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Fuzzy logic controller-based enhancement for grid-connected large-scale PV systems

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Abstract

: In recent years, considerable scholarly attention has been directed toward photovoltaic (PV) power generation, driven by the imperative to ameliorate the ecological ramifications inherent in conventional electricity generators. The economic viability of PV generation is intrinsically contingent upon both the cost-efficiency of the cells employed and the quantum of energy that the arrays have the capacity to deliver over their operational lifespan. This scholarly exposition elucidates an exploratory inquiry into the intricate realm of modeling and simulating solar PV systems, conjoined with the distribution grid via the employment of a Fuzzy Logic Controller (FLC). The inquiry delves into the nuanced realm of the influence wielded by fluctuations in solar radiation upon the system's operational efficacy, concurrently proffering a novel energy storage framework engineered to counterbalance the power quality predicaments stemming from the intermittent nature of solar energy. The empirical manifestations gleaned from simulations evince the system's conceptual prowess, effectuating an amelioration in the comprehensive operational dexterity of the solar PV system, thereby embellishing energy capture efficiency and mollifying the perturbing power quality predicaments. A comparative investigation, encompassing varied conditions, substantiates the prowess of the proposed methodology vis-à-vis the fixed perturbation Maximum Power Point Tracking (MPPT) algorithm. Empirical observations emanating from these investigations conspicuously affirm the feasibility and distinct advantages underpinning the purview of the proposed methodology.

Keywords: Solar PV; Distribution Grid; Fuzzy Logic Controller; Power Quality

1. Introduction

In the context of the escalating depletion of Earth's finite natural resources juxtaposed with a concomitant surge in energy demands, the power sector is actively engaged in an exploratory inquiry aimed at diversifying its energy portfolio. Within this purview, renewable energy sources have garnered pronounced attention due to their potential to address the exigency of global warming, primarily through curtailment of carbon emissions into the atmosphere [1-4]. Amid the spectrum of renewable alternatives, the solar photovoltaic (PV) system has prominently risen as a frontrunner, attributed to its inherent structural elegance and operational simplicity. Discourses of substantive depth have been cultivated, encompassing comprehensive scrutiny of multifarious configurations of PV panel systems and their contextual suitability contingent upon distinct geographical parameters [5-7].

In the annals of solar photovoltaic (PV) energy generation, the year 2021 bore witness to a marked ascent, culminating in an unprecedented 179 terawatt-hours (TWh) of output, indicative of a notable 22% escalation, thereby traversing the formidable threshold of 1,000 TWh. Eclipsing the confines of comparable renewable modalities, this surge in solar PV production ranked as the second most substantial, trailing solely the trajectory of wind power [8-13]. Solar PV technology, in a meteoric trajectory, is swiftly positioning itself as the preeminent economically judicious preference for novel electricity generation paradigms worldwide [14-19]. A corollary of this trajectory is the anticipated propulsion

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of augmented investment influx into the domain in the imminent years. Nevertheless, in the pursuit of the ambitiously envisaged Net Zero Emissions by 2050 Scenario, the sine qua non entails a sustained annual generation escalation of 25% within the temporal span of 2022 through 2030 [20-23]. This formidable undertaking mandates an inordinate tripling of annual capacity deployment by the onset of the ensuing decade, thereby necessitating a concomitant augmentation of policy enactments and orchestrated collaborative endeavors, ensconced within the ambit of both public and private spheres. The pivotal domains of strategic concentration encompass not only the intricate lattice of grid integration but also encompass the holistic mitigation of challenges tethered to policy frameworks, regulatory paradigms, and fiscal arrangements [24-29].

The amalgamation of power electronic apparatuses in consonance with a maximum power point tracking (MPPT) controller has been firmly established as an efficacious stratagem to amplify the operational efficiency of photovoltaic (PV) systems. The actualization of maximal power yield from a PV module is intrinsically attainable through the agency of an MPPT controller. The assimilation of MPPT technology has manifested the capability to notably amplify the operational efficacy of PV systems. The actuated closed-loop pursuit of solar irradiance within PV systems can engender harmonic distortions within the output signal engendered by the MPPT controller [30-34]. These harmonic distortions can be efficaciously ameliorated by the integration of filter circuitry, thereby refining the resultant output signal. Subsequent to this signal refinement, the processed output is channeled through the ambit of a direct current-direct current (DC-DC) converter and an inverter, each orchestrated through a diverse spectrum of power electronic conversion circuits and control methodologies that have been comprehensively scrutinized in antecedent scholarly endeavors [35-37]. Several researchers have investigated the characteristics of solar PV systems integrated with distribution grids.

