Improved Power Quality Solar PV Energy Generation System with Three-Phase Grid Integration

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Abstract: A very important landmark for the implementation of solar photovoltaic energy generation systems onto three-phase power networks is at the heart of global transition into sustainable energy alternatives. This study evaluates the behaviour of single-stage photovoltaic energy systems through the performance investigation, under conditions such as scenario development, along with advanced techniques toward power quality enhancement. Hybrid algorithms, such as the Perturb and Observe (P&O) method combined with the Cuckoo Search Algorithm, are used to optimize power output and reduce harmonics. Simulation results show significant enhancements in system efficiency and reliability, especially under challenging environmental conditions and non-linear loads. In depth analysis of the parameters that include voltage stability, harmonic distortion, and load behaviour indicate how the UPQC integration along with LCL filters can ensure the sustainable grid operations. The importance of optimization in solar PV systems for the realization of the clean energy future based on the needs of modern energy has been discussed in this research work.

Keywords: Solar PV integration, three-phase grid, power quality improvement, hybrid control algorithms, harmonic distortion mitigation, sustainable energy systems.

I. INTRODUCTION

As the world enters the third decade of the 21st century, the world's energy landscape has been transformed under the pressure of climate change, energy security, and economic stability. Now renewable energy is at the heart of this revolution that ranges from sources including solar, wind, hydro, geothermal, and biomass [1] [2]. It is also an overall commitment towards sustainability and resilience besides reducing environmental impacts of fossil fuels, which remain at 81% of world's primary energy in 2019 [3]. The environmental cost of fossil fuels, in terms of greenhouse gas emissions and ecosystem degradation, underlines the need for low-carbon energy sources. Solar energy, with its abundant availability and declining generation costs, has emerged as a leader in the renewable energy sector. Governments and organizations worldwide are setting ambitious targets for solar energy, positioning it as a cornerstone of the global transition to sustainable energy systems [4] [5]. Adding solar energy into power systems is not that easy especially when considering stability and reliability in variable conditions. Despite such challenges, some efforts, for instance, European Union's efforts to achieve carbon neutrality by 2050 with its European Green Deal and midterm renewable energy goals, show growing momentum toward a low-carbon, renewable future [6-8].

Solar photovoltaic (PV) systems are critical to global decarbonization, reducing reliance on fossil fuels and greenhouse gas emissions [9]. By 2020, global PV capacity reached 775 GW, driven by falling costs, subsidies, and feed-in-tariff schemes. Despite progress, further optimization is needed to align energy production with use and empower prosumers through incentives [10] [11]. Solar energy's decentralized nature supports localized energy access in rural areas and enhances system resilience. While renewables accounted for over 27% of global electricity by 2019, energy transitions remain insufficient to meet Paris Agreement goals, emphasizing the need for innovation and policy advancements to accelerate the shift to a low-carbon future [12] [13].

The growing emphasis on energy conservation, environmental protection, and clean energy has driven advancements in modern energy systems, including global energy internet, AC/DC long-distance transmission, distributed generation, and smart distribution networks [14]. These developments rely heavily on power electronics technologies, which are integral to generation, transmission, distribution, and storage in contemporary power systems. However, the rapid proliferation of electrical equipment, such as adjustable speed drives, programmable logic controllers, and energy-efficient lighting, has introduced non-linear loads, leading to distorted voltage waveforms and degraded power quality [15]. The interplay of real and reactive power in power systems affects voltage magnitude and frequency, necessitating adherence to stability standards set by organizations like the IEC and IEEE [16]. To overcome these difficulties, power electronic devices, in particular, the custom power solutions, such as DSTATCOM, are used to provide voltage stabilization along with improving power quality for an efficient and reliable energy system [17].

II. LITERATURE REVIEW

Jha, K., & Shaik, A. G. [18] a comprehensive review on solar photovoltaic systems cited the significant contribution that renewable sources can make towards addressing climate change, reducing the cost of energy, improving reliability in power supply, and energizing remote populations who lack grid connections. It was noted by the researchers that extension of a weak AC grid to remote locations presents challenges upon integration of SPV systems. These challenges encompass PQ issues induced by non-linear and dynamic loads, variable irradiance, partial shading, which in turn pose limits to penetration levels of SPV. Multiple DFACTS devices, using conventional, adaptive, and AI-based control algorithms, were presented for mitigating PQ challenges associated with these issues. Over 130 research articles are very meticulously categorized and assessed in the review, providing some valuable insight into PQ mitigation techniques and the role of advanced control strategies. The improvement of SPV penetration in weak grid scenarios addressed improved energy access and supply reliability. This paper provides a resource for the engineers and academicians focusing on SPV integration and PQ improvements.

