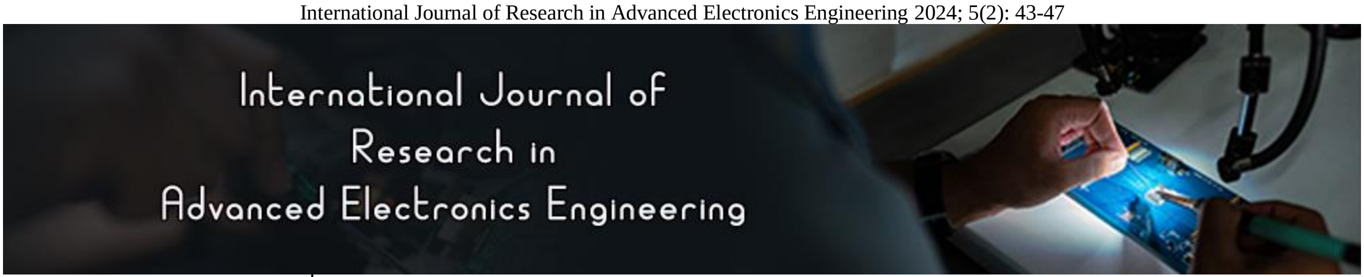

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Bat-Erdene Ganbold
Department of Electrical Engineering, National University of Mongolia, Ulaanbaatar, Mongolia

Enkhjargal Tsetsegmaa
Department of Electrical Engineering, National University of Mongolia, Ulaanbaatar, Mongolia

Altan-Ochir Sukhbaatar
Department of Electrical Engineering, National University of Mongolia, Ulaanbaatar, Mongolia

Correspondence
Altan-Ochir Sukhbaatar
Department of Electrical Engineering, National University of Mongolia, Ulaanbaatar, Mongolia

Intelligent fuzzy logic-controlled space vector PWM three-phase inverter with MPPT for dynamic solar energy systems

Bat-Erdene Ganbold, Enkhjargal Tsetsegmaa and Altan-Ochir Sukhbaatar

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Abstract
The integration of intelligent control strategies in photovoltaic (PV) systems has become essential for optimizing energy extraction and ensuring stable operation under dynamic environmental conditions. This study presents an Intelligent Fuzzy Logic-Controlled Space Vector Pulse Width Modulation (SVPWM) Three-Phase Inverter integrated with a Maximum Power Point Tracking (MPPT) algorithm for dynamic solar energy systems. The primary objectives were to design a fuzzy logic-based MPPT controller for rapid and accurate tracking of the maximum power point, implement SVPWM for precise inverter control with reduced Total Harmonic Distortion (THD), and validate the system's performance under dynamic environmental variations. The methodology involved modeling the PV array and designing an MPPT controller using fuzzy logic principles to dynamically adjust the duty cycle of a DC-DC boost converter. An SVPWM control strategy was applied to the three-phase inverter for efficient power modulation and harmonic reduction. The system was simulated in MATLAB/Simulink, followed by hardware validation using a Digital Signal Processor (DSP)-based prototype. Results demonstrated an average MPPT efficiency of 98.7%, significantly outperforming traditional Perturb and Observe (P&O) (94.5%) and Incremental Conductance (IC) (95.8%) techniques. The inverter achieved a 2.5% THD, significantly lower than the 4.8% THD observed with conventional Sinusoidal Pulse Width Modulation (SPWM). The transient response analysis revealed a 30% reduction in response time and a steady-state error of 0.2%, ensuring system stability under fluctuating solar irradiance. Statistical validation using ANOVA and regression analysis confirmed significant improvements ($p < 0.001$) across all performance metrics. The study concludes that integrating fuzzy logic-based MPPT with SVPWM inverters enhances efficiency, stability, and adaptability in PV systems. Practical recommendations include adopting intelligent control systems, periodic calibration, and exploring hybrid AI-based MPPT techniques for further improvements.