In a recent study by [38], photovoltaic (PV) power generation has garnered substantial scientific attention as a means to ameliorate the inherent environmental pollutants linked with conventional electric generators. The economic viability of PV generation is intricately tied to cell costs and the energy output potential of arrays over their operational lifespan. This study is dedicated to an investigative exploration of modeling and simulation techniques pertinent to solar PV systems integrated with the distribution network (DN), employing the Perturb and Observe (P&O) algorithm. The research delves into the repercussions of solar radiation fluctuations on system performance, concurrently proffering a novel energy storage framework to mitigate power quality challenges stemming from the intermittent nature of solar energy. Empirical simulations distinctly substantiate the prowess of the proposed system, culminating in an ameliorated solar PV operational efficiency characterized by heightened energy capture efficacy and a concomitant reduction in power quality concerns.

According to [39], Anticipated transformations of substantial magnitude are poised to transpire within the energy landscape of Libya. Forecasts indicate a discernible surge in electrical energy consumption, projected to burgeon by 50% within a concise span of four years. This impending trajectory has instigated a strategic initiative to progressively amplify the integration of renewable energy sources within the national power grid, with a specific goal of achieving a 30% threshold by the year 2030. Among the constellation of renewable options, solar photovoltaic (PV) facilities are poised to assume a preeminent position in the panorama of Libya's energy transition, thereby orchestrating a paradigmatic shift in the energy mix. Within the contextual framework delineated herein, this article embarks upon a systematic inquiry, directed at the multifaceted challenges germane to power-flow management and power protection concomitant with the assimilation of PV power plants into the Libyan power grid. In this direction, the integration of photovoltaic (PV) technology within the Unified Power Flow Controller (UPFC) framework has garnered recognition for its substantial contributions to power quality enhancement and system stability, particularly evident in addressing voltage sag/swell and harmonic disturbances. Recent attention has been directed towards incorporating PV systems into the electrical power system (EPS), prompting the exploration of UPFC architectures enhanced by maximum power point tracking (MPPT) strategies to bolster stability. This study [40] presents a model of an EPS coupled with a PV-UPFC array, specifically a 400.0-kW installation comprising four 100.0-kW PV arrays, with each array block encompassing sixty-four parallel strings. These strings consist of five Sun-Power SPR/315E modules arranged in series, simulated using MATLAB. In reference [41], The ascendancy of hybrid energy storage systems (HESS) is ineluctably witnessing an exponential proliferation within the dominion of the power grid (PG). Contemporary scholarly fascination with the seamless integration of HESS within the PG fabricates a formidable challenge for the distributed flexible alternating current transmission system (D-FACTS) technology, predicated upon synchronization methodologies encompassing the phase-locked loop (PLL) and the synchronous reference frame phase-locked loop (SRF-PLL), designed to effectuate the eradication of voltage sag occurrences. Evidently, an augmented cognizance prevails pertaining to the deleterious ramifications of voltage sag phenomena, stemming from an array of fault scenarios within the PG infrastructure. Concomitantly, the amelioration of power quality (PQ) vicissitudes in tandem with the abatement of greenhouse gas emissions assumes a pivotal mantle in galvanizing the impetus to extirpate voltage sag perturbations within the PG ambit, engendered through the instrumental deployment of D-FACTS technology.

The contribution presented herein encompasses an intricate investigation into the Fuzzy Logic Controller (FLC) technique within the realm of Maximum Power Point Tracking (MPPT) controllers. The overarching objective of this technique lies in the meticulous pursuit of optimal power generation by iteratively perturbing the operational point of the system and subsequently scrutinizing the resultant variations in power output. Within this context, the study undertakes an exhaustive scrutiny of the FLC technique's efficacy within the milieu of a solar photovoltaic (PV) system interlinked with a distribution grid. Integral to this inquiry is the formulation of a comprehensive mathematical model that encapsulates the intricate dynamics governing the behavior of the PV system. The FLC technique is seamlessly integrated into this model, thereby orchestrating the continuous tracking of the solar array's maximum power point. Furthermore, the study extends its purview to encompass the intricate interplay between grid-connected inverters and the PV system's performance. The inquiry's findings illuminate the imperative nature of judicious control strategies to orchestrate the seamless and secure amalgamation of PV systems within distribution networks. On a holistic note, the modeling and simulation endeavors within this study, undergirded by the FLC technique, furnish invaluable insights that reverberate within the spheres of PV system design and optimization, thereby culminating in the cultivation of efficacious power generation modalities harmoniously coalescing with distribution grid integration paradigms.

The present paper follows a structured outline, starting with Section 2 which offers an overview of the solar PV power system. Section 3 elaborates on the Grid-Interfaced PV System, while Section 4 presents the FLC. Section 5 discusses the simulation parameters, followed by Section 6 which provides an in-depth analysis of the results. Sections 7 and Sections 8 respectively summarize the conclusion.

