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Enhancing of single-stage grid-connected photovoltaic system using fuzzy logic controller

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ABSTRACT

The power generated by photovoltaic (PV) systems is influenced by environmental factors. This variability hampers the control and utilization of solar cells' peak output. In this study, a single-stage grid-connected PV system is designed to enhance power quality. Our approach employs fuzzy logic in the direct power control (DPC) of a three-phase voltage source inverter (VSI), enabling seamless integration of the PV connected to the grid. Additionally, a fuzzy logic-based maximum power point tracking (MPPT) controller is adopted, which outperforms traditional methods like incremental conductance (INC) in enhancing solar cell efficiency and minimizing the response time. Moreover, the inverter's real-time active and reactive power is directly managed to achieve a unity power factor (UPF). The system's performance is assessed through MATLAB/Simulink implementation, showing marked improvement over conventional methods, particularly in steady-state and varying weather conditions. For solar irradiances of 500 and 1,000 W/m^2, the results show that the proposed method reduces the total harmonic distortion (THD) of the injected current to the grid by approximately 46% and 38% compared to conventional methods, respectively. Furthermore, we compare the simulation results with IEEE standards to evaluate the system's grid compatibility.

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1. INTRODUCTION

The integration of photovoltaic (PV) systems into the global energy matrix has gained significant momentum due to their inherent advantages, including renewable and clean energy generation. These systems harness solar radiation to produce electricity, contributing to reduced carbon emissions and greater energy independence [1]. However, the performance of PV systems is intricately tied to external factors, such as temperature variations and solar radiation intensity. These environmental dependencies hinder the precise control and efficient utilization of generated power, posing challenges to achieving optimal system performance [2]. This research endeavors to surmount these limitations by proposing an innovative approach that amalgamates advanced control techniques with state-of-the-art power conversion strategies, leading to a paradigm shift in grid-connected PV systems [1].

The performance of PV systems is critically linked to environmental dynamics, affecting their output power and overall efficiency. This dependence complicates the task of extracting maximum power from solar cells, particularly during periods of erratic weather conditions [3]. Conventional methods for power conversion and control often fall short in mitigating these challenges, leading to suboptimal power quality, heightened distortion, and reduced overall system efficiency [4], [5].

In the context of grid-connected PV systems utilizing voltage source inverter (VSI), two main configurations stand out: two-stage and single-stage systems. The two-stage system, potentially pricier due to an added DC/DC conversion stage, offers better power flow control, reducing voltage fluctuations and harmonics [6]. The two-stage system, however, introduces complexity and potential efficiency losses. On the other hand, the single-stage approach boasts cost-effectiveness by directly integrating PV generation with the grid, resulting in fewer components and higher efficiency [5]. However, this simplicity leads to issues like harmonic distortions and voltage spikes due to fluctuations in PV array voltage during weather changes. The choice depends on balancing economic factors, efficiency, and addressing power quality challenges within the dynamic landscape of grid-connected PV systems [7], [8].

In grid-connected PV systems utilizing VSIs, effective control strategies are essential to enhance performance, improve power quality, and reduce total harmonic distortion (THD). Voltage-oriented control (VOC) is a prevalent approach that aligns the current vector with the line voltage vector using internal current control loops [5]. However, limitations arise from the need for coordinated translation and active/reactive component decoupling.

An alternative strategy, direct power control (DPC), involves selecting optimal voltage vectors through a switching table approach. By comparing estimated and reference active/reactive power values and considering vector position, this method offers simplified calculations without requiring pulse width modulation (PWM) modulators or inner current loops [9]. Despite the promise of DPC, conventional DPC (C-DPC) has drawbacks such as difficulty discerning error magnitudes and voltage vector sectors, leading to potential instability, frequency ripples, and undesired harmonics affecting THD. This prompts ongoing research into refined control strategies for improved grid-connected PV system performance [10].

In this study, fuzzy logic direct power control (FL-DPC) is provided. It combines fuzzy logic (FL) and direct power control (DPC). FL-DPC uses linguistic variables to handle uncertainty and directly controls power flow in converters. FL-DPC uses fuzzy logic to adjust control signals for DPC, enhancing performance, adaptability, and efficiency in power converter systems. It solves the issue of selecting a proper switching voltage vector, which reduces the ripple of active and reactive power and, therefore, the current injected into the grid. In addition, to optimize power output, fuzzy logic-based maximum power point tracking (FL-MPP) is proposed. It reduces error during steady-state operation as well as error during operation under rapid environmental conditions. Further, it increases the response time. The following is a brief outline of our contributions: i) A FL-DPC for switching inverters is proposed that utilizes a single-stage converter. The integration of fuzzy logic in DPC facilitates precise voltage vector selection, mitigating issues associated with harmonic injection and voltage spikes during grid connection, ii) We integrate MPP with FL to enhance power extraction. FL-MPP optimizes power output by dynamically adjusting perturbation step sizes, enabling efficient and rapid maximum power point tracking, iii) Our research includes a rigorous simulation and comparative analysis to validate the performance of the proposed method. Through these simulations, conducted using MATLAB/Simulink, we demonstrate significant advancements over the conventional method. Key areas of improvement include enhanced stability and power quality.

The remainder of this paper is organized as follows: Section 2 presents an overview of related work. Sections 3 and 4 demonstrate the conventional and fuzzy logic-based controller methods for elucidating the integration of two systems with the grid. Section 5 offers comprehensive details of the simulation setup, showcasing the results and performance improvements achieved through the proposed framework. Finally, Section 7 concludes the paper by summarizing the research contributions and discussing potential future directions in the field of advanced PV system control and integration

2. RELATED WORK

The integration of renewable sources like solar into the existing power network has led to challenges with power quality. Currently, two main control strategies within the voltage-based control category, namely VOC and DPC, have encountered issues. In [5], both VOC and DPC strategies are examined and compared under heavy loads. VOC excels at quickly reaching the desired voltage reference, yet it exhibits higher THD compared to DPC. In [1] and [9], VSI using DPC has been proposed. The approach does not necessitate an inner-loop current regulator. The approach uses a control mechanism to control real and reactive power based on DPC. It, however, has a relatively higher time response compared to VOC.