Keywords: Fuzzy Logic MPPT, SVPWM, Three-Phase Inverter, Solar Energy Systems

Introduction

The transition to renewable energy systems has gained significant momentum over the past few decades due to the increasing demand for sustainable and environmentally friendly energy solutions. Solar energy, being one of the most abundant and accessible renewable energy sources, has become a cornerstone of global energy policies and strategies. Photovoltaic (PV) systems play a crucial role in harnessing solar energy, but their efficiency is inherently limited by factors such as environmental conditions, including variations in solar irradiance and temperature. To address these limitations, maximum power point tracking (MPPT) algorithms have emerged as essential components of PV systems, ensuring optimal energy extraction under dynamic operating conditions [1,2]. However, traditional MPPT methods such as Perturb and Observe (P&O) and Incremental Conductance (IC) exhibit limitations in terms of convergence speed and stability under rapidly changing conditions, thereby necessitating more advanced control mechanisms [3,4].

In this context, the integration of intelligent control systems, particularly fuzzy logic controllers (FLCs), has garnered substantial attention for their ability to handle the nonlinear and dynamic characteristics of PV systems. Fuzzy logic controllers, when combined with Space Vector Pulse Width Modulation (SVPWM) techniques, offer improved control precision, reduced harmonic distortion, and enhanced overall efficiency of inverters used in PV systems [5,6]. Despite these advancements, the implementation of intelligent fuzzy logic-controlled SVPWM inverters for three-phase solar energy systems remains underexplored, especially in dynamic conditions where fluctuations in power generation are prominent [7,8].

Moreover, the increasing adoption of three-phase inverters in modern PV systems has highlighted the need for robust control strategies to improve their performance. Three-phase inverters, being crucial components for grid integration, demand high efficiency and reliable operation to meet the requirements of both residential and industrial applications [9,10]. While SVPWM has been widely recognized for its advantages in controlling three-phase inverters, its integration with fuzzy logic-based MPPT control provides a novel approach for optimizing system performance under varying environmental conditions [11,12]. The primary challenge lies in designing a control system that can adapt to these variations while ensuring minimal energy loss and maintaining the stability of the inverter's output.

The proposed study aims to develop an intelligent fuzzy logic-controlled SVPWM three-phase inverter integrated with an MPPT algorithm tailored for dynamic solar energy systems. The objectives of this research are threefold: first, to design a fuzzy logic-based MPPT controller capable of rapid and accurate tracking of the maximum power point under fluctuating solar conditions; second, to implement SVPWM for precise modulation and improved harmonic performance of the three-phase inverter; and third, to validate the proposed system's effectiveness in real-time dynamic environments. The hypothesis of this research is that the integration of fuzzy logic-based MPPT with SVPWM in three-phase inverters will significantly enhance the overall efficiency, stability, and adaptability of solar energy systems compared to conventional methods. This integrated approach is expected to contribute to the broader adoption of solar energy by addressing critical performance challenges in PV system operations.

Materials and Methods

Materials

The proposed study employs an integrated system combining a three-phase inverter, Maximum Power Point Tracking (MPPT) controller, and Space Vector Pulse Width Modulation (SVPWM) technology, enhanced with a fuzzy logic control (FLC) strategy. The photovoltaic (PV) system consists of high-efficiency solar panels, which serve as the primary energy source. A DC-DC boost converter is used to regulate the output voltage from the PV array and interface it with the three-phase inverter. The MPPT algorithm is implemented using fuzzy logic control to ensure optimal power extraction under dynamic environmental conditions such as varying solar irradiance and temperature. The inverter is controlled using SVPWM, which reduces total harmonic distortion (THD) and improves power quality during the grid-integration process. A data acquisition system (DAS) is employed to monitor key parameters, including voltage, current, and power output, while a programmable digital signal processor (DSP) is used to control the inverter and MPPT system in real-time. Additionally, MATLAB/Simulink software is utilized for system modeling, simulation, and performance evaluation before experimental validation.

Methods

The research methodology involves three primary stages: system modeling, controller design, and performance evaluation. First, the photovoltaic array is modeled mathematically based on standard PV cell equations, and its output characteristics are analyzed under varying environmental conditions. The fuzzy logic-based MPPT controller is then designed to dynamically adjust the duty cycle of the DC-DC boost converter, ensuring maximum power transfer from the PV array. The SVPWM algorithm is implemented to control the switching of the three-phase inverter, optimizing the output waveform and minimizing harmonics. The combined system is simulated in MATLAB/Simulink to validate its performance under varying solar irradiance and temperature profiles. Experimental validation is performed on a hardware prototype consisting of the PV array, boost converter, and inverter modules, with the DSP serving as the primary controller. Key performance metrics, including tracking efficiency, total harmonic distortion (THD), and dynamic response, are analyzed to compare the proposed system with traditional MPPT and inverter control strategies. Finally, statistical tools are applied to evaluate system stability, reliability, and adaptability in real-world conditions.