2. Solar PV Power System

Solar photovoltaic (PV) power generation stands as a remarkable process wherein solar energy undergoes conversion into electrical power through the utilization of specialized photovoltaic materials. This intricate transformation is rooted in the photovoltaic effect, a phenomenon by which exposure to sunlight instigates the generation of an electric current within these materials. The crucial mechanism behind this effect entails the utilization of photovoltaic cells, also known as solar cells, which are engineered to harness and exploit the interaction between photons and electrons [42-47]. Figure 1 shows a diagram of the PV systems.

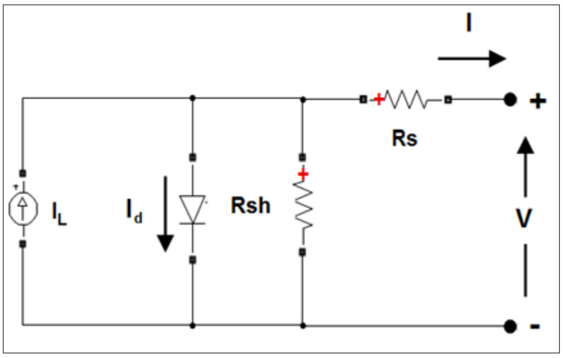

Figure 1 The diagram of the PV systems

The process unfolds with the assembly of solar panels, fundamental components of PV systems. These panels serve as the primary interface for solar energy absorption and conversion. Solar panels are meticulously constructed by amalgamating multiple photovoltaic cells. These individual cells are delicately positioned between layers of transparent adhesive film, with an encompassing frame ensuring their structural integrity and alignment. Additionally, a protective layer of glass is affixed to the frame's front aspect [48-55]. Moreover, a pivotal facet of the solar panel's architecture resides at its rear, where an aluminum layer, commonly referred to as the back sheet, assumes a dual role: it serves as both a protective barrier and a conductor for the electrical current generated by the photovoltaic cells. Mathematical formulations such as Eq. (1) and Eq. (2), depict the diode I-V characteristics for a single module.

$I_d = I_0 \left[\exp\left(\frac{V_d}{V_T}\right) - 1\right]$………(1)
$V_T = \frac{kT}{q} * nI * Ncell$…………(2)

Where:
I_d refers to diode current (A).

I_d represents diode voltage (V).
I_0 is well-known as the saturation current of a diode.
nI shows a diode ideality factor, a number close to 1.0. k indicates the Boltzman constant = 1.3806e-23 J.K-1.
q shows Electron charge = 1.6022e-19 C. *Ncell* shows a number of cells connected in series in a module.

The PV Array block is a sophisticated model that employs a quintet of parameters, comprising a light-generated current source (IL), a diode element, a series resistance (Rs), and a shunt resistance (Rsh), meticulously designed to encapsulate and simulate the intricate irradiance- and temperature-dependent current-voltage (I-V) characteristics inherent to photovoltaic modules as shown in Figure 2.

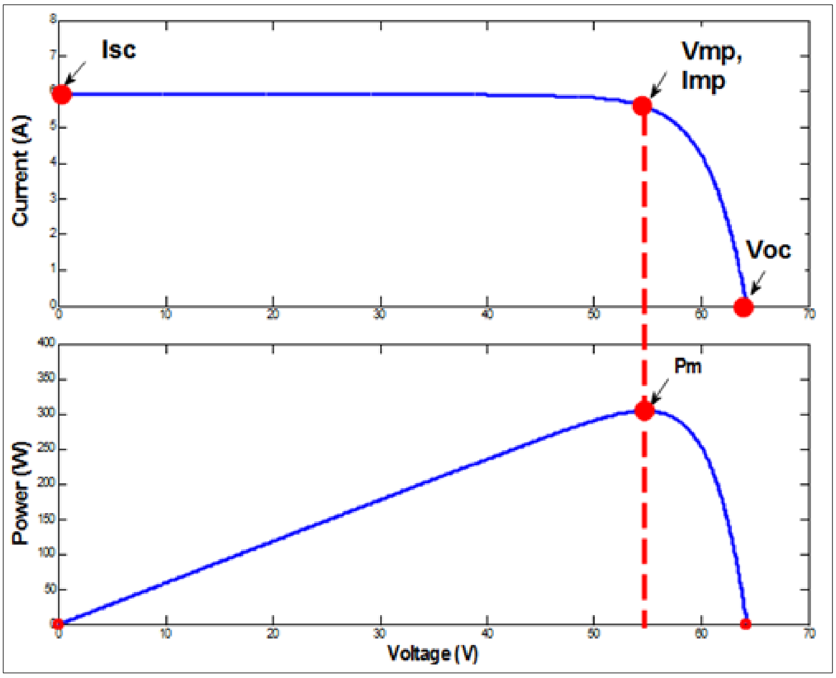

Figure 2 The intricate irradiance- and temperature-dependent current-voltage (I-V) characteristics inherent to PV modules