Recently, model predictive control (MPC) has gained popularity as an effective strategy, especially MPC-DPC, which maintains a constant switching frequency [7], [10], [11]. While MPC-DPC generally demonstrates favorable closed-loop behavior, it does introduce additional computational demands and the risk of suboptimal voltage sequence selection. However, these methods exhibit variable switching frequencies, which complicates the implementation of line filters due to unpredictable harmonic patterns caused by the fluctuating switching frequency [12].

The direct control of solar cell connections to the power grid is investigated in [7] and [8]. It uses both single-stage and two-stage configurations. Ensuring the proper integration of solar cells into the grid is pivotal to incorporating renewable energy sources. Various techniques have been investigated, with some involving direct control of solar cell capacity. These configurations range from two-stage systems, which separate conversion and control functions, to single-stage systems that simplify the process, reducing costs and improving efficiency [13], [14]. However, because the input voltage of single-stage PV grid-connected systems fluctuates over a wide range of voltage boost operations, it may be difficult to stabilize the output voltage at a desired value. So, control strategies must be employed to optimize energy extraction from the solar panels and ensure grid stability [15].

To optimize maximum power from solar panels and maintain grid stability, effective control strategies are crucial. Perturb and observe (P and O) and INC are well-known MPPT methods due to their simplicity [3]. P and O is easy to implement but has limitations tied to fixed perturbation step sizes. Larger steps enhance tracking speed but introduce fluctuations, while smaller steps reduce fluctuations but might impact efficiency during rapid environmental changes [3]. To mitigate these limitations, a solution called FL-MPP has emerged. FL-MPP adapts the perturbation step size dynamically, optimizing MPP tracking efficiency while minimizing fluctuations and steady-state losses [16]. This adaptive approach accommodates varying environmental conditions effectively, enhancing overall performance [17].

3. CONVENTIONAL METHOD

This section presents an in-depth overview of the DPC methodology and its integration into a grid-connected PV system. DPC uses a switching table to choose voltage vectors based on active and reactive power errors and the source voltage vector's position, introduced by "T. Ohnishi" and further developed by "T. Noguchi and I. Takahachi" [18]. Figure 1 illustrates the overall schematic of the system that typically uses the DPC method together with incremental conductance (INC) MPPT. The schematic depicts the conventional elements of a grid-connected PV setup. Line currents and voltages are measured, and Clark's transformation is applied to calculate instantaneous active and reactive power as follows [19]:

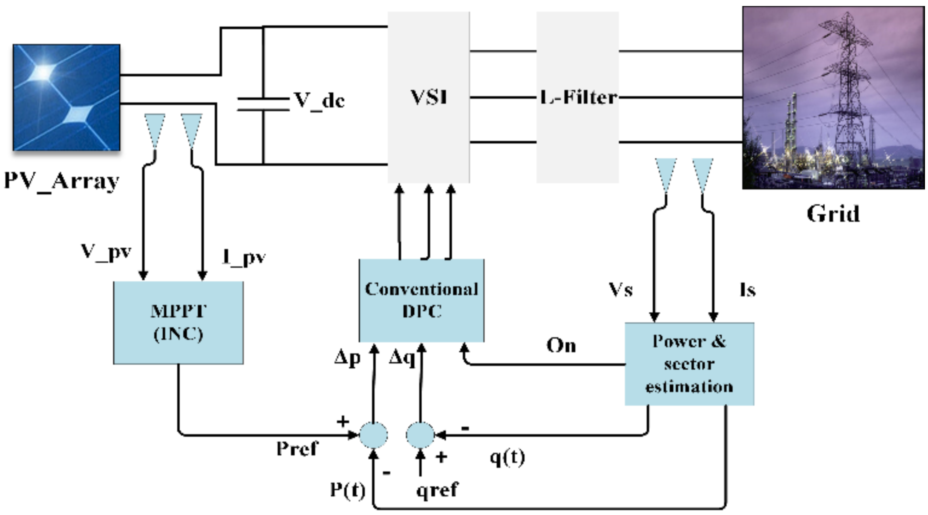


Figure 1. PV gride connected using conventional method

$$P_s(t) = V_{sa} \cdot i_{sa} + V_{sb} \cdot i_{sb} + V_{sc} \cdot i_{sc} \tag{1}$$

$$q_s(t) = -\frac{1}{\sqrt{3}}(V_{sa} - V_{sb}) \cdot i_{sa} + (V_{sb} - V_{sc}) \cdot i_{sb} + (V_{sc} - V_{sa}) \cdot i_{sc} \tag{2}$$

Two-level hysteresis controllers play a vital role in the control strategy by responding to the disparities between estimated and reference power. These controllers ensure precise power regulation. The controller's output is determined using (3) and (4), represented by digital signals d_p and d_q[6], [10], [16]:

$$d_p = \begin{cases} 1, P_{ref} - P \geq 0 \\ 0, P_{ref} - P < 0 \end{cases} \quad (3)$$

$$d_q = \begin{cases} 1, q_{ref} - q \geq 0 \\ 0, q_{ref} - q < 0 \end{cases} \quad (4)$$

The grid voltage vector is digitally represented by dividing it into 12 sectors at 30-degree intervals. Figure 2 represents the fixed positions of these sectors. These sectors are feasible through the utilization of the following numerical expression [16]:

$$(n-2)\frac{\pi}{6} < \theta_n \leq (n-1)\frac{\pi}{6}, \quad (5)$$

where $n \in [1:12]$. Moreover, to determine the angle of the voltage vector, an inverse tangent function is employed, as indicated by (6) [16]:

$$\theta = arctan\frac{V_\alpha}{V_\beta} \quad (6)$$

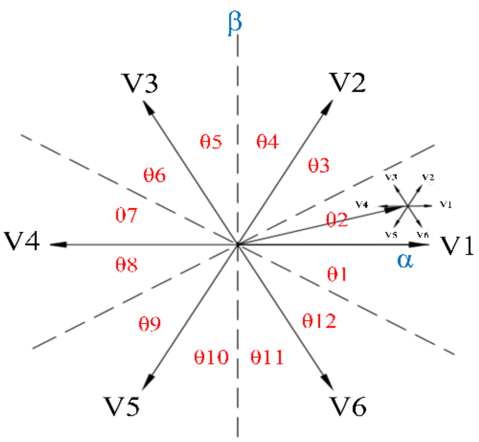


Figure 2. The voltage vector divided to 12 sectors

Following this, the digitized signals d_p, d_q, and θ_n are introduced into the switching table as inputs, with the inverter's voltage vector as the resultant output. To make optimal selections of inverter switch states during each sampling period, Table 1 serves as a guide. Table 1 presents the C-DPC switching table, which maps combinations of d_q and d_P signals to specific voltage vectors across angular sectors. This table guides the optimal selection of inverter switch configurations for efficient control [20], [21].

