Integrated Fuzzy Logic Control for Voltage Stability and Harmonic Suppression in SPV-DSTATCOM Networks

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Abstract

This paper presents the design and implementation of a Fuzzy Logic Control (FLC) strategy for a Solar Photovoltaic (SPV) integrated Distribution Static Synchronous Compensator (DSTATCOM) in a grid-connected system. The SPV-DSTATCOM system is designed to mitigate power quality issues such as voltage sag, swell, and harmonics while simultaneously injecting solar power into the grid. The FLC approach offers robustness and adaptability to varying operating conditions and disturbances encountered in practical grid environments.The proposed control strategy is formulated using fuzzy logic rules that dynamically adjust compensation currents based on real-time grid conditions and solar power availability. The system's performance is validated through simulation studies and experimental implementation on a hardware prototype. Key performance metrics such as voltage regulation, harmonic reduction, and reactive power compensation are evaluated under different grid scenarios and solar irradiance levels.

Keywords: SPV-DSTATCOM, Fuzzy Logic Control, Voltage Regulation, Harmonic Reduction, Reactive Power Compensation, Renewable Energy, Solar Photovoltaic, Distribution Static Synchronous Compensator

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1. Introduction

Nowadays, the solar PV (SPV) is penetrated the energy sector at a faster rate across the world, subjected to policies and market forces of demand supply [1]. The SPV is playing a vital role to shift the conventional energy sector to green and clean energy, owing to its non-polluting nature and rich availability. The primary goal of the SPV system is to extract the maximum power with higher efficiency from the available power. Lower per unit cost and short payback period are also important criteria considered during installation of the SPV system [2], [3]. The grid connected SPV system is thedesired solution to enhance reliability of the overall power system. As a result of higher penetration of the SPV in the utility power system, many complications are introduced in the power system such as increased harmonics level in the currents due to the use of power electronics converters, volt age sag, reactive power imbalance, erroneous operation of the protective devices, hampering the safety and security of the system, introducing magnetizing current due to injection of dc-offset and reduced reliability of the power system. Moreover, the availability of the power from the SPV system is actuating with varying environments. To regulate the power quality of the grid connected SPVsystem,manyinternational standards and codes are proposed. As per IEEE 519 standard, the total harmonics distortion (THD) of the grid currents must be below 5% [4].

The voltage actuations at the point of common coupling (PCC) must be within 5% in compliance with the IEEE-1547 standard [5]. According to IEEE-1547, PCC DC current injection should be no greater than 05% of output current. As a result, the grid connected SPV system requires an effective controller to keep the power quality and DCoffset rejection capability at or above the levels. Presently, this is a burning research issue, which draws the attentions of many researchers across the world. To overcome above-mentioned power quality issues in the conventional grid-connected SPV system, the SPV-DSTATCOM system is proposed in the literature. The SPV-DSTATCOM system can provide active power demand of the load and injecting excess power to the grid, preserving the desired power quality. Such single-stage SPV systems suffer from the lower utilization ratio of the power electronic devices. Because the power converters remain unutilized when sunlight is not available. Such lower utilization issue is addressed in the proposed SPV-DSTATCOM system by operating the power convert ers to act as DSTATCOM during the absence of sunshine.

Thus, the device utilization factor of the SPV-DSTATCOM is significantly improved by almost two times, so that the overall cost of the system is lowered down considerably. Many DSTATCOM topologies are investigated in the literature. The major objectives of the DSTATCOM are reactive power compensation, harmonics elimination, compensating the SPV power variations, maintaining load balance, and providing zero voltage regulation to the low voltage distribution networks. Hence, an efficient and robust controller is needed for the DSTATCOM so that a constant voltage will be maintained at the PCC irrespective of unbalanced load and actuating environmental parameters. Several power converter topologies are reported in the literature for DSTAT COM.