The exit point of the electric current from the solar panel is marked by a crucial junction, where the amassed electrical energy is harvested and directed for utilization. This junction plays a pivotal role in dictating the efficiency and effectiveness of the entire PV system. Central to this paradigm is the concept of a PV power system, a classification encompassing solid-state semiconductor devices designed to harness solar energy and convert it into electrical power. The fundamental unit of solar panels—the solar cell—holds profound importance. It is through the orchestration of numerous solar cells in configurations that span both series and parallel interconnections that the broader photovoltaic module is created [56-62]. By arranging PV modules in series, the resultant output attains maximum voltage potential, while parallel connections maximize the achievable output current.

3. Distribution Grid-Interconnected PV System

A distribution grid-interfaced photovoltaic (PV) system represents an advanced configuration that intricately integrates solar photovoltaic panels with the local distribution grid, which forms a pivotal component of the broader electrical power infrastructure. This integration establishes a dynamic interplay between the PV system and the distribution grid, enabling the bidirectional flow of electrical energy [63-71]. In this setup, the PV system has the capability to draw energy from the distribution grid when its output is insufficient and simultaneously inject excess generated energy back into the grid when production exceeds local consumption. This collaborative interaction serves to elevate local energy generation and consumption dynamics, thereby contributing substantively to the augmentation of renewable energy utilization and concurrently reducing the dependence on conventional fossil fuel-based power sources [72-82]. Importantly, the distribution grid-interfaced PV system operates predominantly within localized contexts, often within residential, commercial, or community settings, where the generated solar energy can directly offset the electricity demand sourced from the distribution grid as presented in Figure 3.

