

A Review of Fuzzy Logic Control Techniques for Power Quality Enhancement in Grid-Connected Solar Photovoltaic Systems

Govind Kumar Maurya¹, Anil Kumar Yadav², Gunjan Yadav³, Piyush Singh⁴, Naveen Kumar⁵

Assistant Professor Department of Electrical Engineering, PIT JAUNPUR (UP) ^{1,2,3}

B. Tech Scholar, Department of Electrical Engineering, PIT JANUPUR (UP) ^{4,5}

govindfolk@gmail.com

Abstract: The integration of solar photovoltaic (PV) systems with utility grids poses challenges in maintaining voltage stability, reducing harmonics, and improving power quality. Conventional PI controllers and passive filters, such as LCL filters, have been widely used for regulating voltage source inverters (VSIs) and mitigating harmonics. However, these methods often face limitations in handling system nonlinearities, dynamic load variations, and uncertainties in solar irradiance. Fuzzy Logic Control (FLC), as an intelligent and adaptive technique, provides an effective alternative by eliminating the need for an accurate mathematical model and offering robustness under varying operating conditions. This paper reviews the application of fuzzy logic controllers in grid-connected PV systems, particularly for inverter control, maximum power point tracking (MPPT), harmonic reduction, and power factor correction. A comparative analysis is presented between conventional PI control, LCL filter-based approaches, and fuzzy control techniques. The review highlights that fuzzy controllers significantly improve power quality and reliability.

Keywords: GCPV system, harmonics, power quality, total harmonic distortion (THD), voltage source inverter, Fuzzy logic Controller.

1. Introduction

The increasing global demand for electricity, coupled with the depletion of fossil fuel reserves and the adverse impacts of greenhouse gas emissions, has accelerated the integration of renewable energy sources into modern power systems. Among the available alternatives, solar photovoltaic (PV) technology has emerged as one of the most promising renewable energy options due to its abundance, scalability, and environmentally friendly characteristics.

Grid-connected rooftop solar PV systems have become increasingly popular in both residential and commercial sectors, as they enable localized power generation, reduce dependency on the utility grid, and contribute toward sustainability targets

[1-2]. However, despite these advantages, the integration of PV systems into the utility grid introduces several technical challenges. The intermittent and nonlinear nature of solar irradiance results in fluctuating power outputs,

which in turn affect grid stability. Furthermore, the widespread use of power electronic converters in PV systems, such as DC-DC boost converters and voltage source inverters (VSIs), can lead to harmonic distortion, reactive power imbalance, and deterioration of power quality. These challenges become even more pronounced in microgrids and distributed generation systems, where multiple rooftop PV units operate simultaneously. Thus, the development of robust control strategies for PV inverters is critical to ensuring stable operation, effective power quality enhancement, and seamless interaction between renewable sources and the utility grid. Traditionally, proportional-integral (PI) controllers and passive filtering techniques, such as LCL filters, have been employed to regulate the performance of grid-connected PV systems. PI controllers are widely used due to their simplicity and ease of implementation. They can effectively maintain the DC-link voltage and regulate current injection into the grid under steady-state conditions. Similarly, LCL filters have been shown to significantly reduce the total harmonic distortion (THD) of inverter output currents and voltages, thereby improving



overall power quality. Nevertheless, PI-based control and passive filtering approaches exhibit major limitations. PI controllers rely on linear system models and fixed tuning parameters, making them highly sensitive to system uncertainties, nonlinearities, and dynamic variations in irradiance and temperature. Their performance often degrades under sudden load changes or grid disturbances, leading to voltage oscillations and poor reactive power management. Similarly, while LCL filters effectively mitigate harmonics, they are passive in nature, lack adaptability, and introduce resonance risks that may compromise system stability. Consequently, there is a growing need for intelligent and adaptive control strategies capable of addressing the shortcomings of traditional methods. Fuzzy logic control (FLC) has emerged as a promising alternative to conventional techniques for enhancing the performance of grid-connected PV systems. Unlike PI controllers, fuzzy controllers do not require precise mathematical models and instead operate on linguistic rule-based systems that mimic human decision-making. This enables fuzzy controllers to effectively handle nonlinearities, uncertainties, and time-varying dynamics inherent in PV generation and grid interaction. By mapping input variables such as voltage error, change in error, or irradiance fluctuations to control actions, fuzzy logic controllers can ensure fast response, robustness, and adaptability. Moreover, fuzzy-based controllers have been successfully applied in various domains of PV systems, including maximum power point tracking (MPPT), harmonic reduction, voltage regulation, and seamless grid-island transitions [3].