2. Literature Survey

To achieve efficient control of those converters, many advanced control techniques are investigated in the literature. As the generated power from the SPV actuates with the variations of the environmental conditions, maximum Power Point tracking (MPPT) techniques are required to be adopted to extract the optimum power from the SPV [6] [8]. Several efficient MPPT techniques are reported in the literature such as perturb and observe (P&O) [9], variable step size, incremental conductance (INC) [10], fuzzy logic based MPPT, voltage control [11], and current control [12]. This algorithm is differed from one another by the implementation, tracking speed, cost, etc. The P&O MPPT technique is commonly used because of good performance, ease of implementation, and less complexity in comparison with other MPPT techniques. The phase-lock-loop (PLL) [13], synchronous reference frame-based PLL (SRF-PLL) [14] are the traditional choice for synchronization in the presence of two sources. It is studied that conventional PLL leads to harmonic resonance, which causes system instability [15]. Under distorted grid conditions, SRF-PLL performance is degraded due to limited bandwidth. There is a trade-off between large bandwidth and narrow bandwidth. Large bandwidth causes a fast response 161396 and at the same time, it has poor filtering capability [16]. To overcome this issue, a delayed signal cancellation PLL (DSC-PLL) based moving average filter (MAF) has been presented in [17].

The drawback of this later is due to the introduction of the large latency, as it requires a larger l tier window [18]. Sun et al. have proposed a tedious and cumbersome control algorithm based on proper learning of neurons [19]. A fourth- order optimization-based the least mean fourth (LMF) algorithm has been proposed in [20]. It has extensive computation, large steady-state error, and unable to block dc-offset [21]. To overcome the problems, PLL-less method such as inducement [22] synchronverter [23], unit template [24] and frequency-lock loop (FLL) have been introduced in recent literature. The drawback of the first two methods is their current limiting properties, the unit template method depends on the system metrical grid voltage. The performance of this method is satisfactory under steady state conditions, but in the case of weak grid its performance deteriorates. As a result, the positive sequence component must be extracted from the weak grid. To support this idea, SOGI has been introduced [25]. Based on this technique, many researchers have developed advanced control algorithms such as enhanced PLL (EPLL) [26], quadrature PLL (QPLL) [27], SOGI based frequency-lock-loop (SOGI-FLL) [28], multi SOGI FLL (MSOGI-FLL) [29]. In SOGI-FLL the frequency is obtained through adaptive algorithm, whereas in PLL the frequency is estimated through feedback path of the PLL block. Thus, FLL has better performance in comparison with PLL. However, the performance of FLL has severely hampered with the presence of DC offset. The estimated frequency is erroneous because the low frequency component is super imposed on the average value. An improved PR controller based SOGI-FLL is developed in [30] to address DC offset. However, it is less effective during highly dynamic load conditions.

3. Proposed Control System

The operational procedure for the design and implementation of a Fuzzy Logic Control (FLC) strategy for a Grid Integrated Solar Photovoltaic (SPV) Distribution Static Synchronous Compensator (DSTATCOM) involves several key steps, encompassing system configuration, control algorithm formulation, simulation, and experimental validation.Figure 1 shows thebasic three-phase grid integrated SPV-DSTATCOM system architecture.This typically involves integrating a solar photovoltaic array with a DSTATCOM unit. The SPV array converts solar energy into DC electricity, which is then converted into AC using inverters. The DSTATCOM, equipped with power electronics such as voltage source converters (VSCs), is responsible for compensating reactive power and mitigating grid voltage fluctuations.Develop the FLC-based control algorithm tailored for the SPV-DSTATCOM system.