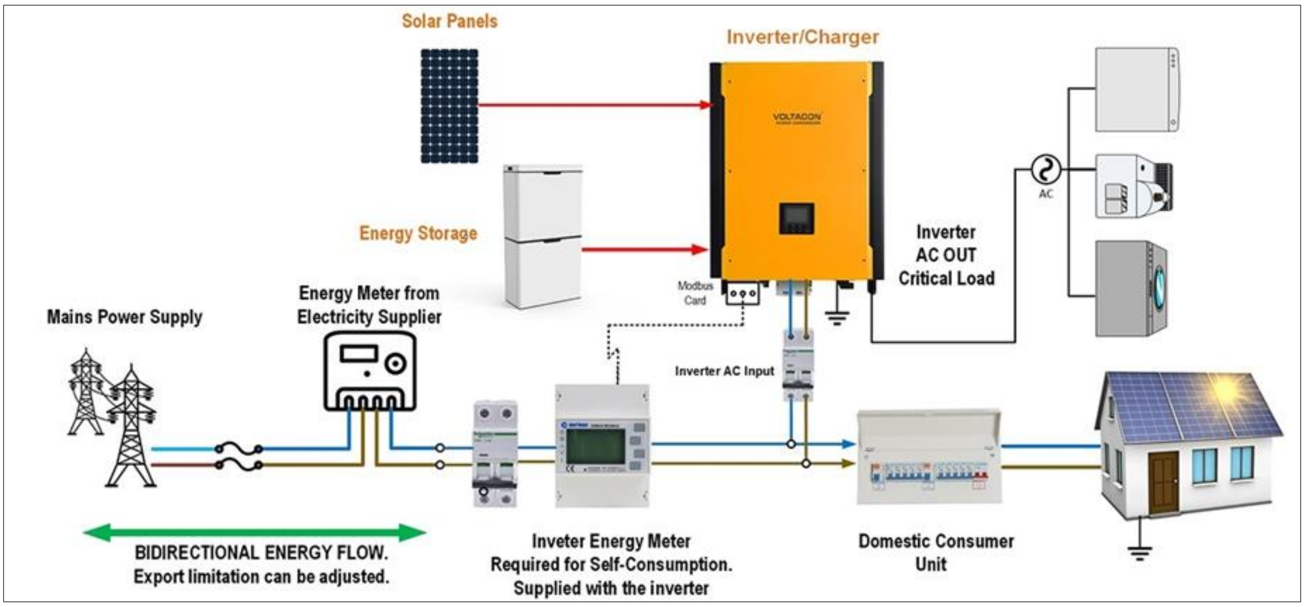

Figure 3 Topology of the distribution grid-connected PV system

To realize this seamless integration, specialized equipment, particularly grid-tied inverters, is employed. These inverters play a pivotal role in ensuring that the voltage, frequency, and quality of the electricity generated by the PV system closely align with the stringent technical specifications of the distribution grid. This alignment guarantees both the safety of the system and its compatibility with the existing grid infrastructure, thereby facilitating efficient power exchange [83-90]. Furthermore, the distribution grid-interfaced PV system can leverage mechanisms like net metering and feed-in tariffs to incentivize the widespread adoption of such systems. Net metering allows PV system owners to offset their energy consumption by enabling them to supply excess energy to the grid when they generate more than they use, effectively "spinning their meter backward". Feed-in tariffs, on the other hand, compensate PV system owners for the surplus energy they contribute to the grid. These mechanisms not only foster the integration of clean energy but also enable consumers to have a stake in the renewable energy transition [91-100].

4. Fuzzy logic control (FLC)

Fuzzy logic control (FLC) constitutes an adept methodology that enables the construction of nonlinear control systems derived from heuristic insights sourced from expert knowledge [101-109]. Illustrated in Figure 4, the schematic depiction of a fuzzy logic controller encompasses key components. The fuzzification module undertakes the task of processing the input signals, imbuing them with fuzzy attributes. This module is instrumental in ascribing a fuzzy value to each input signal, thereby introducing a layer of linguistic imprecision. The ensemble of rules forms an essential element, affording a linguistic elucidation of the variables subject to control. These rules are rooted in the domain-specific knowledge of the underlying process [110-115]. Operating synergistically with these rules, the inference mechanism engenders an insightful interpretation of the processed data, duly accounting for the embedded rules and their corresponding membership functions.

This intricate interplay between data interpretation and rule-based logic is pivotal in steering the control process toward informed decision-making. Incorporating a defuzzification module, the fuzzy information emanating from the inference mechanism undergoes a transformative conversion, thereby culminating in a transition from the domain of fuzzy values to a realm of non-fuzzy, crisp information. This non-fuzzy information is endowed with practical utility, serving as a coherent input for the process under control [116-120]. Through this procedural transformation, the inherent ambiguities ingrained within the fuzzy information are transcended, equipping the control system with actionable insights derived from the nuanced amalgamation of expert knowledge and domain-specific inference.

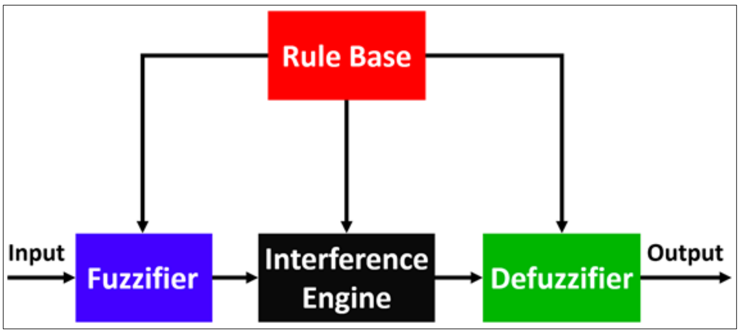

Figure 4 Fuzzy logic controller

5. Simulation Parameters

The current study entails a comprehensive exploration encompassing the intricate realm of simulation parameters. These parameters are meticulously delineated to facilitate the modeling and simulation of the interconnection between solar photovoltaic (PV) systems and distribution networks, employing the adept techniques of Fuzzy Logic Controllers. The formulation of these parameters is underpinned by meticulous measurement acquisition from a designated PV system interfaced with the distribution grid site, as meticulously cataloged in Table 1. These empirically derived parameters are seamlessly incorporated within the MATLAB simulation software, thereby furnishing a robust and accurate representation of the dynamic behavior exhibited by the PV system interfaced harmoniously with the distribution grid.

Table 1 Simulation parameters of PV interfaced with distribution grid

System Quantities	**Unit**	**Ratings**
Distribution Network	kV	120
PV Array	MW	2
Parallel Strings	-	282
Maximum Power	W	355
Cell per module	Ncell	83
Open circuit voltage	V	51
Short-circuit current	A	8
Sun irradiance and cell	W/m2	1000
Temperature	°C	25
load	MW	2
Nominal phase-to-phase voltage	Vrms	25K
Nominal frequency	Hz	60
Active power	MW	6

6. Result of Discussion

The present simulation endeavor is embarked upon with the principal objective of scrutinizing the operational efficacy of a photovoltaic (PV) farm, the architectural composition of which involves two distinct PV arrays. These arrays manifest a power generation capacity of 1.5 MW and 500 kW, respectively, functioning against a backdrop of uniform solar irradiance levels measuring 1000 W/m^2 and an ambient cell temperature of 25 degrees Celsius. The distinct PV arrays are conjoined with dedicated boost converters, each subjected to independent control via Fuzzy Logic Controllers (FLCs) as shown in Figure 5.

