmatrix} E\sin(\omega t) \\ E\sin\left(\omega t - \frac{2\Pi}{3}\right) \\ E\sin\left(\omega t + \frac{2\Pi}{3}\right) \end{bmatrix} \tag{10}$$

Figure 2 shows how this voltage is going to enter the Park conversion (11) to control the AC voltage and current of the changer by creating cite for the d and q channels.

$$T_{abc/dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\delta)\cos\left(\delta - \frac{2\Pi}{3}\cos\left(\delta + \frac{2\Pi}{3}\right)\right) \\ -\sin(\delta) - \sin\left(\delta - \frac{2\Pi}{3}\right) - \sin\left(\delta + \frac{2\Pi}{3}\right) \end{bmatrix} \tag{11}$$

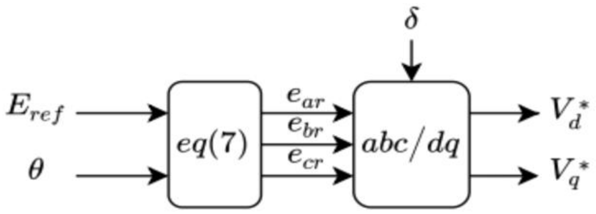

Figure 2. The outer loop value is created using the VSG target angle θ and standard voltage level E_{ref}

3.2. Virtual flux orientation control

VSG adjusts the converter operating point during load changes synchronization. To get the angles of the Park transformation input, phase-locked loops (PLLs) use the grid voltage to calculate the frequency and phase angle. When dealing with harmonic distortion, PLL uses virtual flux orientation control to identify the basic voltage component, unlike voltage-oriented control, which is effective with normal voltage but fails miserably when dealing with grid voltage harmonics (see Vf (12), V_{abc}).

$$\psi_{abc} = \int \mathrm{V_{abc}} \cdot dt \tag{12}$$

When flux (ψabc) touches the d-axis of the SRF, there is a neap lag among flux and voltage (V_{abc}). To get the Park transformation position angle, calculate the input angle in (13), after transforming ψabc to αβ cite build employ the Clarke conversion.

$$\delta = \tan^{-1}\frac{\psi_\beta}{\psi_\alpha} \tag{13}$$

While lowering the filter's cut-off frequency (ωc) may help, it may also decrease its bandwidth and worsen its dynamics. This study uses a thorough virtual flux computation (14).

$$g_3(s) = \frac{\psi(s)}{V(s)} = G_{BPF}(S) \cdot G_C(s) \tag{14}$$

3.3. Grid connection pre-synchronization

In islanded mode, DGs provide microgrid power and frequency. This voltage reference may vary from grid. Park converting converts DG voltage and current into SRF for control. Local reference frames for grid parameters and ZVSG. These control parameters have the same angular speed but may have a d (or q) axis phase mismatch. A current impulse will cause grid failure or overcurrent protection relay tripping. Thus, converting all state variables to one SRF requires pre-synchronization. This investigation's grid voltage phase monitoring, as shown in Figure 3, is based on VFOC. The ZVSG output voltage and grid phase difference (1 θ) are controlled by the control. The components of dq are shown in Figure 4 when the grid voltage va is parallel to the d axis and the VFOC introduces a 90° phase.

3.4. Proposed topology

Fuzzy logic controllers solve challenging problems because they are simple, adaptive, and robust and provide correct answers. Thus, system responsiveness will improve. This system's simulations are evaluated using MATLAB/Simulink. FLC's installation is easy to arrange, but its implementation requires qualitative knowledge. In the graphics below, it has one output and two inputs: error and error change. Figure 4 shows the FLC employed in this work.