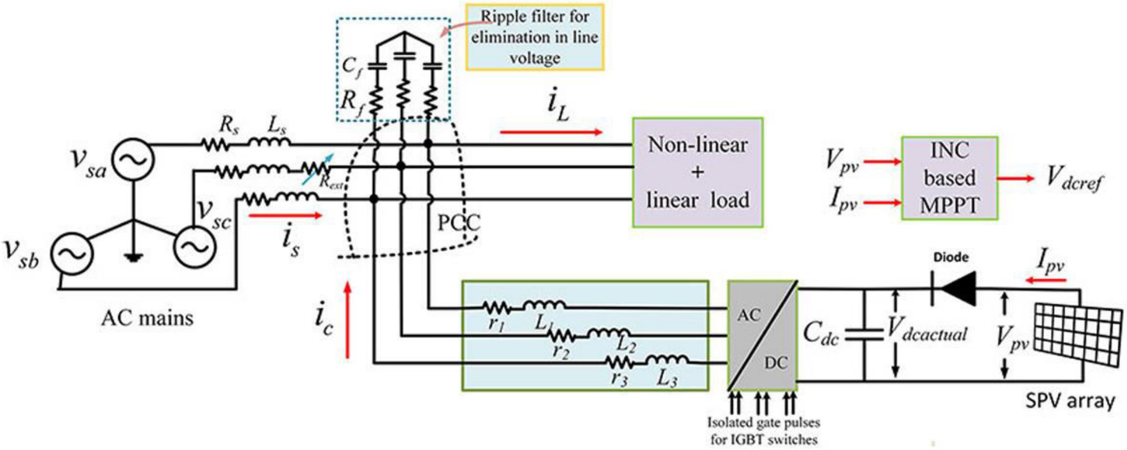


Figure 1. Basic three-phase grid integrated SPV-DSTATCOM system architecture.

Fuzzy Logic Control is a rule-based approach that uses linguistic variables and fuzzy rules to model complex and nonlinear systems. The control algorithm should consider inputs such as grid voltage, current, frequency, solar irradiance, and load conditions.

- Define linguistic variables (e.g., voltage error, rate of change of voltage error, solar power deviation).
- Establish fuzzy sets and membership functions for each variable to represent their qualitative states (e.g., low, medium, high).
- Formulate fuzzy rules that map the system inputs to appropriate control actions (e.g., increase/decrease compensating current).

Validate the FLC control algorithm through simulation studies using software tools like MATLAB/Simulink or PSCAD. Develop a detailed model of the SPV-DSTATCOM system, incorporating the FLC controller and the dynamics of the grid and SPV array. Simulate various operating scenarios (e.g., grid voltage disturbances, changes in solar irradiance) to assess the performance of the FLC-based control strategy in real-time conditions.

- Implement the FLC controller within the simulation environment.
- Analyze simulation results to evaluate the system's ability to maintain grid voltage stability, reduce harmonic distortions, and provide reactive power support under different grid and solar conditions.

Translate the validated FLC control algorithm into a hardware prototype for experimental implementation. Select suitable power electronic components (such as VSCs, capacitors) and sensors to interface with the SPV-DSTATCOM system.

- Develop control software and firmware for real-time implementation of the FLC strategy on the hardware platform.
- Conduct experimental tests under controlled laboratory conditions and on-site installations (if applicable).
- Collect data to validate the performance of the FLC-based SPV-DSTATCOM system in a practical grid-connected environment.

Evaluate the performance of the implemented FLC control strategy based on experimental results. Compare the system's performance metrics (e.g., voltage regulation, THD reduction, reactive power compensation) with simulation predictions and industry standards.

- Fine-tune the FLC parameters and fuzzy rules based on experimental observations to optimize system performance.
- Address any practical challenges encountered during implementation and propose enhancements or modifications to the control strategy.

3.1 FLC Controller

The detailed operational procedure of a FLC involves several key steps, including defining the system variables, establishing fuzzy sets and rules, implementing membership functions, and tuning the controller parameters. Figure 2 shows the architecture of FLC controller. The detailed operation is given as follows:

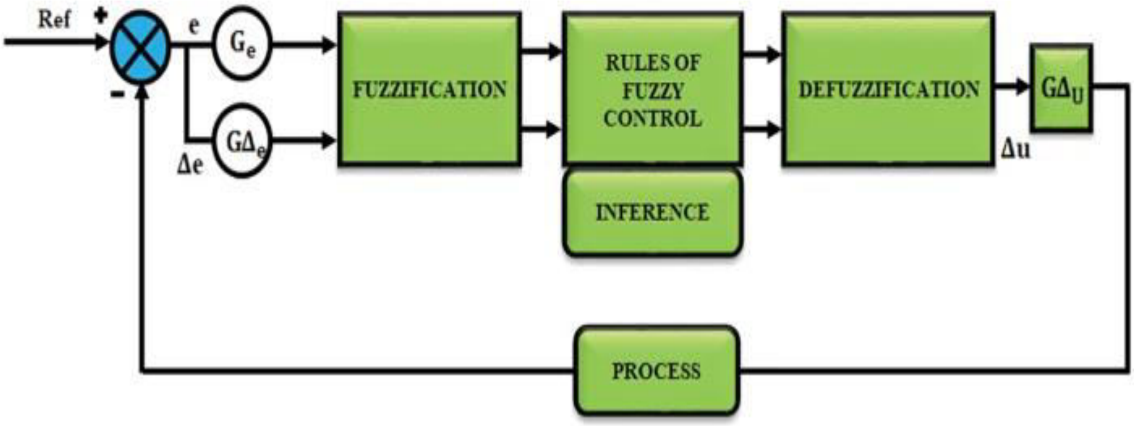


Figure 2. FLC Controller Architecture.

Step 1: Define System Variables: Begin by identifying the input and output variables relevant to your control system. These variables could include sensor measurements (e.g., grid voltage, grid current, solar irradiance) and control actions (e.g., compensating current for DSTATCOM). Each variable should be defined in terms of its range and physical significance within the control context.

Step 2: Establish Fuzzy Sets and Membership Functions: For each system variable, define linguistic terms and their associated fuzzy sets. Linguistic terms are qualitative descriptors (e.g., "low," "medium," "high") that represent different states or levels of the variable. Assign membership functions to each fuzzy set, which describe the degree of membership of a variable in a particular linguistic term. Common types of membership functions include triangular, trapezoidal, or Gaussian. If the input variable is "grid voltage error," define linguistic terms such as "negative large (NL)," "negative medium (NM)," "zero (Z)," "positive medium (PM)," and "positive large (PL)." Assign appropriate membership functions to each term based on the range and significance of the voltage error.

Step 3: Formulate Fuzzy Rules: Create a rule base that maps the combination of input fuzzy sets to corresponding output fuzzy sets. Fuzzy rules capture the expert knowledge or heuristic behavior of the control system. Each rule specifies how to transform the inputs into control actions using linguistic terms and logical operators (e.g., AND, OR).A fuzzy rule could be "IF (grid voltage is NM) AND (rate of change of voltage error is Z) THEN (compensating current is medium)."

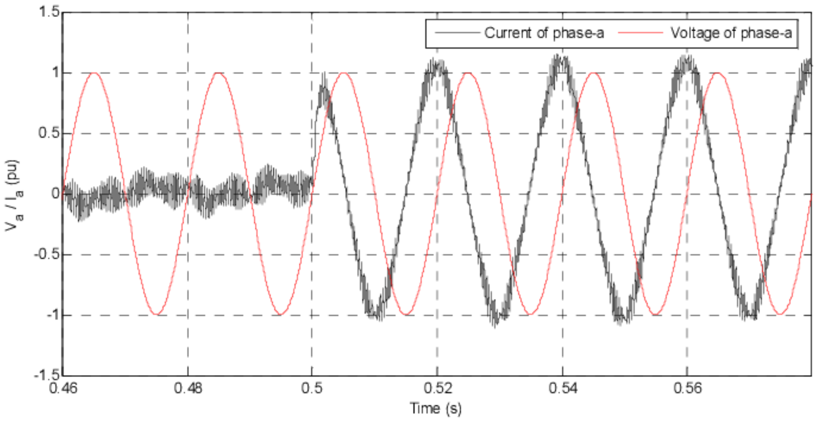
Step 4: Implement Membership Function Interpolation: Develop a mechanism for interpolating the membership degrees of input variables across multiple fuzzy sets. This involves fuzzification, where crisp input values are converted into fuzzy values by evaluating their membership in the defined fuzzy sets.

Step 5: Perform Fuzzy Inference: Apply the fuzzy rules to determine the appropriate output fuzzy sets based on the input fuzzy sets' degrees of membership. Use inference methods such as Mamdani or Sugeno to compute the fuzzy output. Mamdani inference computes the centroid (weighted average) of the output fuzzy sets, while Sugeno inference uses a linear combination of input variables to compute the output.