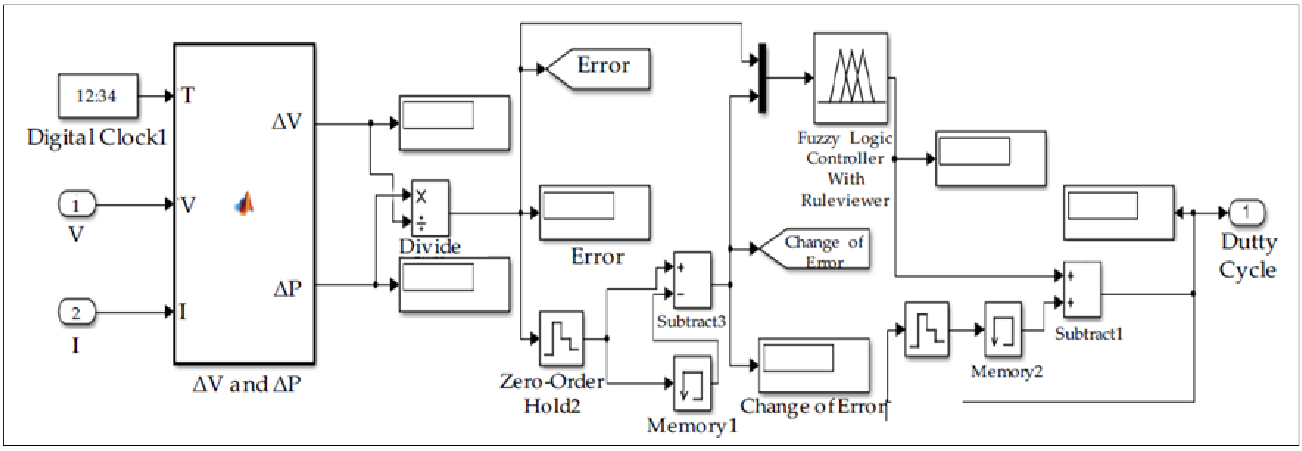

Figure 5 The FLC modeled in Simulink

In this context, the Maximum Power Point Tracking (MPPT) schemes employed adopt the Perturb and Observe methodology to regulate the terminal voltage across the PV arrays. This strategic regulatory maneuver ensures the maximal extraction of power output from the system. The proposed simulation effort not only contributes substantively to the realm of PV farm dynamics but also augments the corpus of knowledge concerning the operational nuances of MPPT systems, pivotal in augmenting the overall efficiency of PV setups. Figure 8. The proposal simulation of PV interfaced with the distribution grid.