Table 1. Switching table of C-DPC

d_q	d_P	Θ1& Θ12	Θ2&Θ3	Θ4&Θ5	Θ6&Θ7	Θ8&Θ9	Θ10&Θ11
0	0	V2	V3	V4	V5	V6	V1
	1	V1	V2	V3	V4	V5	V6
1	0	V4	V5	V6	V1	V2	V3
	1	V6	V1	V2	V3	V4	V5

To assess the effects of changes in power, a modified INC method is employed. This technique detects slight changes in voltage and current within the PV array. Moreover, the controller's role has been modified to compute the reference power for DPC. This adjustment aims to maximize power output from the PV system [3]. Figure 3 delineates the step-by-step process of the INC MPPT, while Figure 4 represents the power-voltage characteristic of the INC technique. In this process, if the rate of change of current to voltage, $\frac{\Delta I}{\Delta V}$, is greater than the ratio of current to voltage, $\frac{I}{V}$, the reference power, $Pref$, is adjusted downward by a specific value, ΔP. Conversely, if the rate of $\frac{\Delta I}{\Delta V}$ is smaller than $\frac{I}{V}$, the $Pref$ is incremented by the same value,

ΔP. When the change rate aligns with the negative, $\frac{I}{V}$, indicating a position at the MPP, the $Pref$ remains unchanged. This logical structure ensures effective management of the $Pref$ to optimize the system's operation around the MPP, enhancing overall power generation efficiency.

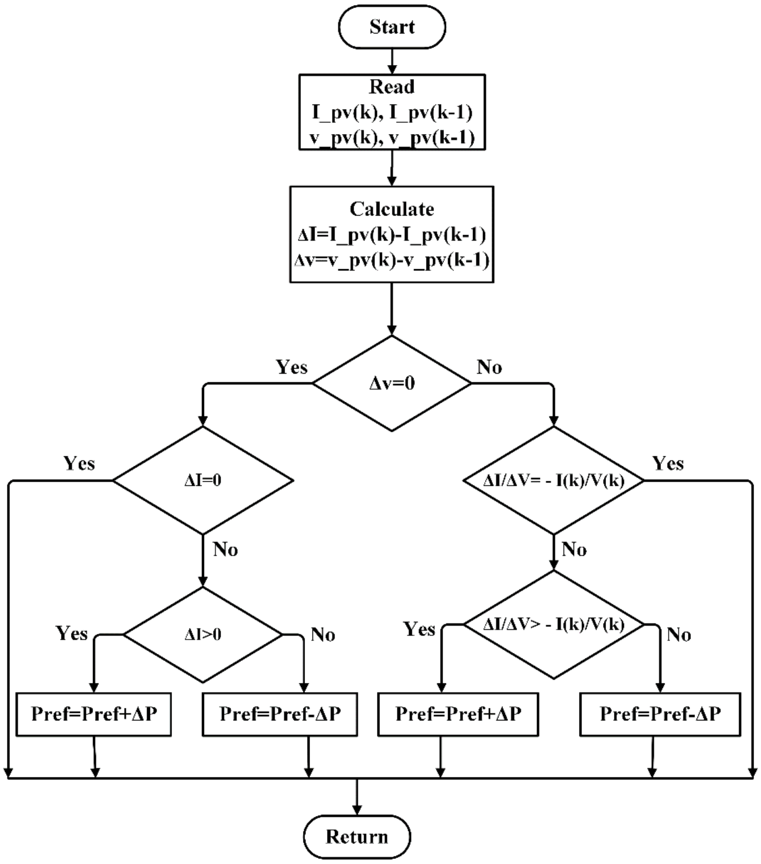


Figure 3. Flowchart of INC MPPT

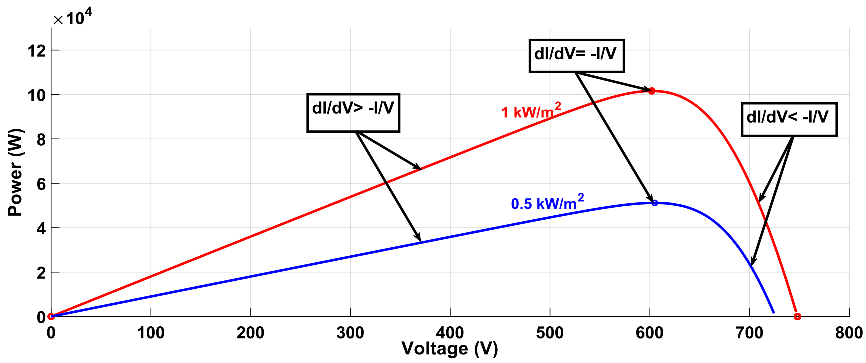


Figure 4. Operational modes of INC technique on P-V carves

4. PROPOSED METHOD

This section presents a FL-DPC that improves power flow in converters. FL-DPC uses fuzzy logic to manage uncertainties and fine-tune control signals, leading to smoother power flow, reduced grid current ripple, and more stable operation. Additionally, the study introduces FL-MPP for efficient power output, even in changing environments. FL-MPP enhances steady-state performance, adapts well to rapid environmental shifts, and speeds up control responses.

The proposed method integrates double fuzzy systems. It presents an innovative replacement for both the traditional DPC and INC MPPT methods. Initially, the FL-DPC approach was introduced to simplify the hysteresis comparators and switching tables from C-DPC. Notably, from Table 1, neighboring sectors share the same switching voltage vector states, allowing sectors to merge to result in sectors spanning 60 degrees rather than 30 degrees. Therefore, this led to a reduction in the sector count from twelve to six. To facilitate this, the space voltage vector plane is shifted and rotated 30° clockwise. This adjustment is illustrated in Figure 5.