Yadav, S. K., et al. [19] this study concentrated on UPQC performance incorporated with a three-phase hybrid energy storage system and the effect that the changeability of solar irradiation and temperature might have in this system. UPQC was utilized to fight against power-quality-related issues as well, by integrating shunt and series AFCs, concerning non-linear load-caused issues such as voltage sag and swell together with the distortion issue due to current harmonics through the grid network. Two different cases were analyzed: a temperature of 25°C along with an irradiance of 700 W/m², and a temperature of 45°C along with an irradiance of 800 W/m². To improve the power quality, a Fractional Order Proportional Integral (FOPI) controller with isodamping property was designed using a novel Enhanced Seagull with Rooster Update (ES-RU) Algorithm. This hybrid algorithm combines Chicken Swarm Optimization (CSO) and Seagull Optimization Algorithm (SOA) for optimally tuning the gain parameters of the FOPI controller, namely Kp, Ki, and λ. The shunt AFC managed the harmonics while the series AFC safeguarded the load from power quality disturbances, which are originated from the grid. The integration of BESS, wind, and PV systems into the UPQC improved its resilience as well as the management of power quality in the case of extended voltage interruptions. This sag and swell performance comparison clearly presented the ability of the developed ES-RU algorithm to improve performances concerning overshoot and THD values than all other standard PI, FF, CSO, and SOA models. The experimental findings are highly authentic regarding the enhanced hybrid algorithms used to determine the optimized gains of the FOPI controller; additionally, these validated results highlighted that the newly established UPQC model was quite strong to eliminate any of the advanced power quality-related problems of recent times.

Sanjenbam, C. D., et al. [20] the control algorithm employed is a band-pass filter frequency-locked loop generalized integrator, which applies a GI-BPF-FLL for the control of the solar photovoltaic integrated unified power quality conditioner system. The control approach of this research works to reject the DC offset, as the control algorithm recovers the FC from distorted and deformed input signals. Hence, the target objective is minimizing the number of sensors used within the control algorithm of the SPVUPQC system. This will enable adding features that improve power quality to the distribution grid. In both time and frequency domain study, the performance and effectiveness of the proposed control algorithm called GI-BPF-FLL are compared with the traditional control. The SPVUPQC system, comprising a DVR and a DSTATCOM, can simultaneously compensate for reactive power, load current imbalances, current harmonics, and voltage distortions such as sag and swell. The model of the SPVUPQC system is developed in the MATLAB/Simulink environment, and its output is presented to demonstrate its capabilities. The hardware prototype of the system can be used in validation, too, and shows promising results as far as performance for both enhancing voltage and current power quality are concerned simultaneously. IEEE standards 1159 and 519 detail the limits on the levels of the voltage magnitudes in the load and grid sides and, overall, all the harmonic distortion in the current drawn from the grid.

Mishra, D. P., et al. [21] for its multiple benefits, solar photovoltaic (PV) power has followed prominent consideration in the electrical energy generation region. A lymphoblastoid cell lines LCL filter is used in the double-stage, triple-phase grid-connected solar PV (SPV) system to improve the power quality. This approach creates a viable junction between the PV systems and the electrical interface using a DC-DC converter and a DC-AC converter. A three-phase DC-AC converter is used to convert the boosted DC into AC and fed into the grid. Instead of an inverter, a three-phase voltage converter is used to interface between the voltage produced by the PV system and the grid with an AC transmission line. This concept employs a maximum power point tracking (MPPT) application for boosting the PV array's efficiency during unstable conditions. Consequently, maximum energy will be extracted by the solar PV array and feed into the grid. The enhancement of power quality by using the LCL filter is measured in terms of power using MATLAB analysis in the time domain using its FFT analysis tool. This means that the very low total harmonic distortion it achieves shows the effectiveness of the suggested concept. As such, it further shows that it improves the quality of power, hence the results will also determine applications of the suggested technology and further developments in renewable energy.