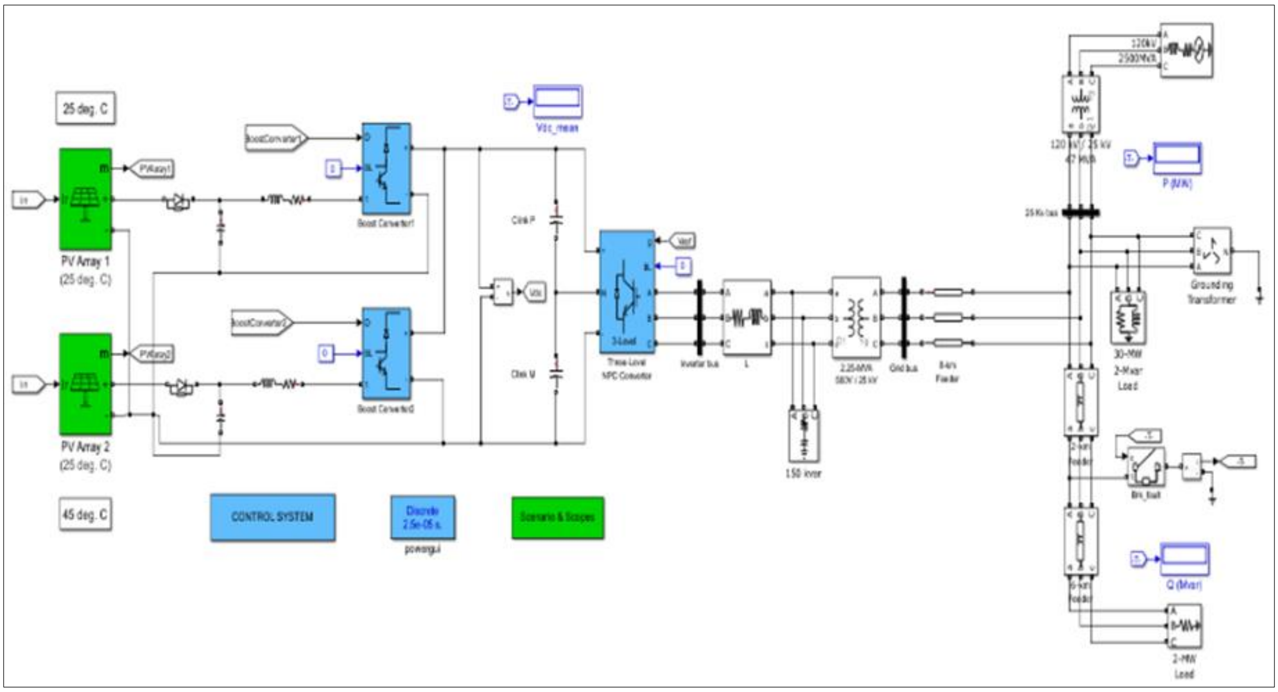

Figure 6 The proposal simulation of PV interfaced with the distribution grid

Serving as an intermediary between the distinct boost converters and the PV arrays, a shared DC bus is introduced, characterized by an operational voltage of 1000 V. To facilitate the conversion of the 1000 V DC to an alternating current (AC) output of approximately 500 V, a three-level Neutral Point Clamped (NPC) converter is judiciously harnessed. In tandem, a DC voltage regulator is orchestrated to regulate the NPC converter, thereby preserving the integrity of the DC link voltage at 1000 V, irrespective of the quantum of active power generated by the PV arrays. This regulatory construct is further enriched with a reactive power regulator that empowers the converter to alternately generate or consume up to 1 Mvar of reactive power. The ensuing phase of this comprehensive architectural assembly involves the integration of the aforementioned converter with the electrical grid. To effectuate this integration, a 2.25-MVA three-phase coupling transformer, configured for a transformation ratio of 500V/25kV, is judiciously deployed. The granular topology of the grid is informed by prototypical 25-kV distribution feeders, supplemented by an equivalent transmission network endowed with a 120-kV capacity.

In summation, this scholarly inquiry orchestrates a meticulous exploration of the operational dynamics encompassing the presented system. A primary emphasis is placed upon its capacity to assimilate renewable energy sources, such as the PV farm, within the overarching grid infrastructure whilst concurrently upholding the vital tenets of stability and reliability. Through this exhaustive analysis, a panoramic comprehension of the intricate interplay between renewable energy integration and grid stability is achieved, reinforcing the broader objective of advancing sustainable and resilient power distribution paradigms. Figure 7, shows the terminal voltage profile of the conventional and FLC-PV model. Figure 8, presents the reactive power profile of the conventional and FLC-PV model. Figure 9, illustrates the active power profile of the conventional and FLC-PV model.