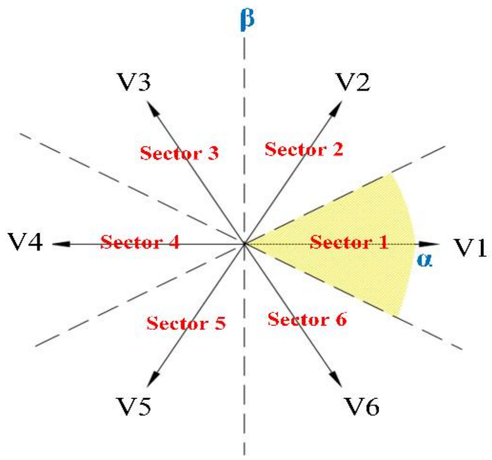


Figure 5. the voltage vector divided to 6 sectors

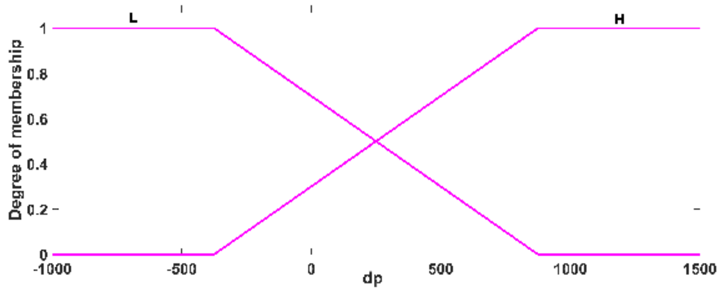
In FL-DPC, the key input parameters include active power errors, d_p, reactive power errors, d_q, and voltage vector angle, $\sec_i$. Its output is the voltage vector number, Vi [18], [22]. Figure 6 illustrates the membership functions of FL-DPC, where the membership functions for inputs d_p and d_q are categorized into two linguistic variables: high (H) and low (L), as presented in Figures 6(a) and 6(b). For precise control, the voltage vector's position is segmented into seven distinct fuzzy sets ($\sec_1$ to $\sec_7$) using triangular membership functions, covering the full operational range $(-180^{\circ}, 180^{\circ})$. This distribution is visualized in Figure 6(c), while the arrangement of the membership function for Vi is depicted in Figure 6(d). Table 2 details the set of 28 rules applied within the VSI for voltage vector regulation. These rules are derived using the FLC methodology, incorporating the middle of maximum (MOM) technique for defuzzification. The implementation of these rules is critical for effectively managing the fuzzy logic component in the DPC scheme, ensuring optimized control and response within the system.

The widely used MPPT algorithms, such as P and O and INC, are recognized for their simplicity but tend to oscillate and converge slowly around the MPP. To address these limitations, a novel FLC-MPP technique is introduced. This method offers stability, ease of implementation, and independence from a mathematical model of the system. However, a fundamental understanding of PV system behavior is essential for designers. The core concept behind FLC-MPP lies in changing the rate of increase of the reference power, unlike the fixed-step approach of typical MPPT algorithms. This enhancement accelerates the system's response time towards reaching the MPP [23]. The inputs for the FLC-MPP consist of error E and change of error CE, calculated using (7) and (8), respectively, where $V(k)$ and $P(k)$ represent the voltage and power of the PV array at the instantaneous sample time, kTs [23]–[25].

$$E = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \tag{7}$$

$$CE(k) = E(k) - E(k-1) \tag{8}$$

The output of the proposed controller is a change in incremental power reference, dP , to readjust the operating point towards the optimal position. This iterative process continues until the slope becomes zero. The linguistic variables big negative (BN), small negative (SN), zero (Z), small positive (SP), and big positive (BP) represent the input and output variables. The defuzzification method employs the center-of-area approach. Table 3 outlines the MPPT fuzzy logic controller's rules, totaling 25 rules, which govern its operation [23]–[25].



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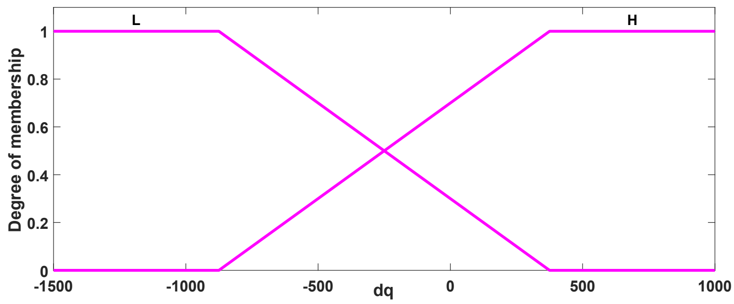

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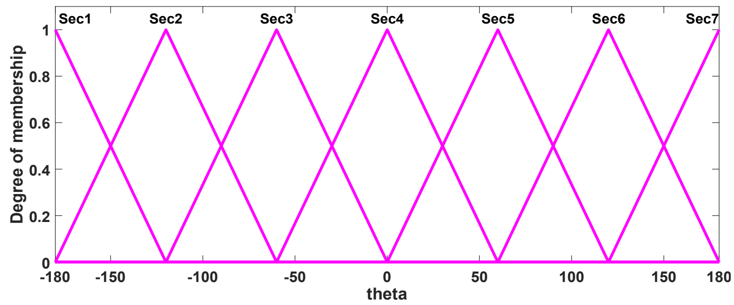

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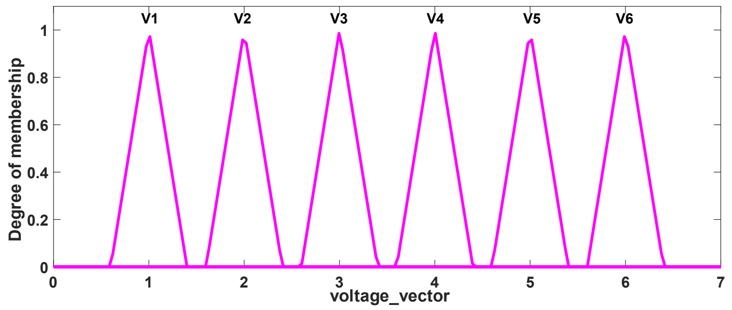


(d)