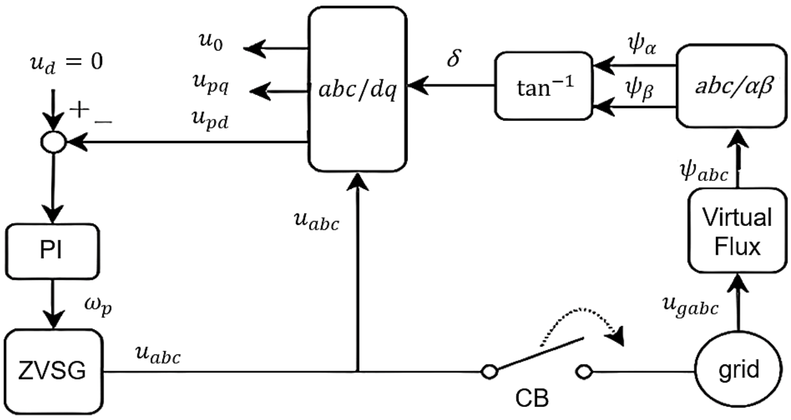

Figure 3. Pre-synchronization control technique based on VFOC

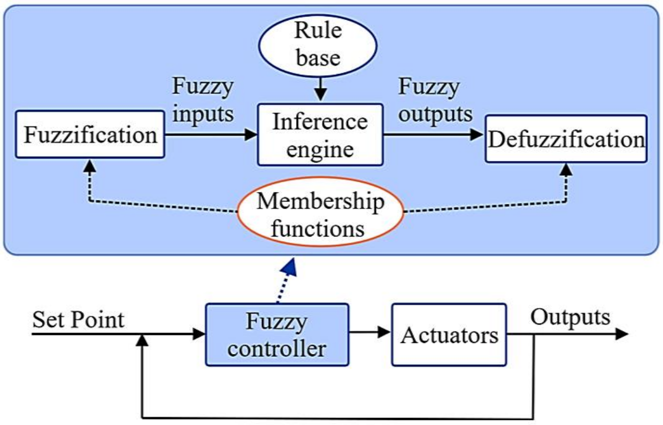

Figure 4. Fuzzy logic controller

4. SIMULATION RESULTS USING FUZZY LOGIC CONTROLLER

Figure 5 shows fuzzy logic controller schematic. ANFIS controller RoCoF charts of the converter while the ZVSG was in MPPT mode are shown in Figure 6. Figure 7 shows the inrush current when a fuzzy logic controller connects the ZVSG to the grid. ANFIS controller measurements of system performance before and after the breakdown are shown in Figure 8. Figure 9 shows fuzzy logic controller load.

Working with regard to the grid voltage, inductor current, and DC link voltage, Figure 10 displays the outcomes of the fuzzy logic controller's operation. Using a fuzzy logic controller, Figure 11 shows the current load value. In Figure 12, we can see how the DC link values are affected by the FLC performance. Figures 13(a) and 13(b) (see in appendix) the results of comparing THD utilizing a fuzzy logic controller.