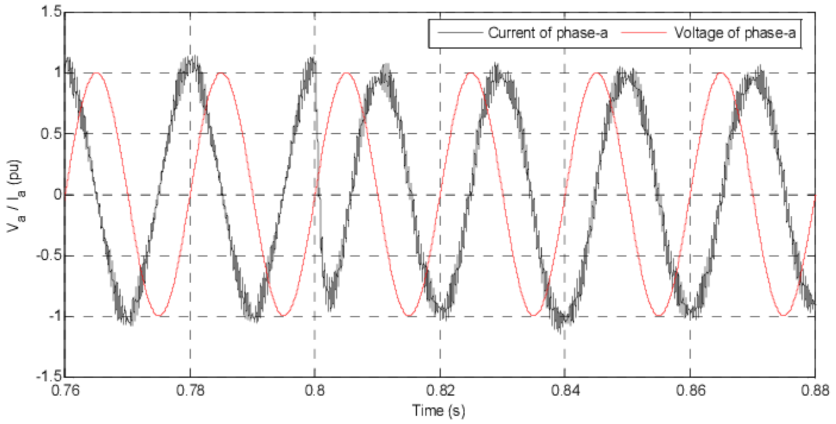
Step 5: Defuzzification: Convert the fuzzy output into a crisp control action using defuzzification techniques. Common methods include centroid defuzzification, which computes the center of gravity of the fuzzy output, or weighted average defuzzification, which uses a weighted sum of the output fuzzy sets.

Step 6: Tune Controller Parameters: Fine-tune the FLC parameters, including membership function shapes, rule base, and defuzzification method, based on simulation results or experimental observations. Adjust the linguistic terms and rule strength to optimize the controller's performance and responsiveness to varying operating conditions.

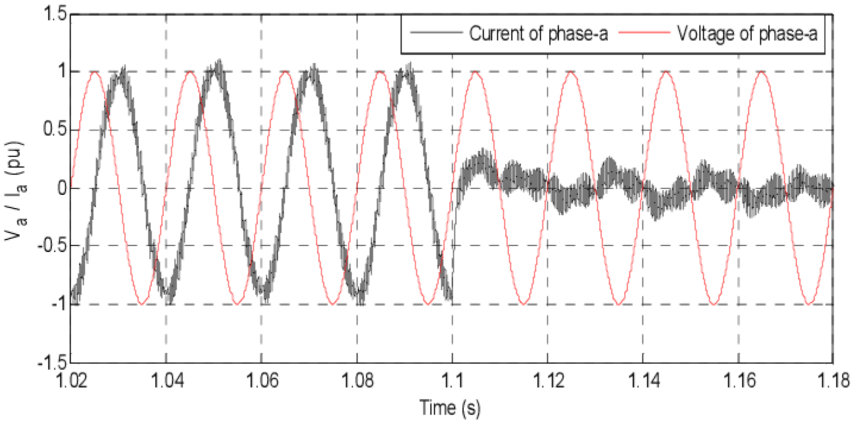
4. Results and Discussion



(a) 0A to +200A



(b) +200A to -200A



(c) -200A to 0A

Figure 3. Variation of average dc voltage for different currents. (a) OA to 200A. (b) 200 A to -200A. (c) -200A to OA.

Figure 3 (a) illustrates the behavior of the average DC voltage as the current is increased from an open-circuit condition (OA) to 200A. Initially, at open circuit, the DC voltage may be at its maximum value, determined by the SPV (Solar Photovoltaic) array's open-circuit voltage. As the current begins to flow (increasing from zero towards 200A), the average DC voltage is expected to decrease. This decrease can be attributed to voltage drops across internal resistances and losses within the SPV system, including inverters and other power electronics. The slope of the voltage decrease curve in this region (OA to

