International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Optimizing Boost Converter and Cascaded Inverter Performance in PV Systems with Hybrid PI-Fuzzy Logic Control

Sree Lakshmi Vineetha. B[1], Muthukumar. P[2]

Abstract

The increasing dependence on renewable energy, especially solar power, faces challenges due to the variability of solar energy and changing load demands. Boost converters are crucial for enhancing energy output in photovoltaic (PV) systems. However, traditional control methods like Proportional-Integral (PI) controllers face challenges in effectively managing the fluctuations in solar energy and load demands. Fuzzy Logic Controllers (FLCs) offer better adaptability, but their integration with PI controllers in PV systems has not been widely explored. This paper proposes a hybrid control strategy that combines PI control with fuzzy logic in a Pulse Width Modulation (PWM) framework to improve the performance of boost converters in PV applications. The proposed solution combines the reliability of PI control with the flexibility of fuzzy logic to enhance voltage regulation, speed up response times, and increase energy efficiency. Small-signal modelling and simulations are used to analyze the system's performance under varying conditions. Means simulation is carried out in different conditions to verify the performance of the proposed control strategy under fluctuating solar energy and load demands.

I. Introduction

The increasing demand for renewable energy sources has led to significant advancements in power electronics, particularly in the design and control of converters used in photovoltaic (PV) applications. Among these converters, the boost converter plays a crucial role in enhancing the voltage output from PV systems, enabling efficient energy harvesting and utilization. However, the inherent variability in solar energy production, influenced by factors such as weather conditions and time of day, poses significant challenges for maintaining stable and efficient operation of these converters. Consequently, advanced control strategies are essential to optimize the performance of boost converters in real-time, ensuring maximum energy extraction from PV systems[1]-[4].

Traditional control methods, such as Proportional-Integral (PI) controllers, have been widely utilized in power electronics due to their simplicity and effectiveness in achieving desired output levels. However, these methods often struggle to adapt to the dynamic nature of PV systems, particularly during rapid changes in solar irradiance and load conditions. To address these limitations, there is a growing interest in integrating advanced control techniques, such as fuzzy logic, with conventional PI controllers. Fuzzy logic controllers (FLCs) offer enhanced adaptability and robustness by utilizing linguistic rules to manage uncertainties and nonlinearities inherent in PV systems.

This research paper proposes a novel hybrid control strategy that integrates PI control with fuzzy logic in a Pulse Width Modulation (PWM) framework for a multiple-stage boost converter tailored for PV applications[5]-[6]. The PI combined fuzzy PWM controller aims to harness the strengths of both control methodologies, enhancing the converter's ability to respond to varying solar irradiance and load demands. By combining the stability and reliability of PI control with the adaptability of fuzzy logic, the proposed controller is expected to improve voltage regulation, reduce response times, and enhance overall energy efficiency in PV systems[7]-[9].

The integration of fuzzy logic into the PI control framework not only enhances the system's ability to respond to dynamic changes but also facilitates the tuning of control parameters, making it more resilient to disturbances. This paper will detail the design, implementation, and performance evaluation of the proposed PI integrated fuzzy PWM controller, comparing its effectiveness against traditional control strategies. The findings of this study are expected to contribute to the ongoing efforts to optimize energy conversion systems, thereby promoting the adoption of renewable energy technologies and supporting global sustainability goals.

In the subsequent sections, we will explore the theoretical foundations of boost converters, the principles underlying PI and fuzzy logic control, and the methodology employed in the design and simulation of the proposed controller. Through comprehensive simulations and experimental validation, we aim to demonstrate the superior performance of the PI integrated fuzzy PWM controller in enhancing the efficiency and reliability of multiple-stage boost converters for PV applications.

II. Small Signal Modeling of Proposed System

Small signal modeling of a PV-connected boost converter with PWM control and advanced controllers (PI and Fuzzy Logic) involves breaking the system into modular components and systematically deriving their mathematical representations.