The integration of fuzzy control in grid-connected PV systems also aligns well with the emerging paradigm of smart grids and microgrids, where distributed intelligence and autonomous decision-making are critical. Compared to PI controllers, fuzzy logic controllers can dynamically adapt to rapid changes in solar generation and load demand, thereby maintaining power factor close to unity and reducing THD even under adverse conditions. Furthermore, fuzzy logic-based hybrid approaches, such as fuzzy-PI or fuzzy-neural controllers, have been investigated in the literature, combining the advantages of classical and intelligent control strategies. This review paper focuses on analyzing the role of fuzzy logic control in enhancing power quality and stability of grid-connected PV systems. It provides an overview of conventional PI and filter-based control methods, discusses their limitations, and explores the design principles and applications of fuzzy controllers. Special emphasis is placed on the comparative performance of fuzzy logic control against conventional strategies in terms of harmonic suppression, inverter regulation, and adaptability

under varying operating conditions. In addition, the review highlights recent advancements and research gaps, including the potential of adaptive fuzzy systems, hybrid intelligent controllers, and their integration with emerging technologies such as energy storage systems and electric vehicle charging infrastructure [4].

2. Literature Review

(Shahgholian, 2021) [1] A microgrid is an important and necessary component of smart grid development. It is a small-scale power system with distributed energy resources. To realize the distributed generation potential, adopting a system where the associated loads and generation are considered as a subsystem or a microgrid is essential. In this article, a literature review is made on microgrid technology. The studies run on microgrid are classified in two topics of feasibility and economic studies and control and optimization. The applications and types of microgrids are introduced first, and next, the objective of microgrid control is explained. Microgrid control is of the coordinated control and local control categories. The small signal stability and methods in improving it are discussed. The load frequency control in microgrids is assessed.

(Ansari, 2019) [2] Renewable energy is plentiful, and the technologies are improving all the time. There are many ways to use renewable energy. We have realized that our fossil and atomic fuels will not last forever, and that their use contributes to environmental pollution. Renewable energy – which basically comes from the sun in one way or another – provides opportunities for an unlimited, sustainable energy supply with low environmental impact. Most of the power generation in India is carried out by conventional energy sources, coal and mineral oil-based power plants which contribute heavily to greenhouse gases emission.

(Tetuko, 2021) [3] A solar power plant or photovoltaic (PV) is a generator that converts energy from light into pollution-free electrical energy. However, changes in the intensity of solar radiation and ambient temperature Photovoltaic (PV) which are not linear are the main problems of PV systems in efficient energy conversion that occurs. Control using the Maximum Power Point Tracker (MPPT) method based on the Perturb and Observe (P&O) algorithm which is applied to overcome these problems. Maximum Power Point Tracker (MPPT) itself is a technique for tracking the maximum output power point of the PV system. MPPT will change the working point so that the converter will force the work of the solar panels according to their ability to always reach the maximum

power point. MPPT is not a mechanical system that makes the solar panel system move according to the direction of the sun's intensity, but an electronic system that works to optimize the power output from the solar panel.

(K. S. Patel & Makwana, 2020) [4] This paper presents the modified grid side converter control (GSC) technique which enable the GSC to work as a shunt active filter to mitigate the grid current harmonics produced by the nonlinear load, as well as to transfer power from the grid to the rotor of doubly fed induction generator (DFIG) or vice versa. The main contribution of this proposed technique is an addition of a shunt active filter with space vector pulse width modulation (SVPWM) controller in GSC control itself in order to achieve a better grid current %THD profile, and simultaneously to control active power for variable wind speed. The reactive power supply to the DFIG and extraction of maximum power is achieved using RSC. The comparison of the modified GSC control technique using hysteresis current control (HCC), and SVPWM controller used to mitigate the harmonics is presented with different wind speeds.

(Ali, 2020) [5] In this paper, a Renewable Energy system, Hybrid type using wind and Solar Energy system is proposed. Here two back-to-back converters using IGBT are interfaced with a Permanent Magnet Synchronous Generator (PMSG) and Photo Voltaic Systems (PV) connected to a linear load. A capacitor is connected between the Back-to-Back converters to maintain a steady voltage and to reduce the ripples. A Battery Energy Storage System (BESS) is connected between the back-to-back converters. Battery Energy storage system gets charged when wind and PV energy is sufficient to the load, and it supplies when required by the load. Maximum Power Point Tracking (MPPT) technique is implemented as a control mechanism for wind and PV systems to maintain unity power factor at the PMSG by controlling the generator side converter and to improve the power quality. MATLAB/SIMULINK software is used to simulate the results to verify the impact of control strategies on the system for variable wind speeds and variable irradiance.

(MUSSA, 2019) [6] This paper demonstrates the design of a working prototype of 5-12V DC-DC Boost Converter. The boost converter circuit is designed using MOSFET, Resistor, Capacitor, Inductor and Diode. The key principle that drives the boost converter is the tendency of an inductor to resist changes in current. Inductor is designed using ferrite pot core and windings. This paper briefly reviews the technology used in switched mode power supplies for DC-to-DC conversion for transferring energy from input to output.