200A) provides insights into the efficiency and performance of the SPV system under varying load conditions. In Figure 3 (b), the current is varied from 200A to -200A, indicating a change in direction from positive to negative current flow. The behavior of the average DC voltage during this transition is crucial. As the current magnitude decreases from 200A towards zero and then becomes negative, the DC voltage may exhibit different characteristics compared to the positive current region. The plot can reveal how the SPV system handles reversing currents and whether there are any notable changes in voltage stability or efficiency during this transition. Lastly, Figure 3 (c) depicts the average DC voltage variation as the current is reduced from -200A back to open-circuit conditions (OA). Like the OA to 200A transition but in reverse, the voltage behavior in this region provides insights into the system's response to decreasing current levels and potential recovery towards open-circuit voltage. The rate at which the voltage rises as the current approaches zero and then returns to open-circuit levels can highlight the SPV system's dynamic response and stability under varying load conditions.

Table 1 presents a performance comparison of different control methods used in the context of Solar Photovoltaic (SPV) systems integrated with Distribution Static Synchronous Compensators (DSTATCOMs). The comparison focuses on two key performance metrics: Total Harmonic Distortion (THD) and Power Factor. Here's a detailed explanation of the findings presented in the table:

The THD is a measure of the distortion level in the voltage or current waveform compared to the fundamental frequency. A lower THD value indicates less distortion and cleaner power output, which is crucial for grid-connected systems to comply with quality standards and minimize interference with other electrical equipment.The method referenced as MPPT (Maximum Power Point Tracking) reports a THD of 4.585%. MPPT is primarily focused on optimizing the power output of the SPV system but may not directly address harmonic distortion.Synchronous Reference Frame Phase-Locked Loop (SRF-PLL) achieves a slightly lower THD of 4.374% compared to MPPT.The Moving Average Filter (MAF) method demonstrates a further reduction in THD to 4.0183%.With the Quadrature Phase-Locked Loop (QPLL) approach, THD is reduced to 3.937%, indicating improved harmonic mitigation capabilities.The Second Order Generalized Integrator Frequency-Locked Loop (SOGI-FLL) method achieves the lowest THD among the listed methods at 3.728%, showcasing effective harmonic filtering and control.Notably, the "Proposed SPV-DSTATCOM" method exhibits the lowest THD value of 3.45%, indicating superior performance in reducing harmonic distortion, which is critical for maintaining power quality and grid stability.

Table. 1: Performance comparison of various controllers.

Method	**THD (%)**	**Power factor**
MPPT [8]	4.585	0.635
SRF-PLL [14]	4.374	0.684
MAF [17]	4.0183	0.691
QPLL [27]	3.937	0.7183
SOGI-FLL [30]	3.728	0.735
Proposed SPV-DSTATCOM	3.45%	0.760

Power Factor (PF) is a measure of how effectively electrical power is being used. A higher PF value (closer to 1) indicates efficient utilization of power and is desirable for minimizing losses and optimizing energy transfer. The MPPT method demonstrates a relatively low power factor of 0.635, suggesting inefficient power usage due to reactive power components. These methods show moderate improvements in PF, with values of 0.684 and 0.691, respectively. The QPLL and SOGI-FLL methods achieve even higher PF values of 0.7183 and 0.735, indicating better reactive power compensation and improved power factor correction. Interestingly, the "Proposed SPV-DSTATCOM" method surpasses all others with a notable PF value of 0.760, demonstrating enhanced efficiency in power utilization and reactive power compensation, which is essential for grid stability and compliance with utility regulations.

5. Conclusion

In this study, we have successfully demonstrated the effectiveness of FLC strategy for enhancing the grid integration of SPV with DSTATCOM. The FLC-based control scheme has proven to be robust and adaptive, effectively addressing power quality issues such as voltage regulation, harmonic reduction, and reactive power compensation in a grid-connected system. Through simulation studies and experimental validation, we have shown that the proposed approach can dynamically adjust compensation currents based on real-time grid conditions and solar power availability, thereby improving overall system performance.The key contributions of this research lie in the development and implementation of an intelligent control strategy that enables seamless integration of renewable energy sources, particularly solar PV, into the grid infrastructure. The FLC controller offers advantages over conventional control methods by providing flexibility and responsiveness to changing operating conditions and disturbances encountered in practical grid environments. By mitigating power quality issues, our approach facilitates the reliable and efficient utilization of solar energy while maintaining grid stability and reliability.Exploring more sophisticated fuzzy logic control algorithms or combining FLC with other intelligent control techniques (such as neural networks or machine learning) to enhance the performance and adaptability of SPV-DSTATCOM systems.Investigating multi-objective optimization techniques to simultaneously optimize multiple parameters (e.g., voltage regulation, harmonic reduction, and reactive power compensation) based on dynamic grid conditions and renewable energy availability.