Figure 6. Membership functions of FL-DPC (a) the active power error, (b) the reactive power error, (c) the voltage vector position, and (d) the switching states variable

Table 2. The fuzzy logic of DPC rules

d_q	d_p	Sec1 & Sec7	Sec2	Sec3	Sec4	Sec5	Sec6
L	L	V3	V4	V5	V6	V1	V2
	H	V2	V3	V4	V5	V6	V1
H	L	V5	V6	V1	V2	V3	V4
	H	V1	V2	V3	V4	V5	V6

Table 3. The MPPT fuzzy logic controller's rules

CE \ E	BP	SP	Z	SN	BN
BP	BP	BP	BP	SP	Z
SP	BP	BP	SP	Z	SN
Z	SP	SP	Z	SN	SN
SN	SP	Z	SN	BN	BN
BN	Z	SN	BN	BN	BN

5. SIMULATION RESULTS

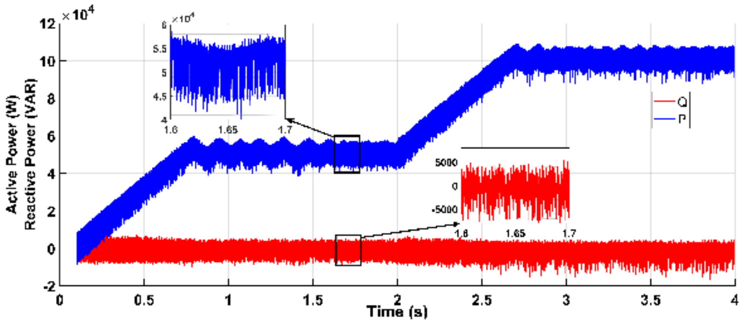
This section introduces a MATLAB/Simulink model designed for the comprehensive simulation and analysis of a grid-connected PV system. The model encompasses both conventional and novel techniques, starting with a baseline test of the former. The simulation includes a three-phase breaker activated at t = 0.1 seconds, with the initial solar irradiance set at 500 W/m² and the temperature at 25 °C. A dynamic scenario is then introduced, transitioning solar irradiation from 500 to 1,000 W/m² at t = 2 seconds while the temperature remains constant. The resulting PV curves in Figure 4, clarify the system's response to changing solar inputs. Additionally, the model evaluates the unity power factor (UPF) by setting the reference reactive power to zero. Table 4 consolidates key parameter values. This section lays the foundation for a deeper exploration of simulation outcomes, offering insights into the grid-connected PV system's behavior and performance.

Table 4. Electrical network parameters

Switching Period	33.3 µs	DC-bus capacitor	4,000 µF
Reactor Resistance	0.56 Ω	Source voltage frequency	50 Hz
Reactor inductance	1.5 mH	AC voltage	400 V

Figure 7 presents the dynamic response of the active and reactive power for two systems. Figures 7(a) and 7(b) emphasize a notable advantage of the proposed method, specifically representing the output of the inverter circuit in a PV system and demonstrating reduced ripples in active and reactive power at the inverter output. It is coupled with a quicker response in tracking maximum power compared to the conventional method. In traditional methods, the ripple range in active power was approximately 15 kW (ranging from 43 to 58 kW), whereas in our method, it was reduced to approximately 10 kW (ranging from 44 to 54 kW). In addition, in our method, the ripple range in reactive power was approximately 8 kVAR (-5 to 3 kVAR), while in the conventional method, it was approximately 12 kVAR (-7 to 5 kVAR). This reduction in ripple magnitude in our method is a significant finding, as it directly correlates with a reduction in THD. This suggests that the proposed method can effectively regulate power output while adapting promptly to changes in solar irradiance. Figures 8 depict the DC voltage and current of the PV array for two systems. The faster reach to steady-state values with minimal fluctuations in the DC bus voltage, as illustrated in Figures 8(a) and 8(b), holds paramount significance as an indicator of the system's stability. Notably, while the conventional method requires approximately 0.75 seconds to achieve this state, the proposed method accomplishes the same in approximately 0.5 seconds. This performance differential showcases a substantial advantage of the proposed method, which outperforms the conventional method by a factor of around 1.5. The proposed method's ability to achieve this underscore its potential to maintain voltage stability in varying operating conditions. The reduction in overshoot observed in the DC voltage values further emphasizes the proposed method's superior transient response. This reduction can contribute to minimizing voltage fluctuations and enhancing the overall stability of the PV system.

The application of fast Fourier transform (FFT) analysis to line currents, as presented in Figure 9 and Figure 10, yields insights into power quality. Both control methods exhibit near-sinusoidal line currents, signifying good waveform quality. However, the proposed method consistently maintains THD values, indicating a cleaner current waveform. This outcome has a direct impact on reducing harmonic distortion and its associated negative effects on the power system. Maintaining injected DC current within the limits (0.5%) specified by the IEEE-929 Standard is critical for grid stability. The proposed method excels in this regard, effectively curbing injected DC current to values well below the prescribed 0.5%. This achievement is particularly noteworthy when considering the changing solar irradiance conditions, affirming the method's robustness in managing injected DC components. Consequently, FFT analysis reaffirms the near-sinusoidal characteristics of the line currents, further supported by previous sections. Furthermore, Figures 11(a) and (b) display the grid voltage and inverter current for both systems. Initially, the inverter current was zero before the activation of the three-phase breaker. Upon activation, there was a gradual increase in current due to power being fed into the grid. A significant increase in current is also observed at $t = 2$ seconds, aligning with a change in solar irradiation levels from 500 to 1,000 W/m². Additionally, the in-phase relationship between grid voltage and inverter current was noted, confirming that the power factor for both systems is unity. The comparison in Table 5 confirms the superiority of the proposed method in terms of THD across varying solar irradiances. For irradiances 500 and 1,000 W/m^2, the results show that the proposed method reduces the THD of the injected current to the grid by approximately 46% and 38% compared to conventional methods, respectively. Notably, the proposed method's values align harmoniously with the IEEE standards (IEEE 1574 [26], IEEE 519 [27], and IEEE 929 [28]), which advocate for THD levels below 5% across diverse weather conditions. Moreover, the injected DC current values remain comfortably below the 0.5% threshold for both methods, a fact corroborated by the data displayed in Figures 9 and 10. The presented results illustrate that the proposed method offers substantial benefits in terms of power quality, response time, and compliance with IEEE standards when compared to the conventional approach. These findings are crucial for practitioners and researchers working on photovoltaic systems, as they provide insights into enhancing system performance, stability, and adherence to industry standards.