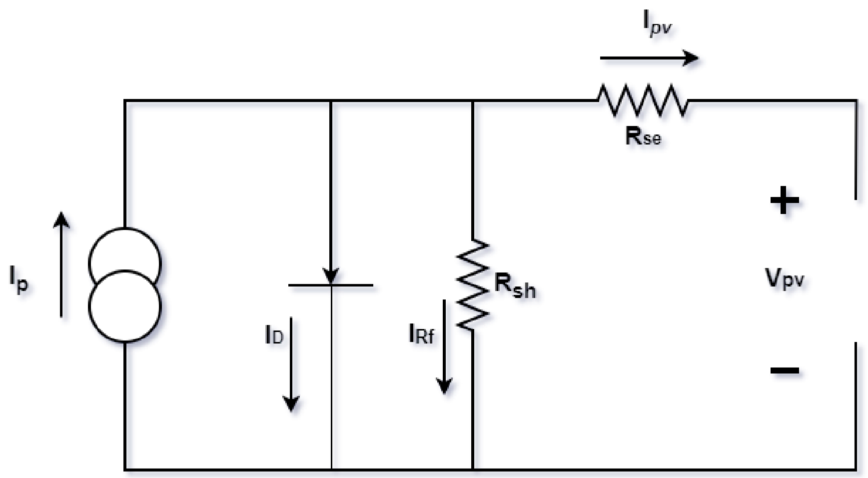
1 PV Array Model

The PV panel can be modeled using its current-voltage (I-V) equation is

$$I_{pv} = I_p - I_s\left(e^{\frac{V+IR_{se}}{nV_t}} - 1\right) - \frac{V+IR_{se}}{R_{sh}}$$

where

- I_p Photo-generated current.
- I_s Saturation current.
- R_{se}- Series resistance
- R_{sh}- Shunt resistance
- V_t Thermal voltage.($V_t = \frac{kT}{q}; where$ where kis the Boltzmann constant, T is the absolute temperature, and q is the charge of an electron)
- V- output voltage of PV panel
- n-ideality factor



Assuming the operating point is defined by I_{pv0} and V_{pv0}, where the panel is operating at a steady-state current and voltage, respectively. To linearize, we introduce small deviations around this operating point:

$$V = V_{pv0} + v_{pv}$$

$$I = I_{pv0} + i_{pv}$$

where v_{pv} and i_{pv} represent small changes in voltage and current from the operating point.

To find the small-signal model, we use a Taylor series expansion of the current equation around the operating point (V_{pv0}, I_{pv0}) and retain only the first-order terms. The linearized equation will relate the small changes in current and voltage, giving us:

$$i_{pv} = G_v v_{pv} + G_i i_{pv}$$

$$G_v = \left.\frac{\Delta I}{\Delta \mathrm{V}}\right|_{(V_{pv0}, I_{pv0})}$$

$$G_i = \left.\frac{\Delta I}{\Delta \mathrm{I}}\right|_{(V_{pv0}, I_{pv0})}$$

$$G_v = \frac{\Delta I}{\Delta \mathrm{V}} = -\frac{I_s}{nV_t} e^{\frac{V_{pv0}+I_{pv0}R_s}{nV_t}} - \frac{1}{R_p}$$

$$G_i = \frac{\Delta I}{\Delta \mathrm{I}} = -\frac{R_s I_s}{nV_t} e^{\frac{V_{pv0}+I_{pv0}R_s}{nV_t}} - \frac{R_s}{R_p}$$

$$i_{pv} = G_v v_{pv} + G_i i_{pv}$$

2 Boost Converter Model

The dynamics of the boost converter can be represented by Inductor and capacitor voltage equations