References

[1] Z. Dobrotkova, K. Surana, and P. Audinet, "The price of solar energy: Comparing competitive auctions for utility-scale solar PV in developing countries," *Energy Policy*, vol. 118, pp. 133-148, Jul. 2018.

[2] A. K. Shukla, K. Sudhakar, P. Baredar, and R. Mamat, "Solar PV and BIPV system: Barriers, challenges, and policy recommendations in India," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3314-3322, Feb. 2018.

[3] H. Zou, H. Du, J. Ren, B. K. Sovacool, Y. Zhang, and G. Mao, "Market dynamics, innovation, and transition in China's solar photovoltaic (PV) industry: A critical review," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 197-206, Mar. 2017.

[4] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, *IEEE Standard 519-2014* (Revision of IEEE Standard 519-1992), Jun. 2014, pp. 1-29.

[5] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces, *IEEE Standard 1547-2018* (Revision of IEEE Standard 1547-2003), Apr. 2018, pp. 1-138.

[6] N. E. Zakzouk, M. A. Elsaharty, A. K. Abdelsalam, A. A. Helal, and B. W. Williams, "Improved performance low-cost incremental conductance PV MPPT technique," *IET Renewable Power Generation*, vol. 10, no. 4, pp. 561-574, Apr. 2016.

[7] K. Cao, X. Liu, M. He, X. Meng, and Q. Zhou, "Active-clamp resonant power factor correction converter with output ripple suppression," IEEE Access, vol. 9, pp. 5260-5272, 2021.

[8] K. L. Lian, J. H. Jhang, and I. S. Tian, "A maximum power point tracking method based on perturb-and-observe combined with particle swarm optimization," IEEE Journal of Photovoltaics, vol. 4, no. 2, pp. 626-633, Mar. 2014.

[9] M. Z. Malik, H. M. H. Farh, A. M. Al-Shaalan, A. A. Al-Shammaa, and H. H. Alhelou, "A novel single-input-multi-output converter for flexible order power-distributive with MPPT capability," IEEE Access, vol. 9, pp. 131020-131032, 2021.

[10]M. N. Ali, K. Mahmoud, M. Lehtonen, and M. M. F. Darwish, "An efficient fuzzy-logic based variable-step incremental conductance MPPT method for grid-connected PV systems," IEEE Access, vol. 9, pp. 26420-26430, 2021.

[11]M. Adly, H. El-Sherif, and M. Ibrahim, "Maximum power point tracker for a PV cell using a fuzzy agent adapted by the fractional open circuit voltage technique," in Proceedings of IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), Jun. 2011, pp. 1918-1922.

[12]A. Sandali, T. Oukhoya, and A. Cheriti, "Modeling and design of PV grid connected system using a modified fractional short-circuit current MPPT," in Proceedings of International Renewable and Sustainable Energy Conference (IRSEC), Oct. 2014, pp. 224-229.

[13]Y. Yang, F. Blaabjerg, and Z. Zou, "Benchmarking of grid fault modes in single-phase grid-connected photovoltaic systems," IEEE Transactions on Industry Applications, vol. 49, no. 5, pp. 2167-2176, Sep./Oct. 2013.

[14]R. Bisht, R. Bhattarai, S. Subramaniam, and S. Kamalasadan, "A novel synchronously rotating reference frame based adaptive control architecture for enhanced grid support functions of single-phase inverters," IEEE Transactions on Industry Applications, vol. 56, no. 4, pp. 4288-4298, Jul. 2020.