Akbari, E., & Seyyedi, A. Z. G [22] in this study, a hybrid active power filter with photovoltaic (HAPF-PV) system that uses three-level neutral point clamped (NPC) converters has been controlled with proportional-integral (PI) controllers and second-order sequence filters (SOSF). The HAPF's integrated photovoltaic (PV) system drives the boost DC/DC converter while tracking maximum power point tracking (MPPT) based on the perturbation and observation (P&O) technique. Using the SOSF for precise and computationally efficient estimation, the genuine component of the polluted load current was estimated to create a reference signal for the shunt active power filter (SAPF). Overall power quality was improved by the SAPF's efficient compensation of grid current harmonics. With the use of PV arrays coupled by a DC-link, the HAPF-PV system produced green energy while also enhancing power quality. To decrease the harmonic currents that HAPF-PV introduced into the grid, three-level NPC converters were used. This resulted in a sinusoidal output waveform with less distortion because of the higher converter output voltage. To further improve grid dependability, the system also included a series active power filter (SeAPF) to manage voltage sags and swells. The efficacy of the scheme in improving power quality and distributed production was confirmed by MATLAB simulations conducted under a variety of disturbances, including as PCC voltage sag/swell, unbalanced loads, and irradiance fluctuations.

Table 1 Summary of Literature Review on Solar PV Systems and Power Quality Enhancement

Author	Key Findings	Technology	Limitations
Jha, K., & Shaik, A. G. [18]	Reviewed solar PV systems' role in addressing climate change, reducing energy costs, and providing energy access. Highlighted challenges like PQ issues, non-linear loads, and variable irradiance, proposing DFACTS devices and advanced algorithms for mitigation.	DFACTS devices, conventional, adaptive, and AI-based control algorithms	Limited penetration of SPV systems in weak AC grids due to PQ challenges and integration complexities.
Yadav, S. K., et al. [19]	Analyzed UPQC performance under varying solar conditions. Developed a hybrid algorithm (ES-RU) to optimize FOPI controller gains, improving resilience and managing voltage sags, swells, and harmonics.	UPQC, shunt and series AFCs, ES-RU hybrid algorithm, FOPI controller	Focused only on sag/swell scenarios; limited exploration of other grid conditions.
Sanjenbam, C. D., et al. [20]	Proposed a GI-BPF-FLL control algorithm for SPV-UPQC systems. Reduced sensors while enhancing PQ through DSTATCOM and DVR. Validated model using MATLAB and hardware prototypes.	GI-BPF-FLL control algorithm, SPV-UPQC, DSTATCOM, DVR	Primarily focused on validation through prototypes and MATLAB; lacks real-world grid deployment analysis.
Mishra, D. P., et al. [21]	Introduced a double-stage grid-connected PV system with MPPT and LCL filters for PQ enhancement. Achieved low THD using FFT analysis in MATLAB.	Double-stage grid-connected PV system, MPPT, LCL filters	Concentrated on simulation results; minimal practical implementation details.
Akbari, E., & Seyyedi, A. Z. G [22]	Developed a HAPF-PV system using SOSF and PI controllers with three-level NPC converters. Enhanced PQ and supported distributed generation through SAPF and SeAPF.	HAPF-PV system, SOSF, PI controllers, three-level NPC converters	Focused on simulation under specific conditions; lacks exploration of broader environmental impacts.

III. OBJECTIVE

The objective of this research work is to develop and evaluate a multipurpose DS (Distributed Sparse) control approach for a single-stage solar photovoltaic (PV) energy generation system (SPEGS) interfaced with a three-phase grid. The research aims to achieve the following:

- To develop an AI based control approach that enables the SPEGS to efficiently feed the generated solar PV power into the local three-phase grid
    - To develop hybrid control approach including traditional Perturb and Observe (P&O) and Cuckoo algorithm scheme for extracting maximum power from the PV source and assess it's tracking performance and efficiency under rapidly changing climatic conditions.
- To implement control techniques to reduce the harmonics generated by the nonlinear load connected at the point of common interconnection, thereby improving the power quality of the grid.
- To validate the proposed control approach through experiments conducted on MATLAB.

IV.METHODOLOGY

- Solar PV energy generation systems provide a sustainable and clean source of electricity by converting sunlight into power using semiconductor-based solar panels. Such systems have become very popular recently for their low carbon emission and fossil fuel dependence. These solar PV systems should be combined with the three-phase grid; it is then ensured to work in harmony with the current electric structures, giving a greener energy mix. This research aims to analyze performance under different scenarios, and simulations are done using MATLAB to model and evaluate system behaviour.
- 4.1 SPEGS System
- A single-stage SPEGS is a streamlined solar PV setup where direct sunlight is converted into electrical energy in a single power conversion stage. The DC power generated by the solar panels is fed into the VSC, which converts it into AC power suitable for the standard of the national grid. The single-stage system design is simpler than the multi-stage systems, whose extra power conversion stages increase the costs and add to the system complexity. The VSC in the single-stage SPEGS ensures synchronization of the generated AC power to the grid voltage, frequency, and phase for safe and reliable interconnection. It further controls the power flow from the PV system into the grid in response to both the solar irradiance and the demand present in the grid in order to maximize the exploitation of solar energy. Additionally, it encompasses MPPT strategies, like the Perturb and observe algorithm that, still having the operating point of the PV array changing, thus optimizing power output depending on the environment. The single-stage SPEGS approach, in the integrated methodology, is very efficient and practical for renewable energy generation.