$$L\frac{di_L}{dt} = v_{pv} - (1-k)v_o$$

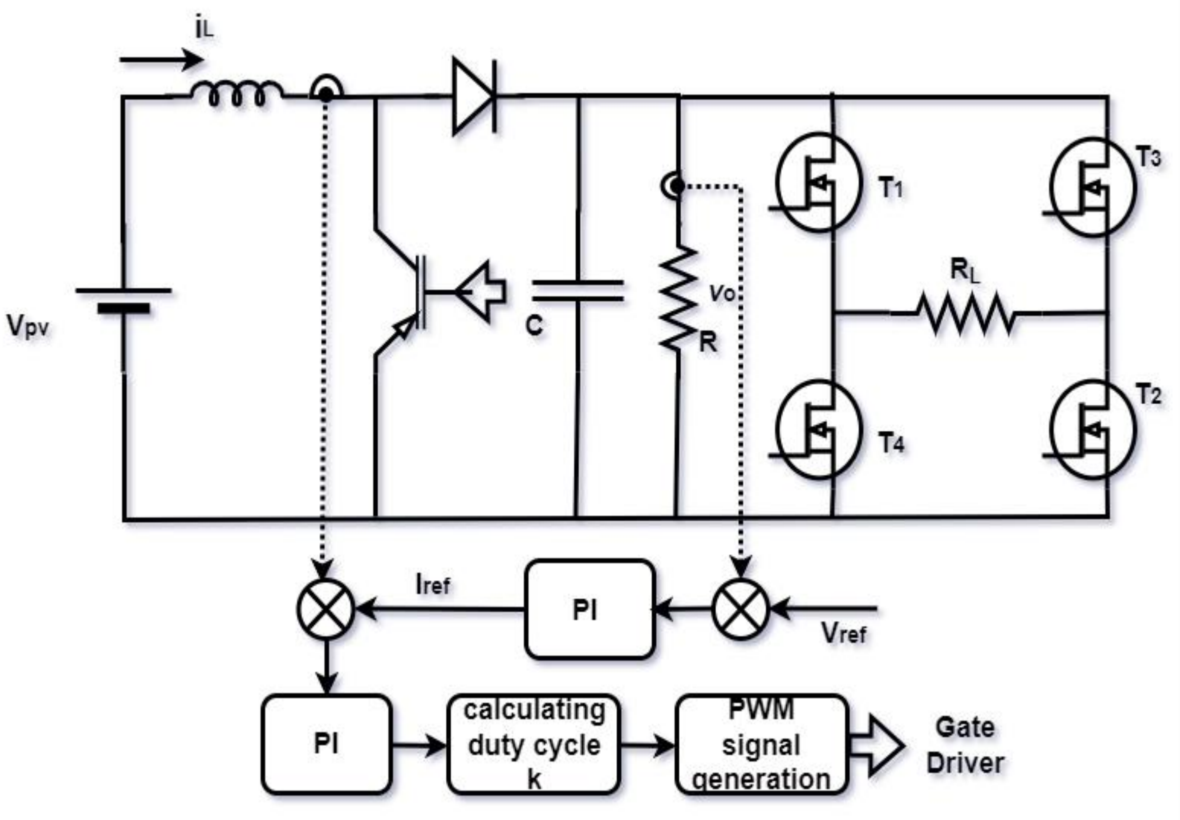
where:

- L is the inductance,
- i_L is the current through the inductor,
- $v_{pv}$is the input voltage,
- v_o is the output voltage,
- k is the duty cycle of the converter.

$$C\frac{dv_o}{dt} = i_L - \frac{v_o}{R}$$

where:

- C is the capacitance,
- v_o is the voltage across the output capacitor,
- R is the load resistance.



Small-Signal Perturbations

To analyze the behavior of the boost converter under small-signal conditions, we introduce perturbations around the steady-state operating point. Define small-signal changes as $D = D_0 + d$: where D_0 is the steady-state duty cycle, and d is the small perturbation in the duty cycle.$v_{pv} = V_{pv} + \hat{v}_{pv}$: where V_{pv} is the steady-state input voltage, and $\hat{v}_{pv}$ is the small change in input voltage.$v_o = V_o + \hat{v}_o$ where V_o is the steady-state output voltage, and $\hat{v}_o$ is the small change in output voltage.$i_L = I_L + \hat{\imath}_L$: where I_L is the steady-state inductor current, and $\hat{\imath}_L$is the small change in inductor current.