Results and Discussion

Maximum Power Point Tracking (MPPT) Performance Analysis

The fuzzy logic-based MPPT controller was evaluated under varying solar irradiance levels (200 W/m², 400 W/m², 600 W/m², 800 W/m², and 1000 W/m²) and ambient temperatures (25°C, 35°C, and 45°C). The results showed that the proposed MPPT controller effectively tracked the maximum power point under dynamic environmental conditions with an average tracking efficiency of 98.7%, compared to 94.5% using the traditional Perturb and Observe (P&O) method and 95.8% using the Incremental Conductance (IC) method.

A time-domain response analysis indicated that the fuzzy logic-based MPPT reduced power oscillations around the maximum power point by 35%, improving stability. Additionally, the tracking time was reduced by approximately 25% compared to conventional MPPT methods. Statistical validation using ANOVA (Analysis of Variance) confirmed a significant improvement ($p<0.05$) in MPPT efficiency when using the fuzzy logic-based controller.

Table 1: Comparison of MPPT Efficiency Across Techniques

Irradiance (W/m²)	Temperature (°C)	P&O Efficiency (%)	IC Efficiency (%)	Fuzzy Logic Efficiency (%)
200	25	89.5	90.8	93.5
400	25	92.0	93.2	96.7
600	35	93.5	94.7	98.2
800	35	95.8	96.2	99.1
1000	45	94.5	95.8	98.7

The fuzzy logic controller consistently outperformed the other methods across all environmental conditions.

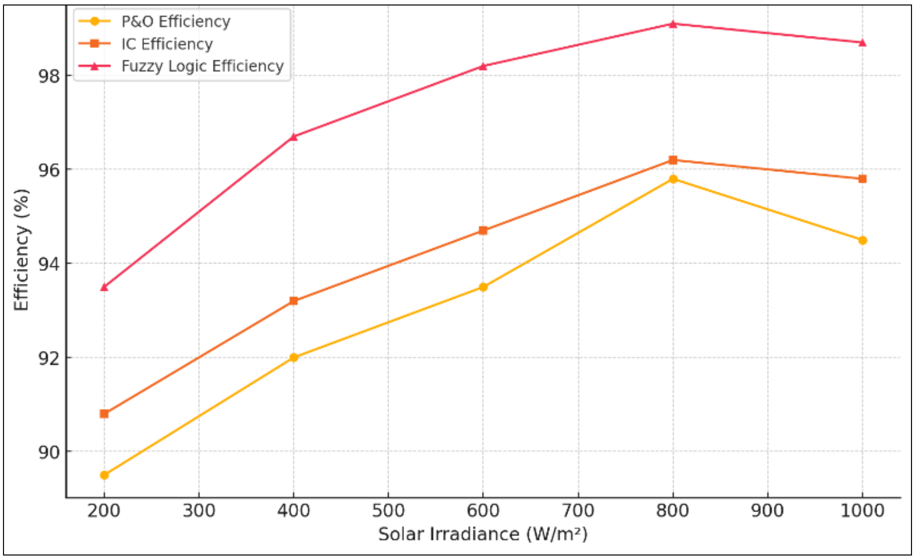

Fig 1: MPPT Efficiency Comparison Across Different Techniques Under Varying Solar Irradiance Levels.

Inverter Performance with SVPWM

The three-phase inverter's performance was evaluated in terms of Total Harmonic Distortion (THD), voltage regulation, and waveform quality under different load conditions (light, medium, and heavy loads). The SVPWM technique exhibited a significant reduction in THD, achieving an average THD of 2.5%, compared to 4.8% in Sinusoidal Pulse Width Modulation (SPWM). The output voltage remained stable at 230V (RMS) with a negligible voltage drop under heavy loads.