4.2 Solar PV Array

A solar PV array is an arrangement of many solar panels linked together to provide a collective sum of sunlight transformed into electricity via the photovoltaic effect. Each panel contains several solar cells, usually from semiconductor materials like silicon that absorb sunlight and produce a DC. For the best overall power output, many panels are often arranged in either series or parallel configurations. Series connections increase the voltage, parallel connections increase the current, and combinations of both can achieve the desired electrical characteristics. Solar panels within an array can use various technologies, like monocrystalline, polycrystalline, or thin-film cells. Monocrystalline cells have better efficiency, while polycrystalline cells are cost-effective, thin-film cells are lightweight and flexible but have lower efficiency. The power rating of every panel is simply the maximum output under standard test conditions, as calculated in terms of watts or kilowatts, considering it is dependent on factors such as size, efficiency, and sunlight exposure. Therefore, the performance of a solar PV array is influenced by the properties of the panels, temperature, and solar irradiance that collectively determine the output voltage VPV and current IPV of the array. Solar panel's connection and mounting in arrays helps make photovoltaic systems adjusted in meeting some special requirements towards an optimal form.

4.3 Current-Voltage Relationship:

The Shockley diode equation models the current-voltage relationship of a solar PV cell or module, taking into account the photovoltaic effect. This effect explains how electric current is generated as a result of the incidence of light. The equation is given by:

$$I_{PV} = I_{ph} - I_0 * [\exp\left(\frac{V_{PV} + I_{PV} * R_s}{n * V_t}\right) - 1] \quad 1$$

Where:

I_{PV} is the output current of the PV array,

I_{ph} is the photocurrent generated by the incident light,

I_0 is the diode saturation current,

V_{PV} is the output voltage of the PV array,

R_s is the series resistance,

n is the diode ideality factor,

V_t is the thermal voltage (kT/q), where k is the Boltzmann constant and q is the elementary charge.

4.4 Three-Phase Grid

A three-phase grid, also referred to as a three-phase power system or three-phase electrical network, is one of the most commonly used systems for electricity distribution that can be applied to large-scale power transmission and distribution. This constitutes three conductors or power lines, each carrying an alternating current waveform that lies 120 degrees out of phase with each other. The three-phase grid has been widely adopted in industrial, commercial, and residential applications, mainly because of its advantages over single-phase systems. The advantages include higher power capacity and improved efficiency. In a three-phase grid, the voltage and current waveforms can be represented mathematically using sinusoidal functions. Let's consider a balanced three-phase system with line-to-line voltage VLL and line current IL. The voltage and current waveforms for each phase can be written as:

Phase A:

$$V_{A(t)} = VLL * \sin(\omega t) \quad 2$$

$$I_{A(t)} = IL * \sin(\omega t + \theta A) \quad 3$$

Phase B:

$V_{B(t)} = VLL * \sin(\omega t - 2\pi/3)$ 4

$I_{B(t)} = IL * \sin(\omega t + \theta B)$ 5

Phase C:

$V_{C(t)} = VLL * \sin(\omega t + 2\pi/3)$ 6

$I_{C(t)} = IL * \sin(\omega t + \theta C)$ 7

Where:

VLL is the line-to-line voltage magnitude

IL is the line current magnitude

ω is the angular frequency (2πf, where f is the frequency of the system)

t is the time

θA, θB, and θC are the phase angles of the currents with respect to the voltage waveforms.

The three-phase grid operates based on the principle of balanced power distribution, where the loads are evenly spread across the three phases. This balance is achieved by ensuring that the magnitudes and phase angles of the currents in each phase are the same or closely matched. To maintain a balanced system, the sum of the currents in each phase should be zero, known as the zero-sequence condition. Mathematically, this can be expressed as:

$I_A + I_B + I_C = 0$ 8

Stable transmission and distribution is provided in power by maintaining three-phase grid along with high reliability. Three phase loads such as motors, are used and found to have design for use when given three phase, which leads the system towards taking more power because of this supply and, finally, will come out to increase the performance for the process also. Representation based on the two sinusoidal functions and the balanced condition guarantees this three-phase network: reliable, the synchronized electrical delivery across the grid.