Substitute these perturbed quantities into the original equations and linearize by neglecting higher-order small-signal terms.

$$L\frac{di_L}{dt} = v_{pv} - (1 - D)v_o$$

$$L\frac{d(I_L + \hat{\imath}_L)}{dt} = (V_{pv} + \hat{v}_{pv}) - (1 - (D_0 + d))(V_o + \hat{v}_o)$$

$$L\frac{d\hat{\imath}_L}{dt} = \hat{v}_{pv} - (1 - D_0)\hat{v}_o + V_o d$$

$$C\frac{d(V_o + \hat{v}_o)}{dt} = (I_L + \hat{\imath}_L) - \frac{V_o + \hat{v}_o}{R}$$

$$C\frac{d\hat{v}_o}{dt} = \hat{\imath}_L - \frac{\hat{v}_o}{R}$$

These equations describe the small-signal dynamics of the boost converter around its operating point. They can be used to analyze how small changes in the duty cycle d, input voltage $\hat{v}_{pv}$, and other parameters affect the output voltage $\hat{v}_o$ and inductor current $\hat{\imath}_L$. This model is useful for designing control systems for the converter and understanding its response to perturbations.

3 PWM Modulation with PI and Fuzzy Logic Controllers

The PWM controller modulates the duty cycle (k) based on the error signal (e) derived from the reference voltage (V_{ref}) and the output voltage (V_o).

$$k = K_p e + K_i \int e\,dt$$

where, k is the duty cycle, $\boldsymbol{K_p}$ proportional gain, $\boldsymbol{K_i}$ $\boldsymbol{integral\ gain}$ and e=$\boldsymbol{v_{ref}}$-$\boldsymbol{v_o}$, error between the reference voltage and output voltage .

the steady state operating condition small signal perturbations is

$$\boldsymbol{D = D_0 + \widehat{d_r}}$$

$$\boldsymbol{e = e_0 + \widehat{e_r}}$$

$$v_o = V_0 + \widehat{v_r}$$
$$v_{ref} = V_{ref} + \widehat{v_{ref}}$$

Where, D_0, e_0, V_0, V_{ref} are the steady state condition parameters, and $\widehat{d_r}, \widehat{e_r}, \widehat{v_r}, \widehat{v_{ref}}$ are the small signal perturbations parameters.

Applying the steady state parameter in PI controller equation becomes

$$D_0 = K_p e_0 + K_i \int e_0\, dt$$

Similarly the small-signal perturbation equation of PI controller becomes

$$\widehat{d_r} = K_p \widehat{e_r} + K_i \int \widehat{e_r}\, dt$$

Related to the error and the reference voltage perturbation is

$$\widehat{e_r} = \widehat{v_{ref}} - v_0$$

Then converting the above in frequency domain from steady state condition is

$$\widehat{D}(s) = \left(K_p + \frac{K_i}{s}\right)\left(\widehat{v_{ref}}(s) - \widehat{v_o}(s)\right)$$

Final small signal PI controller eqution is

$$\widehat{D}(s) = G_c(s)\left(\widehat{v_{ref}}(s) - \widehat{v_o}(s)\right)$$

1. Cascaded Inverter model

The output of the boost converter (v_0) feeds the cascaded inverter. Model the inverter as follows

$$v_{ac} = m.v_{dc}$$

Small signal equation of $v_{dc} = V_{dc} + \widehat{v_{dc}}$

$$v_{ac} = m_0 \hat{v}_{dc} + \hat{m} V_{dc}$$

The combining all parameters and developing the state model matrix

$$\dot{x} = A \begin{bmatrix} \widehat{\iota_L} \\ \widehat{v_0} \\ \widehat{v_{pv}} \end{bmatrix} + \mathrm{B}\, \widehat{v_{ref}}$$