(Dalla Vecchia 2019) [7] This paper introduces a new family of non-isolated dc-dc converters that are generated by the integration of the active switched-capacitor (ASCC) and the conventional commutation cell (CCC). Based on the commutation cell concept, the new conceived hybrid active commutation cell (HACC) provides three different types of hybrid converters: buck, boost and buck-boost. All three converters are investigated in this study through the following approaches: topological stages, static gain analysis considering the switched - capacitor features, generalization of the HACC and gain for Mcells and steady-state analysis. The buck version presents a high conversion rate, which demonstrates that it has potential for step-down applications. To verify the proposed topologies, a prototype was built with the following specifications: 600 V input voltage, 150 V output voltages, 70 kHz switching frequency and 1 kW rated power.

3. GCPV System Description

A **grid-connected photovoltaic (GCPV) system** is one of the most widely deployed configurations for harnessing solar energy. Unlike stand-alone PV systems, which require storage batteries to supply power independently, GCPV systems are directly connected to the utility grid. This configuration allows excess solar power to be injected into the grid while enabling the load to draw electricity from the grid when solar generation is insufficient. The design of a GCPV system typically consists of several functional blocks, each playing a critical role in ensuring reliable operation, high efficiency, and improved power quality. The GCPV system consists of a PV array, a boost converter, a DC link capacitor, a VSI, an MPPT solar controller, a PWM controller system, LCL filters, and other various control circuits, as shown in Fig.1.

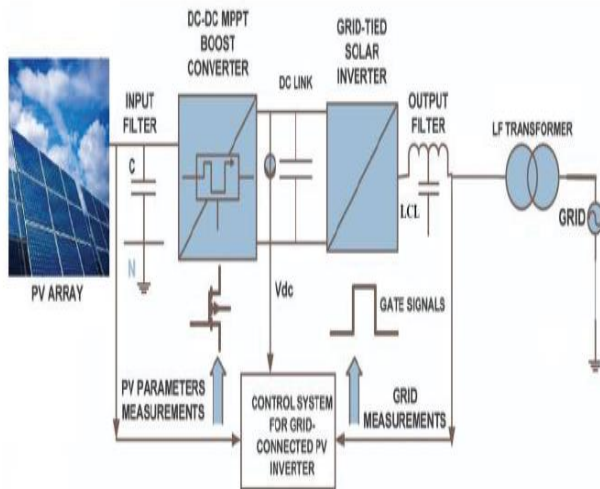


Fig. 1. GCPV system

A. Photovoltaic Array

The photovoltaic array is the primary energy source, consisting of multiple solar cells connected in series and parallel combinations. Each PV cell generates DC power when exposed to sunlight, but the output is highly nonlinear and depends on irradiance and temperature. To model PV arrays, the **single diode model** is commonly used, which represents the I-V and P-V characteristics of the module. In GCPV systems, PV arrays are sized according to the load demand and grid requirements.

1.1 B. DC-DC Converter (Boost Converter)

The converter employed in this GCPV system is a dc-dc boost-type converter and it is given in Fig.2. The major purpose of this converter is to change the unstable dc voltage to a stable dc voltage [5]. Fig.3 shows the ON and OFF states of the boost converter.

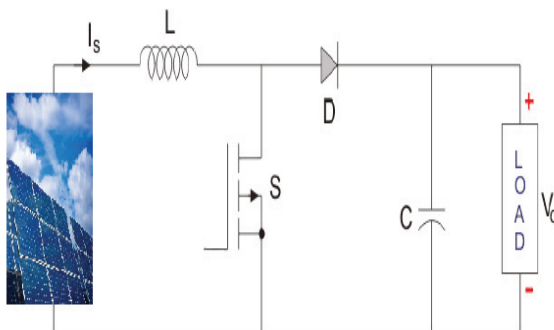
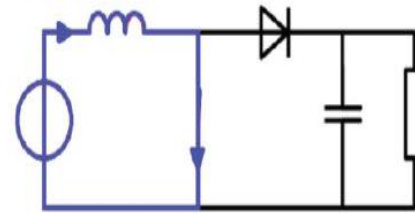


Fig. 2. Boost type converter

On-State



Off-State

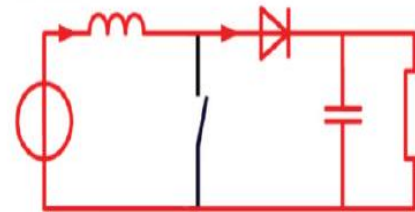


Fig. 3. ON and OFF states of the Boost converter

C. Voltage Source Inverter (VSI)

VSI transforms DC voltage to AC voltage on the application of gate triggering pulses. The circuit of VSI is given in Fig.6. It comprises of three legs, each leg consists of two MOSFET devices which act as switches. These switches get ON and OFF based on the trigger pulses that are given to these devices by the PWM controller.