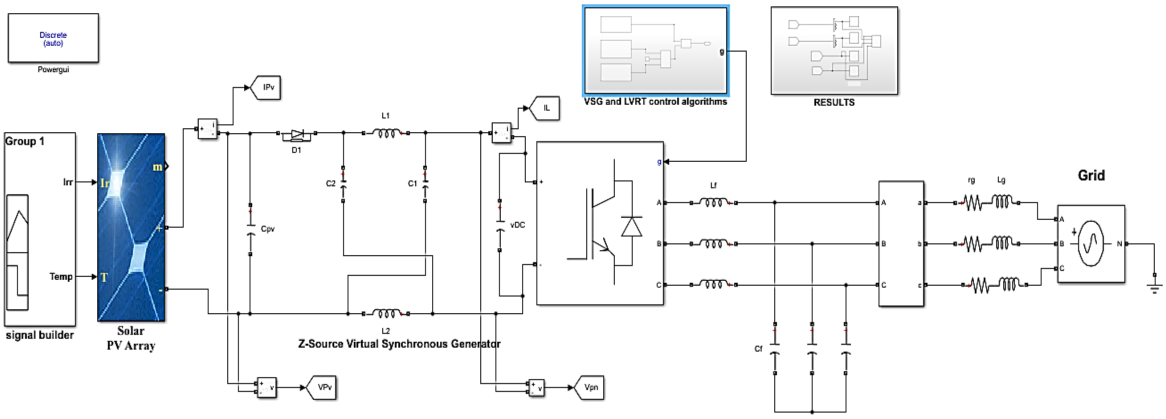

Figure 5. Schematic diagram of FLC

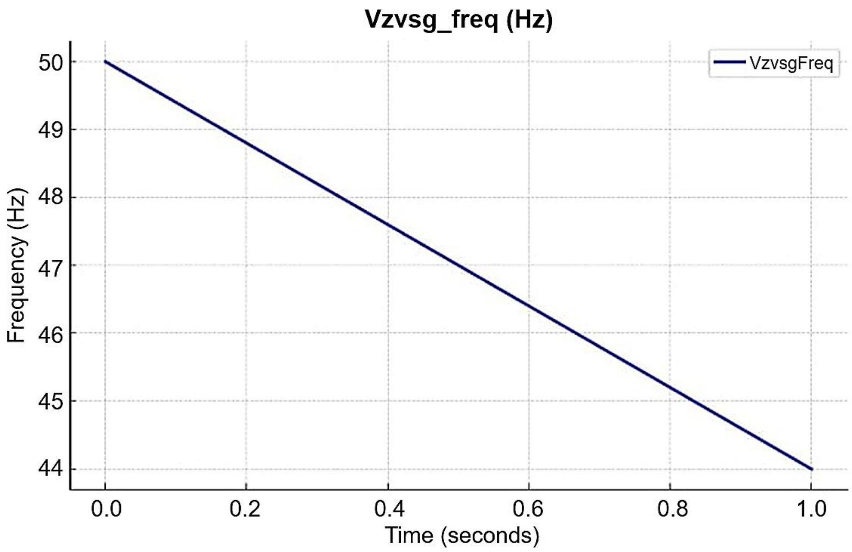

Figure 6. Frequency at ZVSG side (time vs frequency)

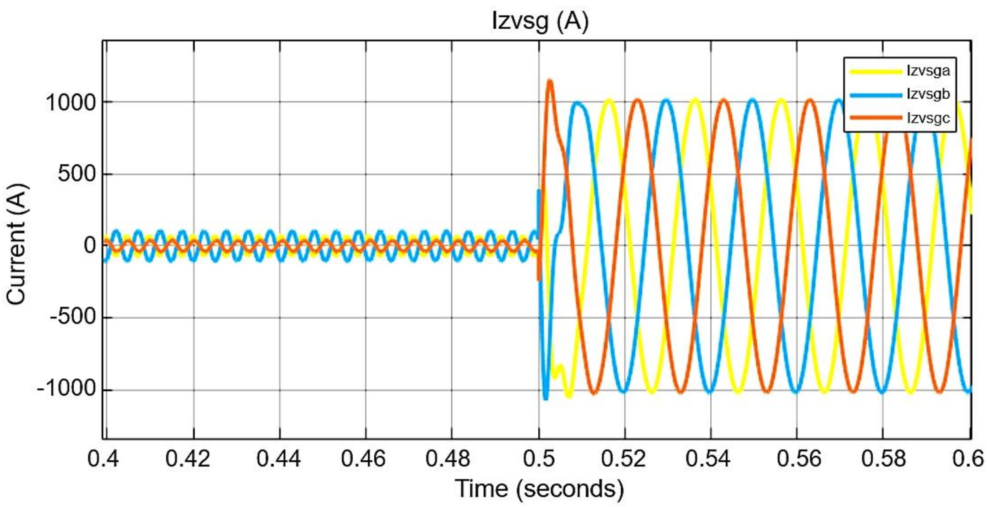

Figure 7. Izvsg (time vs current)

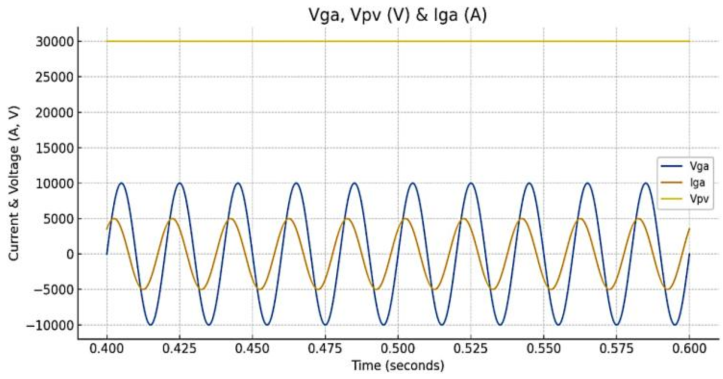

Figure 8. Vga, Vpv Iga (time vs voltage)

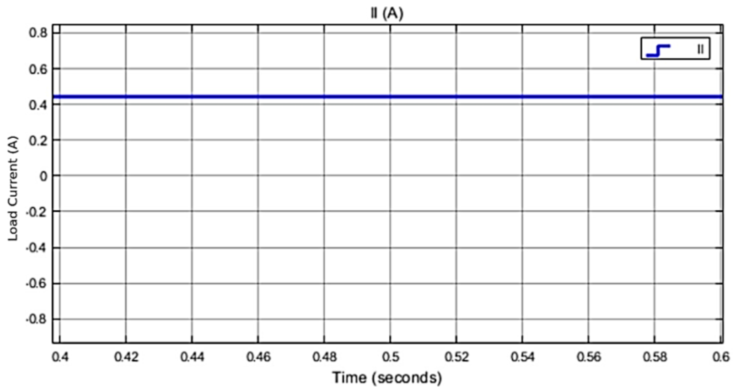

Figure 9. IL (A) (time vs load current)