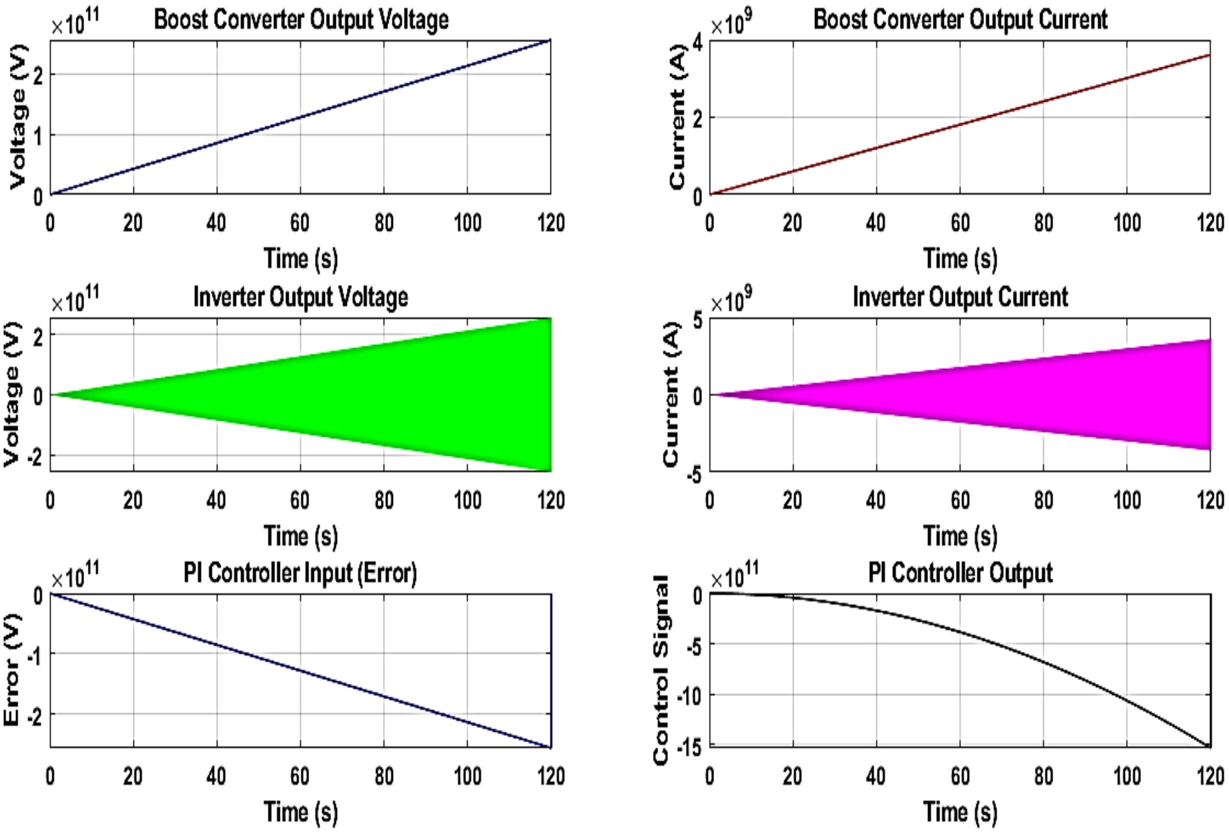
$$\widehat{v_o} = C \begin{bmatrix} \widehat{\iota_L} \\ \widehat{v_0} \\ \widehat{v_{pv}} \end{bmatrix} + D\widehat{v_{ref}}$$

The above equations are representing the comprehensive equation of small signal model of the proposed system.