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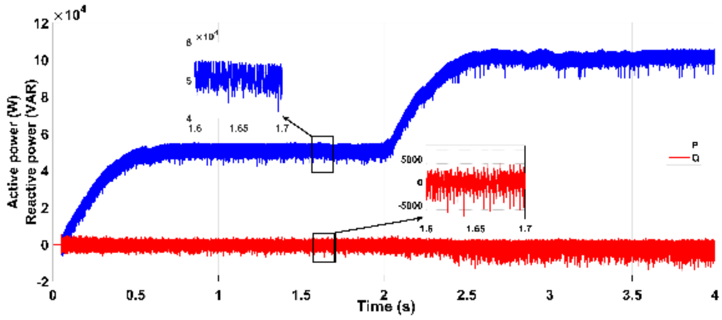
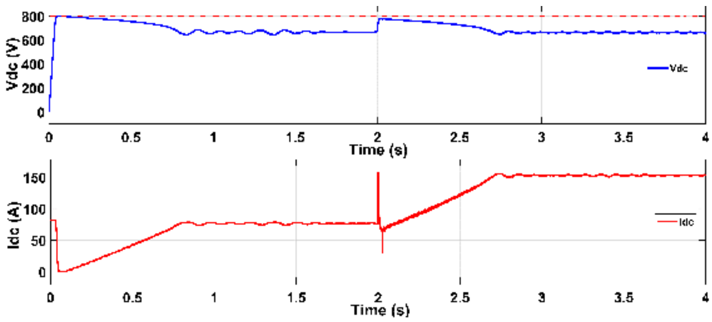


(b)

Figure 7. Dynamic response of the active and reactive power for two systems (a) conventional method and (b) proposed method



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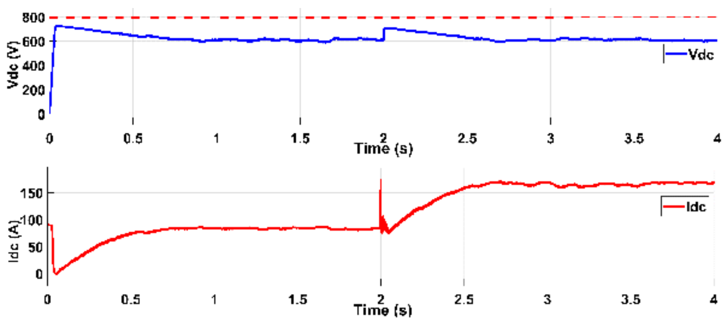
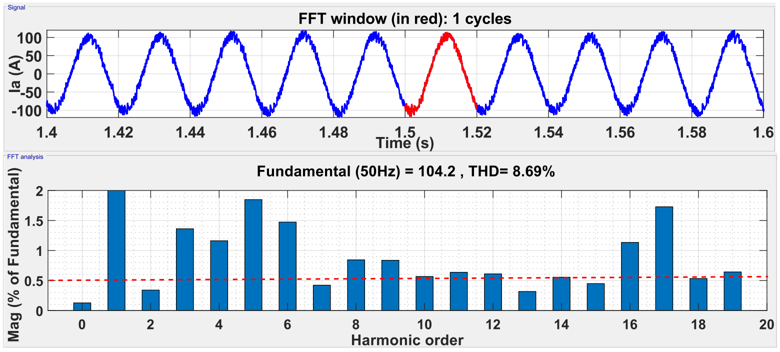


(b)

Figures 8. DC voltage and current of PV array for two systems (a) conventional method and (b) proposed method



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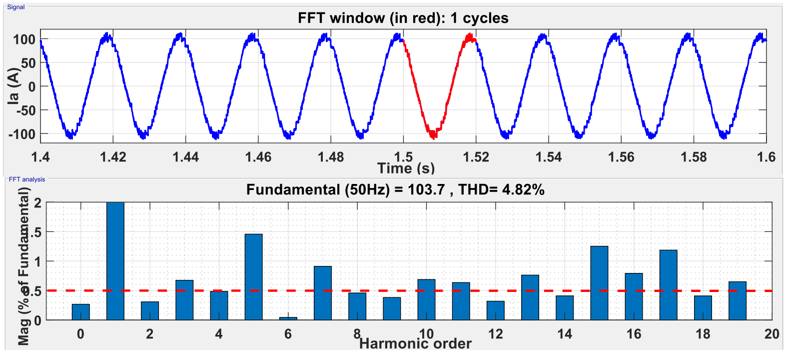
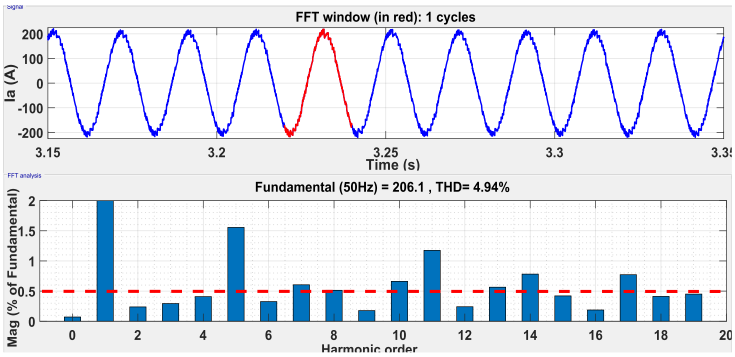


(b)

Figures 9. FFT analysis for two systems at solar irradiance 500 W/m^2 (a) conventional method and (b) proposed method