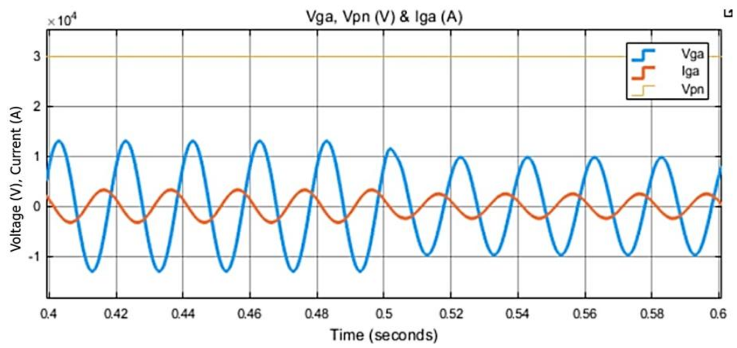

Figure 10. Vga, Vpn and Iga (time vs voltage, current)

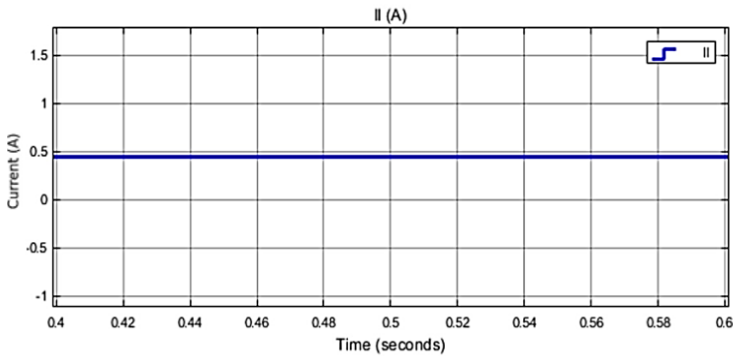

Figure 11. IiL (A) (time vs current)

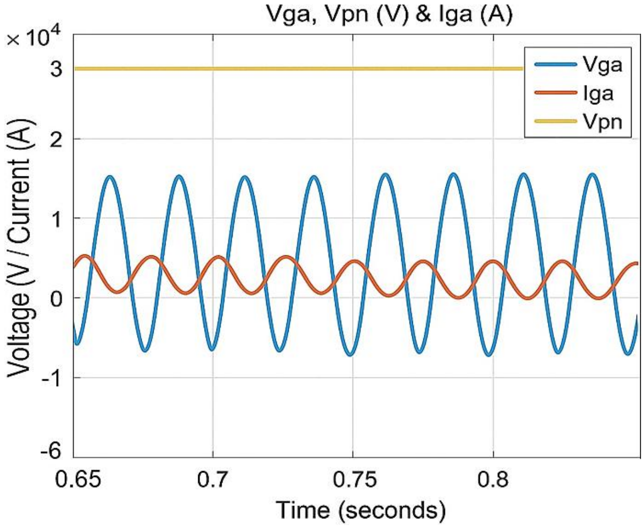

Figure 12. Vga, Vpn, and Iga (A) (time vs voltage, current)

5. CONCLUSION

Finally, a potential strategy for improving the multi-mode control of Z-source virtual synchronous generator (ZVSG) in photovoltaic (PV) systems is to use a fuzzy logic controller. When it comes to controlling the DC-link voltage and making sure the system is stable, the suggested control method takes use of both ZVSG and VSG. To enhance the system's dynamic reaction under varying operating circumstances, the fuzzy logic controller is used to real-time change the PI controller's gain. Results from the simulations demonstrate that the suggested control method is capable of achieving adequate performance in regulating the DC-link voltage, synchronising the grid, and rejecting disturbances. The fuzzy logic controller is superior than the conventional PI control approach in several respects, including its ability to lessen the system's sensitivity to load and irradiance fluctuations, as well as its overshoot and settling times. In addition, the suggested control method is more resistant to disturbances and has more flexibility in responding to unknown parameters. In conclusion, the suggested fuzzy logic controller-based improved multi-mode control of ZVSG for PV systems shows promising results in terms of PV system stability, efficiency, and reliability, and might have a significant impact in the area of renewable energy control and production.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Vempalle Rafi	✓	✓	✓			✓			✓	✓				
Pradyumna Kumar Dhal				✓	✓			✓		✓		✓	✓	
Shaik Hussain Vali				✓	✓				✓		✓	✓	✓	
Sadhu Radha Krishna					✓		✓			✓		✓		
Uppuluri Suryavalli			✓			✓		✓		✓		✓		
S. Vinoth John Prakash		✓	✓				✓			✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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APPENDIX