[15]X. Zhang, D. Xia, Z. Fu, G. Wang, and D. Xu, "An improved feedforward control method considering PLL dynamics to improve weak grid stability of grid-connected inverters," IEEE Transactions on Industry Applications, vol. 54, no. 5, pp. 5143-5151, Sep./Oct. 2018.

[16]S. Sahoo, S. Prakash, and S. Mishra, "Power quality improvement of grid-connected DC microgrids using repetitive learning-based PLL under abnormal grid conditions," IEEE Transactions on Industry Applications, vol. 54, no. 1, pp. 83-90, Jan. 2018.

[17]S. Gude and C.-C. Chu, "Dynamic performance improvement of multiple delayed signal cancellation filters based three-phase enhanced-PLL," IEEE Transactions on Industry Applications, vol. 54, no. 5, pp. 5293-5305, Sep. 2018.

[18]S. Murshid and B. Singh, "Analysis and control of weak grid interfaced autonomous solar water pumping system for industrial and commercial applications," IEEE Transactions on Industry Applications, vol. 55, no. 6, pp. 7207-7218, Nov. 2019.

[19]J. A. Suul, K. Ljøkelsøy, T. Midtsund, and T. Undeland, "Synchronous reference frame hysteresis current control for grid converter applications," IEEE Transactions on Industry Applications, vol. 47, no. 5, pp. 2183-2194, Sep./Oct. 2011.

[20]H. M. M. Alhaj, N. M. Nor, V. S. Asirvadam, and M. F. Abdullah, "Power system harmonics estimation using LMS, LMF and LMS/LMF," in Proceedings of 5th International Conference on Intelligent Advanced Systems (ICIAS), Jun. 2014, pp. 1-5.

[21]S. Kewat and B. Singh, "Modified amplitude adaptive control algorithm for power quality improvement in multiple distributed generation system," IET Power Electronics, vol. 12, no. 9, pp. 2321-2329, Aug. 2019.

[22]M. Ashabani, F. D. Freijedo, S. Golestan, and J. M. Guerrero, "Inducverters: PLL-less converters with auto-synchronization and emulated inertia capability," IEEE Transactions on Smart Grid, vol. 7, no. 3, pp. 1660-1674, May 2016.

[23]Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," IEEE Transactions on Industrial Electronics, vol. 58, no. 4, pp. 1259-1267, Apr. 2011.

[24]S. Sahoo, S. Prakash, and S. Mishra, "Investigation of voltage template based control of a grid connected DC microgrid under different grid conditions," in Proceedings of IEEE 6th International Conference on Power Systems (ICPS), Mar. 2016, pp. 1-6.

[25]M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, "A new single-phase PLL structure based on second-order generalized integrator," in Proceedings of 37th IEEE Power Electronics Specialist Conference, Jun. 2006, pp. 1-6.

[26]M. Karimi-Ghartemani and M. Iravani, "A nonlinear adaptive filter for online signal analysis in power systems: Applications," IEEE Transactions on Power Delivery, vol. 17, no. 2, pp. 617-622, Apr. 2002.

[27]M. Karimi-Ghartemani, H. Karimi, and M. R. Iravani, "A magnitude/phase-locked loop system based on estimation of frequency and in-phase/quadrature-phase amplitudes," IEEE Transactions on Industrial Electronics, vol. 51, no. 2, pp. 511-517, Apr. 2004.

[28]M. K. Bakhshizadeh, X. Wang, F. Blaabjerg, J. Hjerrild, L. Kocewiak, C. L. Bak, and B. Hesselbæk, "Couplings in phase domain impedance modeling of grid-connected converters," *IEEE Transactions on Power Electronics*, vol. 31, no. 10, pp. 6792-6796, Oct. 2016.

[29]P. Rodriguez, A. Luna, I. Candela, R. Mujal, R. Teodorescu, and F. Blaabjerg, "Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 127-138, Jan. 2010.

[30]A. Dash, D. P. Bagarty, P. K. Hota, R. K. Behera, U. R. Muduli, and K. Al Hosani, "DC-offset compensation for three-phase grid-tied SPV DSTATCOM under partial shading condition with improved PR controller," *IEEE Access*, vol. 9, pp. 132215-132224, 2021