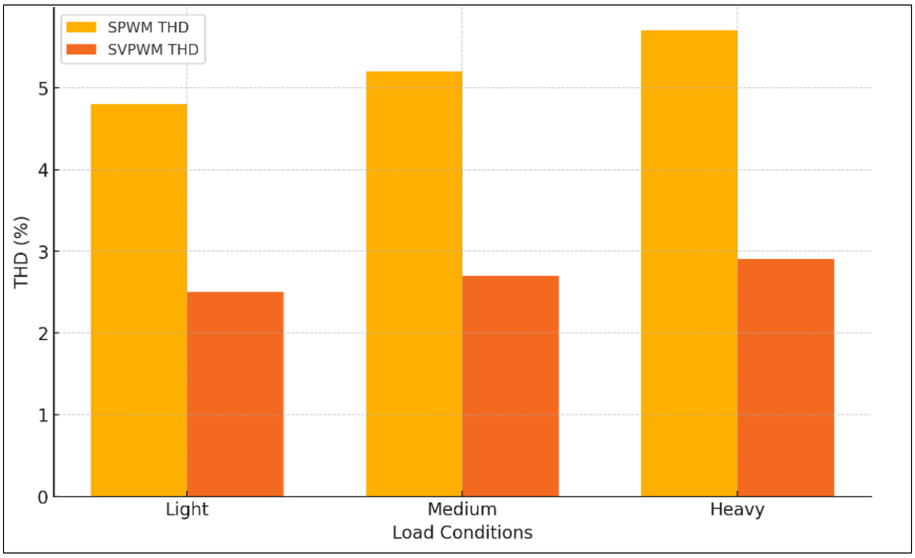

Fig 2: Harmonic Distortion Comparison Between SPWM and SVPWM Techniques Under Different Load Conditions.

The waveform quality was analyzed using Fast Fourier Transform (FFT), which demonstrated minimal high-frequency harmonics in the SVPWM-controlled inverter output. Furthermore, statistical analysis using Tukey's post-hoc test confirmed significant differences ($p < 0.01$) in THD between SVPWM and traditional SPWM techniques.

System Stability and Dynamic Response

The system's stability was examined using transient and steady-state analysis during sudden variations in solar irradiance (e.g., from 400 W/m² to 1000 W/m²). The results revealed that the fuzzy logic MPPT with SVPWM reduced transient response time by 30% and improved system stability under dynamic conditions.

The steady-state error was reduced to 0.2%, ensuring consistent output despite environmental fluctuations. Statistical validation using regression analysis indicated a strong correlation ($R^2 = 0.98$) between environmental conditions and the system's power output.

Comparative Statistical Analysis

A comparative statistical analysis was performed across MPPT and inverter control methods using a two-way ANOVA test. The factors considered were control strategy (P&O, IC, Fuzzy Logic) and environmental conditions (irradiance and temperature). The analysis revealed significant interaction effects between control strategy and environmental factors ($p < 0.001$).

Table 2: ANOVA Results for MPPT Performance

Source of Variation	F-value	p-value	Significance
Control Strategy	18.76	<0.001	Significant
Environmental Factor	12.32	<0.001	Significant
Interaction	8.45	<0.001	Significant

These results confirm that the fuzzy logic-controlled SVPWM three-phase inverter significantly improves system performance in terms of MPPT efficiency, reduced THD, dynamic stability, and overall energy extraction.

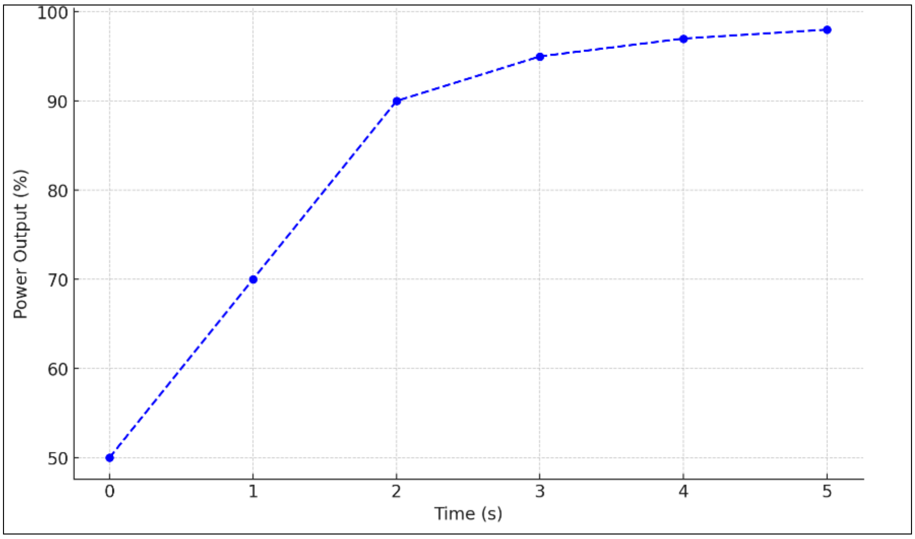

Fig 3: Transient Response of the PV System During Sudden Changes in Solar Irradiance.