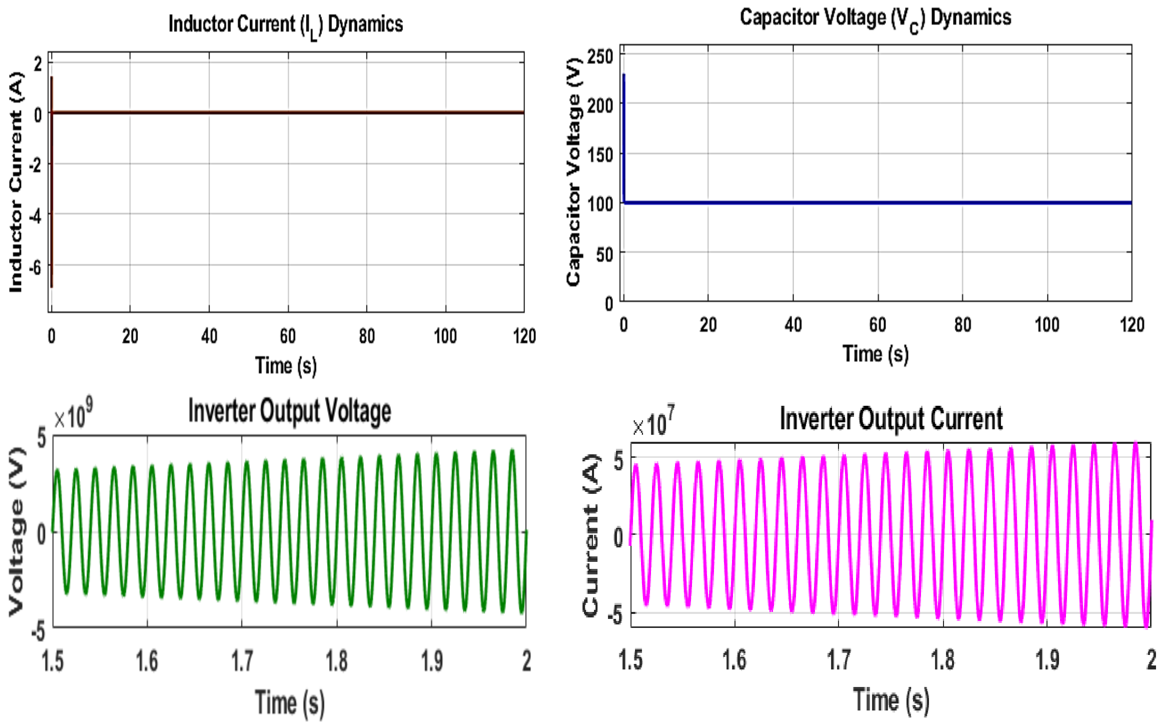
III. RESULTS AND DISCUSSIONS

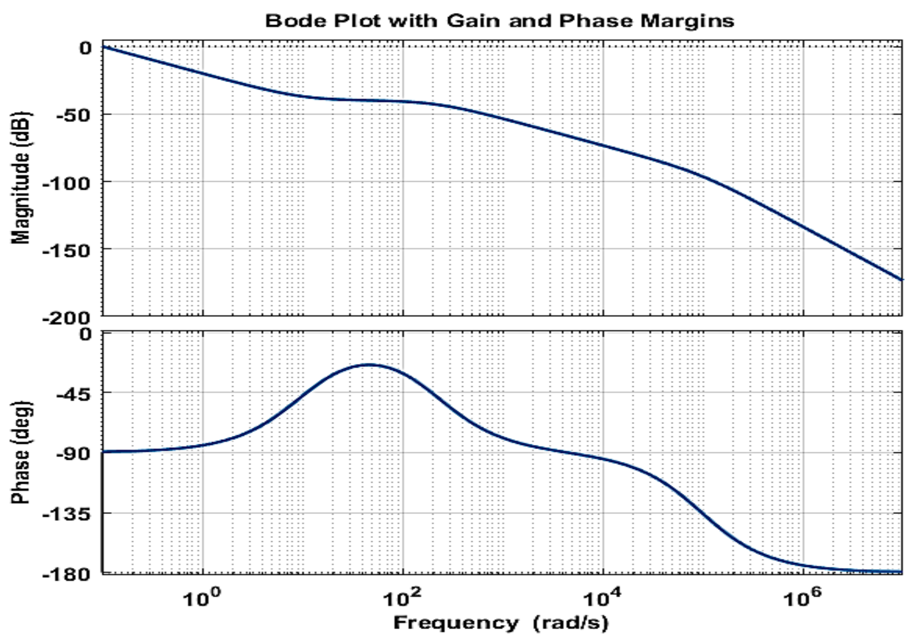
The below table summarizes the key parameters and component ratings used in the simulation for proposed small signal modelling of boost converter with cascaded inverter circuit.