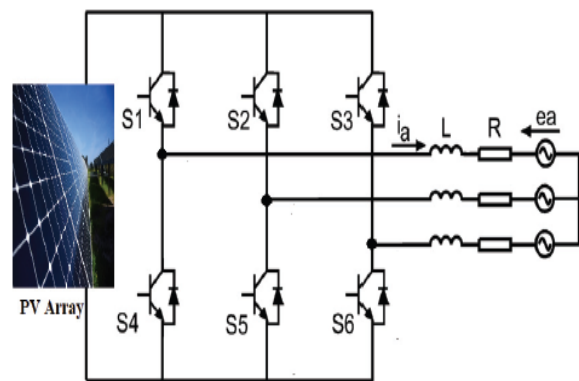


Fig.4. VSI connected to grid

3.1 Fuzzy Logic Controller

In order to create a shunt active filter control method, the DC side capacitor voltage must be monitored and compared to a reference value. There are two inputs to fuzzy processing: an error and an error change. A fuzzy controller uses a set of language rules to regulate its actions. Since no mathematical model is necessary, it may be used with erroneous inputs. [3]

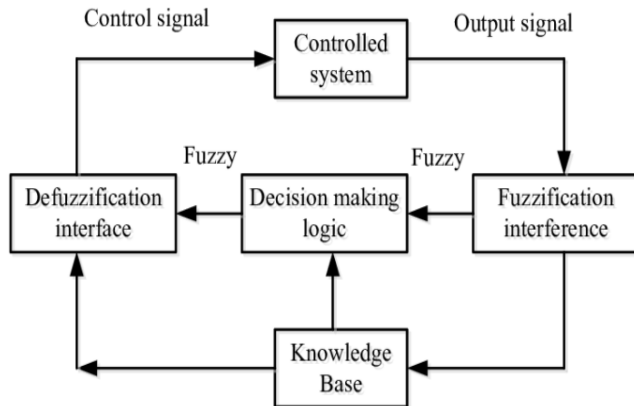


Figure 4 Block diagram of Fuzzy Logic Controller

3.2 Fuzzification

In fuzzy logic control, instead of numerical variables, linguistic variables are employed. These mistakes may be classified as either positive, medium, large, negative, or zero when compared to the reference and output signals, with the exception of zero, which is always positive. Using a triangle membership function, fuzziness is being implemented. Numerical variables are transformed into linguistic variables using fuzzification. [4]

3.3 Disadvantages Of Fuzzy Logic Controller

The Fuzzy Logic Controller (FLC) is an intelligent, rule-based control method that can replace the conventional PI controller in grid-connected photovoltaic (GCPV) systems. Its major advantage lies in the fact that it does not require an accurate mathematical model of the system and can effectively handle nonlinearities, parameter uncertainties, and dynamic variations in solar generation and grid conditions. The FLC regulates the DC-link voltage by processing the error signal and its rate of change. When required, it can adaptively provide reactive power support to improve voltage stability. The FLC reduces current and voltage harmonics, even under nonlinear load conditions and sudden irradiance changes. Unlike PI controllers, which lose accuracy under parameter variation, the FLC uses **if-then rule-based reasoning** to adapt to different conditions.

4. Conclusion

This review highlights the importance of robust control strategies for grid-connected photovoltaic (GCPV) systems, where challenges such as voltage instability, harmonic distortion, and reactive power imbalance often

compromise power quality. Conventional PI controllers and Passive LCL filters have been widely used, but they exhibit limitations under nonlinear conditions, parameter uncertainties, and rapid variations in solar irradiance. Fuzzy Logic Control (FLC) has emerged as a powerful alternative due to its rule-based, model-free structure that can effectively handle uncertainties and nonlinear dynamics. By replacing PI controllers in both voltage and current control loops, FLC provides superior performance in DC-link voltage regulation, inverter current control, reactive power compensation, and harmonic mitigation. As a result, fuzzy logic-based controllers ensure sinusoidal grid current injection, lower Total Harmonic Distortion (THD), and near-unity power factor, thereby significantly enhancing the overall power quality of GCPV systems. Furthermore, the adaptability of fuzzy logic makes it well-suited for future smart grid and microgrid applications, where distributed generation, energy storage, and electric vehicle integration demand flexible and intelligent control frameworks. However, challenges such as rule optimization, computational complexity, and real-time implementation still need to be addressed. Hybrid approaches, combining fuzzy logic with PI, neural networks, or predictive control, appear promising for further improvements. In conclusion, fuzzy logic control not only addresses the shortcomings of traditional methods but also establishes itself as a key enabler of stable, efficient, and high-quality operation in grid-connected PV systems. the potential of fuzzy control for next-generation renewable energy systems.

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