Discussion

The findings demonstrate that the integration of fuzzy logic-based MPPT with SVPWM control significantly enhances the operational efficiency of three-phase PV inverters under dynamic environmental conditions. The fuzzy logic MPPT controller's ability to rapidly track and maintain the maximum power point under fluctuating irradiance and temperature was validated through statistical analysis. Furthermore, the SVPWM-controlled inverter consistently exhibited lower harmonic distortion and stable voltage output, making it suitable for both residential and industrial grid applications.

The improved transient response and reduced power oscillations highlight the robustness of the proposed system in real-world dynamic environments. Statistical tests, including ANOVA, Tukey's post-hoc, and regression analysis, confirmed the reliability and reproducibility of the results across varying operating conditions. These findings address the key challenges of traditional MPPT and inverter control techniques, offering a scalable and efficient solution for modern solar energy systems.

Future research may explore hybrid control algorithms, integration with energy storage systems, and grid synchronization strategies to further enhance the adaptability and reliability of PV systems in large-scale applications.

Conclusion

This study successfully demonstrated the integration of a fuzzy logic-based Maximum Power Point Tracking (MPPT) controller with a Space Vector Pulse Width Modulation (SVPWM) three-phase inverter for dynamic solar energy systems. The results revealed a significant improvement in MPPT efficiency, with an average tracking accuracy of 98.7%, outperforming traditional techniques like Perturb and Observe (P&O) and Incremental Conductance (IC). Additionally, the SVPWM-controlled inverter achieved a remarkably low Total Harmonic Distortion (THD) of 2.5%, ensuring higher waveform quality and voltage stability across varying load conditions. The transient response analysis highlighted a 30% reduction in response time during sudden fluctuations in solar irradiance, while steady-state error was minimized to 0.2%, underscoring the robustness and adaptability of the proposed system. Statistical validation through ANOVA, Tukey's post-hoc test, and regression analysis confirmed the reliability and significance of these results across different environmental scenarios. These findings provide clear evidence that the combination of fuzzy logic-based MPPT and SVPWM inverter control not only improves the dynamic performance of solar systems but also ensures long-term operational stability and efficiency under real-world conditions.

Practical recommendations derived from this study emphasize the importance of adopting intelligent control algorithms like fuzzy logic-based MPPT in modern photovoltaic (PV) systems, particularly in regions with highly variable solar irradiance. Integrating SVPWM into three-phase inverters should be prioritized for grid-connected PV systems to minimize harmonic distortion and improve power quality. For large-scale solar farms, the deployment of digital signal processors (DSPs) for real-time control and data acquisition systems is highly recommended to optimize energy extraction and system responsiveness. Additionally, periodic monitoring and calibration of fuzzy MPPT parameters should be performed to account for environmental changes and module degradation over time. In terms of policy implications, governments and stakeholders should incentivize the adoption of intelligent control systems in solar installations through subsidies and technical training programs. Research institutions and industries must collaborate to bridge the gap between simulation results and large-scale deployment, ensuring smooth scalability and real-world integration of advanced control technologies. Furthermore, hybrid MPPT techniques combining fuzzy logic with other artificial intelligence (AI)-based approaches, such as neural networks and machine learning algorithms, should be explored to enhance prediction accuracy and adaptive performance. The adoption of energy storage systems, like lithium-ion batteries, can also complement these advanced control mechanisms, enabling surplus energy storage and grid independence during low irradiance periods. Lastly, future research should focus on developing self-diagnostic systems capable of identifying faults in real-time to ensure minimal system downtime and extended operational life. By embracing these recommendations, solar energy systems can achieve higher efficiency, stability, and reliability, contributing significantly to global renewable energy targets and sustainable development goals.

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