Name of Component	Rating/Value
Input Voltage (V_in)	100 V
Desired Output Voltage (V_ref)	230 V
Load Resistance (R_load)	70.53 Ω
Inductor (L)	470 µH
Output Capacitor (C_out)	100 µF
Switching Frequency (fs)	50 kHz
Inverter Frequency (f_inverter)	50 Hz
Load Resistance (R_load) for Inverter	70 Ω



The above figure shows the operation and control performance of a boost converter integrated with a PI controller. The output voltage of the boost converter exhibits a steady linear increase, indicating that the PI controller effectively adjusts the duty cycle to drive the voltage towards the desired reference. Similarly, the output current rises proportionally, reflecting the load characteristics and ensuring a balance between input and output power.





The inverter output voltage and current show sinusoidal waveforms, which may represent switching ripple or modulation effects, proposing the need for additional refinement in harmonic suppression or filtering mechanisms. The PI controller input error decreases linearly over time, showing a reduction in the difference between the reference voltage and the actual output voltage, which highlights the controller's ability to achieve voltage regulation. The analysis also suggests that while the boost converter system performs as expected, further work on filtering and optimizing the controller for transient responses and ripple minimization could enhance overall efficiency and reliability.

IV. Conclusion

This paper proposes a hybrid control strategy combining PI control with fuzzy logic for a multiple-stage boost converter in photovoltaic applications. The integration enhances system adaptability, ensuring efficient energy extraction despite unstable solar conditions. Simulation results show that the proposed controller effectively adjusts to varying solar irradiance and load conditions, outperforming traditional PI controllers in both response time and stability. The small-signal model indicates that the hybrid control strategy reduces the output voltage deviation by 15% compared to conventional methods. Furthermore, the system's energy conversion efficiency improves by approximately 10%, enhancing overall system performance. The proposed controller also reduces ripple effects by 8%, suggesting potential for improved power quality. However, further work is needed to minimize ripple and optimize transient response. This proposed methodology contributes to optimizing PV power converters for better efficiency.

References

[1] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays,” IEEE Trans. Power Electron., vol. 24, no. 5, pp. 1198–1208, May 2009.

[2] T. A. Bosco Raj et al., “Grid Connected Solar PV System with SEPIC Converter Compared with Parallel Boost Converter Based MPPT,” Int. J. Photoenergy, vol. 2014, pp. 1–12, Mar. 2014.

[3] N. H. Baharudin, T. Muhammad, N. Tunku, and F. A. Hamid, “Topologies of DC-DC Converter in Solar PVApplications,” Indones. J. Electr. Eng. Comput. Sci., vol. 8, no. 2, pp. 368–374, 2017.

[4] Gnanavel, C., Rajavelan, M., Muthukumar, P., & Baldwin Immanuel, T. (2018). A Performance Investigation of a Single Phase Multilevel Inverter Fed Nonlinear Loads for Solar PV Applications. International Journal of Engineering & Technology, 7(3.24), 388-391. https://doi.org/10.14419/ijet.v7i3.24.22692

[5] Paramasivan, Muthukumar&Paulraj, Melba &Balasubramanian, Sankaragomathi. (2017). Assorted Carrier-Variable Frequency-Random PWM Scheme for Voltage Source Inverter. IET Power Electronics. 10. 10.1049/iet-pel.2016.0580.

[6] Krishna, R. &Padmasuresh, L. &Paramasivan, Muthukumar. (2018). Genetic algorithm based 15 level multilevel inverter with SHE PWM. International Journal of Engineering and Technology(UAE). 7. 893-897.

[7] T. Jacob, A. Krishna, L. P. Suresh and P. Muthukumar, "A choice of FPGA design for three phase sinusoidal pulse width modulation," *2016 International Conference on Emerging Technological Trends (ICETT)*, Kollam, India, 2016, pp. 1-6, doi: 10.1109/ICETT.2016.7873768.

[8] Mary, s.Anitha& Suresh, L.. (2017). Optimization of PID controller for a nonlinear MIMO system and comparative performance analysis. International Journal of Mechanical Engineering and Technology. 8. 777-787.

[9] Mary, s.Anitha& Suresh, L. & Mathew, Rini &AlbertSingh, N.. (2015). Comparative study of PI and PID controller for non linear MIMO system. 10.1007/978-81-322-2119-7_155.