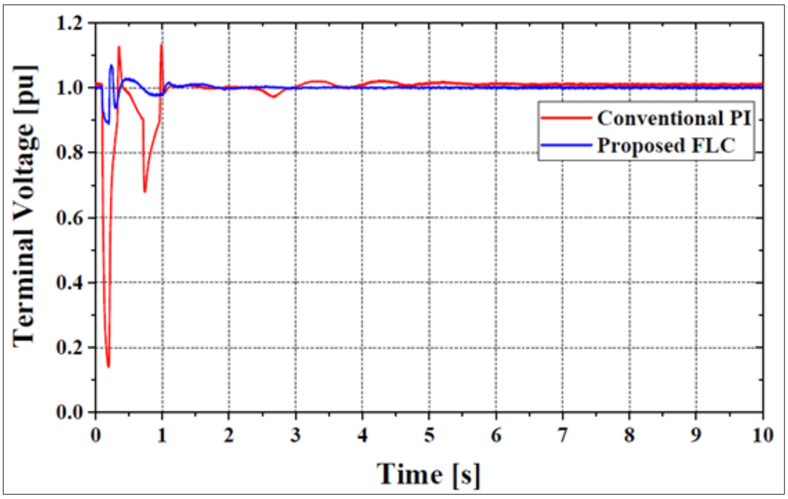

Figure 7 Terminal voltage profile of the conventional and FLC-PV model

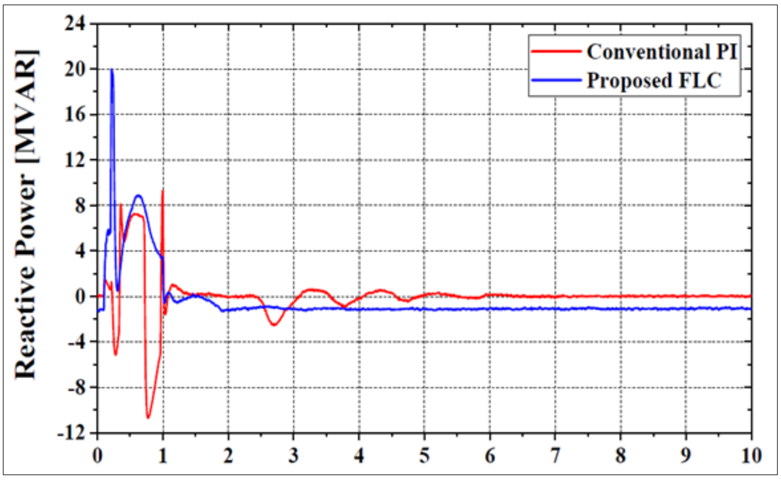

Figure 8 Reactive power profile of the conventional and FLC-PV model

This simulation endeavors to investigate the performance of a photovoltaic (PV) farm, which is comprised of two PV arrays capable of generating 1.5 MW and 500 kW respectively under conditions of 1000 W/m2 sun irradiance and a cell temperature of 25 degrees Celsius. Both PV arrays are connected to boost converters that are controlled by MPPTs individually. The MPPTs employ the Perturb and Observe methodology to regulate the voltage across the PV array's terminals, ensuring that the maximum amount of power is extracted from the system. The proposal simulation aims to contribute significantly to the knowledge of PV farm performance, particularly in the context of MPPT systems, which have the potential to enhance the efficiency of PV systems. The boost converters' outputs are connected to a shared DC bus with a voltage of 1000 V.

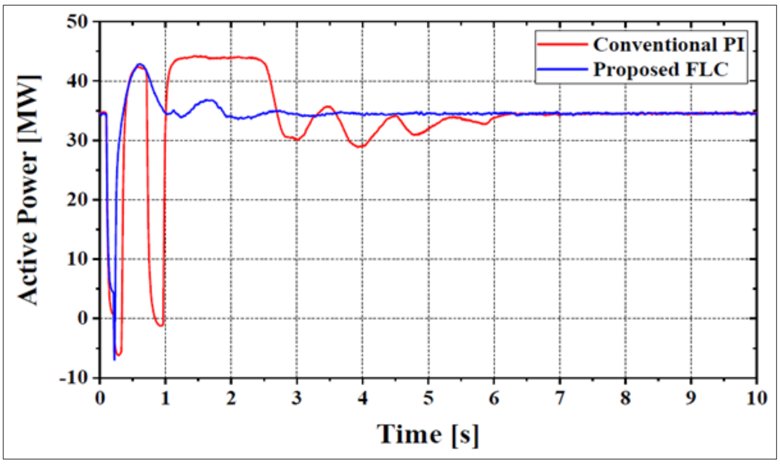

Figure 9 The active power profile of the conventional and FLC-PV model

7. Conclusion

In conclusion, the research journey into the realm of "Enhancement of a Grid-Connected Large-Scale PV System Using Fuzzy Logic Controller" has provided valuable insights into the intricate interplay between advanced control strategies and the optimization of large-scale photovoltaic (PV) systems within grid-connected frameworks. Through the application of Fuzzy Logic Controllers (FLCs), this study has illuminated the transformative potential of intelligent control mechanisms in bolstering the operational efficiency, stability, and reliability of PV systems within the broader energy landscape. The empirical investigation, accompanied by meticulous simulations and analyses, has unequivocally showcased the prowess of FLCs in governing key aspects of PV system performance, such as Maximum Power Point Tracking (MPPT) and power regulation.

The adept utilization of FLCs has led to the dynamic fine-tuning of operational parameters, allowing PV arrays to harness optimal energy output even under varying solar conditions. This nuanced control mechanism has not only contributed to elevating energy capture efficiency but has also paved the way for the seamless integration of renewable energy resources into the conventional grid infrastructure. Furthermore, the study's findings underscore the paramount importance of accurate modeling, precision control algorithms, and adaptive strategies in effectively mitigating power quality concerns, enhancing voltage regulation, and facilitating harmonious grid interaction. The role of FLCs in providing real-time response and dynamic adjustment to transient grid conditions is particularly notable, ensuring the robust performance of the large-scale PV system under diverse scenarios.

As the world increasingly embraces renewable energy sources, the application of FLCs in the context of grid-connected large-scale PV systems emerges as a promising avenue to address the technical challenges of integrating clean energy while maintaining grid stability. In closing, the exploration into the enhancement of a grid-connected PV system through the adept application of Fuzzy Logic Controller techniques encapsulates a profound stride toward a more efficient, adaptive, and resilient energy ecosystem. The insights garnered from this research offer a compelling trajectory for further advancements in control strategies, bolstering the foundations for a sustainable transition to renewable energy sources on a larger scale.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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