(a)

(b)

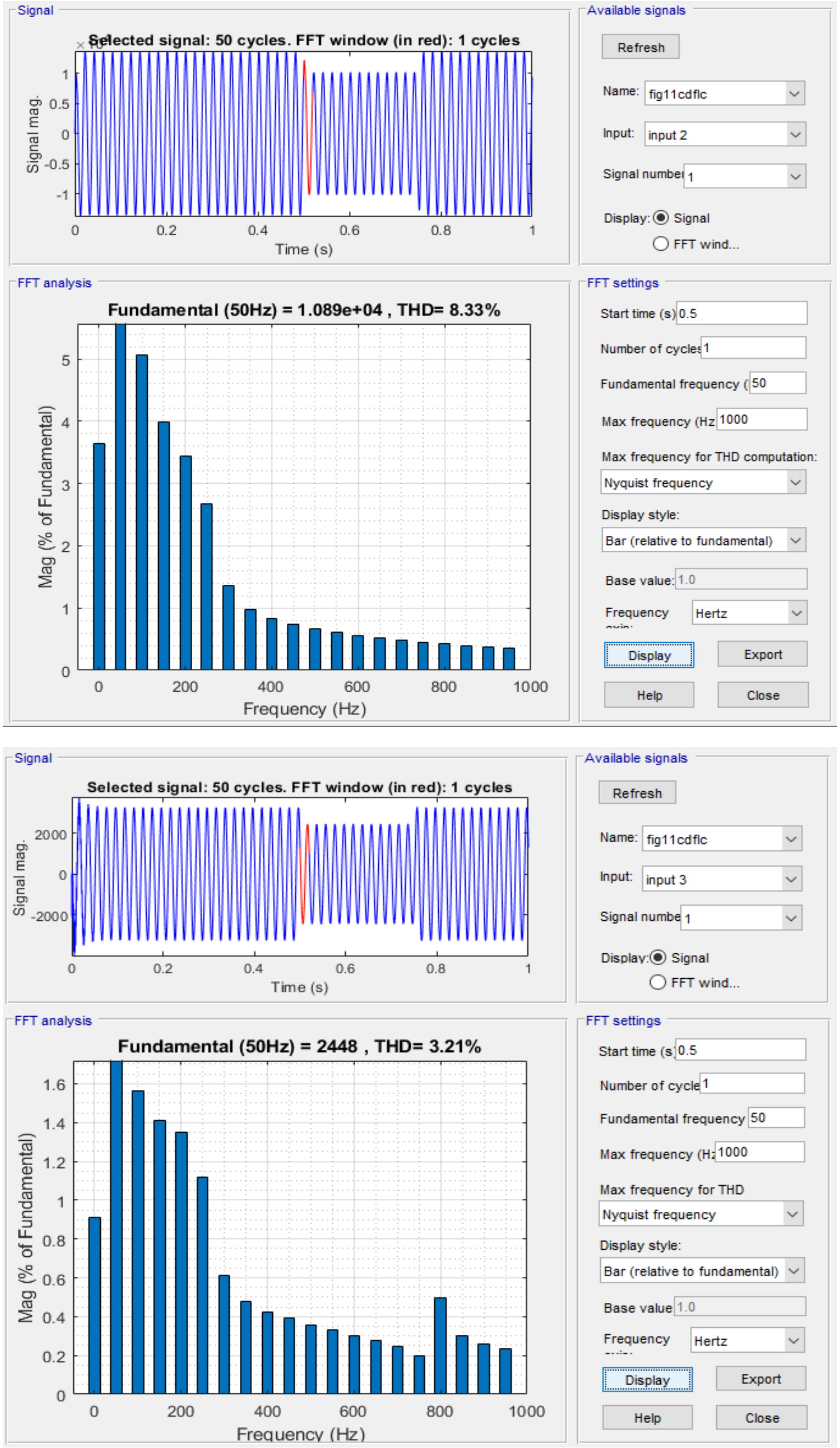

Figure 13. Total harmonic distortion: (a) using existing controller and (b) using proposed fuzzy logic controller

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