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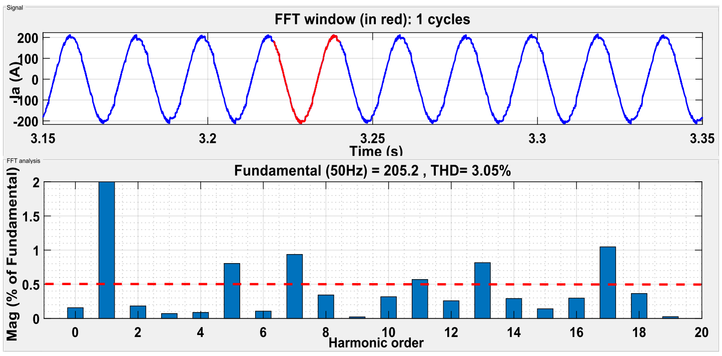
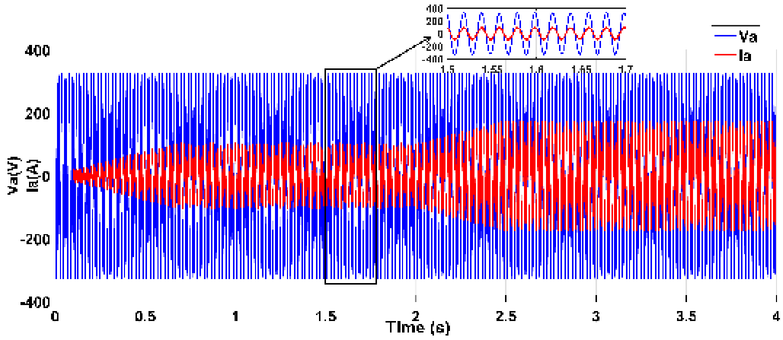


(b)

Figures 10. FFT analysis for two systems at solar irradiance 1,000 W/m^2 (a) conventional method and (b) proposed method



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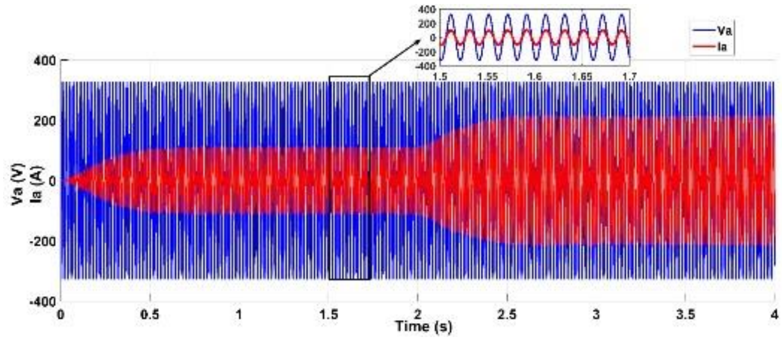

(b)

Figures 11. Grid voltage and inverter current for two systems (a) conventional method, (b) proposed method

Table 5. THD for different solar irradiances

Solar irradiance	500 W/m^2	1,000 W/m^2
THD (Conventional method)	**8.69% > 5%**	4.94% < 5%
THD (Proposed method)	4.63% < 5%	3.05% < 5%

6. DISCUSSION AND IMPLICATIONS

Our research represents a significant leap in the field of PV system, primarily through FL-DPC and FL-MPP. This approach substantially enhances power quality and system stability. In particular, under variable environmental conditions, which is a critical advancement. Appling fuzzy logic enables a more nuanced and adaptable response to changing environmental factors, which a key challenge in traditional photovoltaic systems. Our method shows superior performance compared to existing approach. It notably reducing the total harmonic distortion and offering greater adaptability to environmental changes. Hence, it potentially revolutionizes the future PV system design.

7. CONCLUSION

In this paper, we introduce a robust and effective solution for improving the power quality and performance of grid-connected PV systems. The FL-DPC method, along with FL-MPP, offers substantial advantages over conventional techniques, ranging from power regulation to response time and compliance with IEEE standards. The findings of this study contribute valuable insights into the field of photovoltaic systems, offering a promising avenue for enhancing the efficiency, stability, and grid compatibility of renewable energy systems. As the world continues to transition towards cleaner energy sources, the proposed method holds the potential to play a pivotal role in shaping the future of grid-connected PV systems. Additionally, we plan to explore the system's efficiency in our future work. We believe that this will be a valuable extension of our current research.

REFERENCES

[1] Y. Gui, C. Kim, C. C. Chung, J. M. Guerrero, Y. Guan, and J. C. Vasquez, "Improved direct power control for grid-connected voltage source converters," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 10, pp. 8041–8051, Oct. 2018, doi: 10.1109/TIE.2018.2801835.

[2] B. Meryem, N. Ahmed, and F. Ahmed, "Photovoltaic power control using fuzzy logic and fuzzy logic type 2 MPPT algorithms and buck converter," *Advances in Technology Innovation*, vol. 4, no. 3, pp. 125–139, Jun. 2019. Accessed: Jan. 29, 2024. [Online]. Available: https://ojs.imeti.org/index.php/AITI/article/view/3960

[3] B. Saleh, A. M. Yousef, F. K. Abo-Elyousr, M. Mohamed, S. A. M. Abdelwahab, and A. Elnozahy, "Performance analysis of maximum power point tracking for two techniques with direct control of photovoltaic grid -connected systems," *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, vol. 44, no. 1, pp. 413–434, Mar. 2022, doi: 10.1080/15567036.2021.1898496.

[4] B. E. Youcefa, A. Massoum, S. Barkat, S. Bella, and P. Wira, "DPC method for grid connected photovoltaic system acts as a shunt active power filter implemented with processor in the loop," in *2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM)*, Algiers, Algeria, 2018, pp. 1-7, doi: 10.1109/CISTEM.2018.8613370.

[5] J. Y. Lee, R. Verayiah, K. H. Ong, A. Ramasamy, and M. B. Marsadek, "Voltage oriented control and direct power control strategies in solving under and overvoltage conditions for heavy load application on malaysian distribution representative network," *Electrical Engineering*, vol. 103, no. 3, pp. 1597–1612, Jan. 2021, doi: 10.1007/s00202-020-01143-y.

[6] M. Morey, N. Gupta, M. M. Garg, and A. Kumar, "Performance analysis of voltage sensorless based controller for two-stage grid-connected solar PV system," *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 1, pp. 444–452, Mar. 2023, doi: 10.11591/ijpeds.v14.i1.pp444-452.

[7] M. Khalilzadeh, S. Vaez-Zadeh, and A. Jabbarnejad, "A model-free approach for predictive direct power control of grid-connected converters," in *IECON Proceedings (Industrial Electronics Conference)*, Oct. 2019, vol. 2019-Octob, pp. 6141–6146. doi: 10.1109/IECON.2019.8926958.

[8] H. Essakhi, S. Farhat, Y. Dbaghi, and D. Daou, "Indirect power control of grid-connected photovoltaic system using fuzzy control with a three-level inverter," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 28, no. 1, pp. 76–87, Oct. 2022, doi: 10.11591/ijeecs.v28.i1.pp76-87.

[9] Y. Gui, X. Wang, and F. Blaabjerg, "Vector current control derived from direct power control for grid-connected inverters," *IEEE Transactions on Power Electronics*, vol. 34, no. 9, pp. 9224–9235, Sep. 2019, doi: 10.1109/TPEL.2018.2883507.

[10] D. K. Choi and K. B. Lee, "Dynamic performance improvement of AC/DC converter using model predictive direct power control with finite control set," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 2, pp. 757–767, Feb. 2015, doi: 10.1109/TIE.2014.2352214.

[11] S. Vazquez, A. Marquez, R. Aguilera, D. Quevedo, J. I. Leon, and L. G. Franquelo, "Predictive optimal switching sequence direct power control for grid-connected power converters," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2010–2020, Apr. 2015, doi: 10.1109/TIE.2014.2351378.

[12] M. Abdelrahem, J. Rodríguez, and R. Kennel, "Improved direct model predictive control for grid-connected power converters," *Energies*, vol. 13, no. 10, p. 2597, May 2020, doi: 10.3390/en13102597.

[13] H. Azad, H. Shateri, T. Dragicevic, and C. Zhang, "A Novel robust control strategy for grid-connected PV systems based on modified direct power control," in *6th IEEE International Conference on Predictive Control of Electrical Drives and Power Electronics, PRECEDE 2021*, Nov. 2021, pp. 753–758. doi: 10.1109/PRECEDE51386.2021.9681016.

[14] D. M. Shukla, N. Zaveri, and T. Sutikno, "The performance of a multilevel multifunctional solar inverter under various control methods," *Bulletin of Electrical Engineering and Informatics (BEEI)*, vol. 12, no. 5, pp. 2717–2732, Oct. 2023, doi: 10.11591/eei.v12i5.4097.

[15] B. Lekouaghet, A. Boukabou, N. Lourci, and K. Bedrine, "Control of PV grid connected systems using MPC technique and different inverter configuration models," *Electric Power Systems Research*, vol. 154, pp. 287–298, Jan. 2018, doi: 10.1016/j.epsr.2017.08.027.

[16] S. Ouchen, A. Betka, J. P. Gaubert, S. Abdeddaim, and F. Mazouz, "Fuzzy-direct power control of a grid connected photovoltaic system associate with shunt active power filter," in *Lecture Notes in Networks and Systems*, vol. 35, Springer International Publishing, 2018, pp. 164–172. doi: 10.1007/978-3-319-73192-6_17.

[17] S. Farajdadian and S. M. H. Hosseini, "Optimization of fuzzy-based MPPT controller via metaheuristic techniques for stand-alone PV systems," *International Journal of Hydrogen Energy*, vol. 44, no. 47, pp. 25457–25472, Oct. 2019, doi: 10.1016/j.ijhydene.2019.08.037.

[18] M. Kadem, A. Semmah, P. Wira, and S. Dahmani, "Fuzzy logic-based instantaneous power ripple minimization for direct power control applied in a shunt active power filter," *Electrical Engineering*, vol. 102, no. 3, pp. 1327–1338, Feb. 2020, doi: 10.1007/s00202-020-00943-6.

[19] H. Akagi, E. H. Watanabe, and M. Aredes, *Instantaneous power theory and applications to power conditioning*. Wiley, 2017. doi: 10.1002/9781119307181.

[20] M. Z. Zizoui, B. Tabbache, N. Hannini, and M. Benbouzid, "Direct power control approach for a grid-connected photovoltaic power system," in *Springer Proceedings in Energy*, Springer Singapore, 2021, pp. 295–302. doi: 10.1007/978-981-16-0378-5_39.

[21] M. Ahmed, I. Harbi, R. Kennel, J. Rodríguez, and M. Abdelrahem, "Evaluation of the main control strategies for grid-connected PV systems," *Sustainability (Switzerland)*, vol. 14, no. 18, p. 11142, Sep. 2022, doi: 10.3390/su141811142.

[22] S. Dahmani, A. Semmah, M. Kadem, and P. Wira, "Genetic algorithm optimization of a SAPF based on the fuzzy-DPC concept," *Przeglad Elektrotechniczny*, vol. 95, no. 7, pp. 60–65, Jul. 2019, doi: 10.15199/48.2019.07.13.

[23] M. N. Ali, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "Promising mppt methods combining metaheuristic, fuzzy-logic and ann techniques for grid-connected photovoltaic," *Sensors (Switzerland)*, vol. 21, no. 4, pp. 1–18, Feb. 2021, doi: 10.3390/s21041244.

[24] X. Ge, F. W. Ahmed, A. Rezvani, N. Aljojo, S. Samad, and L. K. Foong, "Implementation of a novel hybrid BAT-Fuzzy controller based MPPT for grid-connected PV-battery system," *Control Engineering Practice*, vol. 98, Art. no. 104380, May 2020, doi: 10.1016/j.conengprac.2020.104380.

[25] D. Toumi *et al.*, "Maximum power point tracking of photovoltaic array using fuzzy logic control," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 4, pp. 2440–2449, Dec. 2022, doi: 10.11591/ijpeds.v13.i4.pp2440-2449.

[26] "IEEE standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces," *IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003*, 2018, doi: 10.1109/ieeestd.2018.8332112.

[27] "IEEE recommended practice and requirements for harmonic control in electric power systems," in *IEEE Std 519-2014 (Revision of IEEE Std 519-1992)*, pp. 1-29, Jun. 2014, doi: 10.1109/IEEESTD.2014.6826459.

[28] IEEE Standards Coordinating Committee 21 on Fuel Cells Photovoltaics Dispersed Generation and Energy Storage, "IEEE recommended practice for utility interface of photovoltaic (PV) systems," *IEEE Std 929-2000*, vol. 2000, Art. no. 32, 2000, doi: 10.1109/IEEESTD.2000.91304.

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