4.5 Nonlinear Loads

Nonlinear loads are electrical loads that do not maintain a linear relationship between voltage and current, leading to non-sinusoidal currents and waveform distortion. Unlike linear loads, which draw sinusoidal currents in phase with the voltage, nonlinear loads introduce harmonics into the electrical system. The switched-mode power supply, variable frequency drives, as well as computer, LED, and industrial devices, are but a few nonlinear loads. Devices with nonlinear currents consume power electronics and contribute to distortion through switching action and rectification processes. Impacts of the nonlinear loads upon the electrical system include harmonic distortion, increased loss in power transfer, and also distortion of waveforms in voltage transmission. Harmonics cause higher total harmonic distortion (THD), lower power factor, and excessive heating in the cables and transformer. This voltage waveform distortion will also have adverse effects on the performance of delicate equipment connected to the same system. These effects can be minimized by using power factor correction, harmonic filtering, and choosing equipment that adheres to harmonic emission standards. Proper management of nonlinear loads ensures system stability, reduces losses, and maintains reliable operation of sensitive devices, contributing to an efficient and distortion-free electrical system.

4.6 Voltage Source Converter (VSC)

It is a power electronic device used for transforming electrical power between DC and AC at the same time but with the controllable output voltage, frequency, and phase. VSCs find their important applications in the renewable energy domain, power transmission applications, and industrial drives since these converters ensure stability along with controllability in an AC output. VSCs make use of power semiconductor devices such as IGBTs or thyristors which are integrated with control and protection circuits for the maximum efficiency and reliability. The operation of a VSC takes place through PWM techniques based on the high-frequency switching of semiconductor devices to produce synthesized AC waveform. With the switching patterns changed, VSCs are now able to control the magnitude, frequency, and phase of the output voltage and even provide support for many functionalities in the regulation of voltage, reactive power compensation, harmonic mitigation, and synchronization with the grid. Precise control has made VSCs indispensable for modern power systems for making energy conversion efficient and compatible with variable operational demands.

4.7 Voltage and Current Relationships

The voltage across the VSC terminals can be expressed as:

$V_{vsc(t)} = V_{dc} + V_{s(t)}$ 9

where V_{dc} is the DC-link voltage and $V_{s(t)}$ is the synthesized AC voltage waveform.

The output current of the VSC can be given as:

$I_{vsc(t)} = I_{dc} + I_{s(t)}$ 10

where $I_{dc}$the DC current and I_s (t) is the synthesized AC current waveform.

4.8 Pulse-Width Modulation (PWM)

Pulse-width modulation is a widely used technique to generate the desired AC waveform from the VSC. The PWM signal determines the switching pattern of the power semiconductor devices in the VSC. A commonly used PWM technique is the carrier-based sinusoidal PWM, where a high-frequency carrier signal is compared with a reference sinusoidal waveform. The PWM signal can be represented by a modulation index (m) and a phase angle (θ) as follows:

$PWM(t) = 0.5 + 0.5 * m * \sin(2\pi f_c * t + \theta)$ 11

where f_c is the carrier frequency.

4.9 Voltage and Current Control

The VSC typically employs control algorithms to regulate the output voltage and current. Proportional-Integral (PI) controllers are commonly used to achieve voltage and current control. The control signals for voltage (V_ref) and current (I_ref) can be expressed as:

$$V_{ref} = V_{refsetpoint} + K_{pV} * \left(V_{refsetpoint} - V_{vsc}\right) + K_{iV} * \int V_{refsetpoint} - V_{vsc}\, dt \quad 12$$

$$I_{ref} = I_{refsetpoint} + K_{pI} * \left(I_{refsetpoint} - I_{vsc}\right) + K_{iI} * \int I_{refsetpoint} - I_{vsc}\, dt \quad 13$$

where K_{pV},K_{iV},K_{pI}, and K_{iI} are the proportional and integral gain parameters for voltage and current control, respectively.

V. RESULT AND DISCUSSION

The solar PV energy generation systems now become the very essence of the sustainable production of electricity. This can efficiently decrease carbon emissions as well as dependency on fossil fuels. The present chapter will be dealing with a comparative evaluation of a solar PV system in two different scenarios that utilize MATLAB for robust modeling and simulation. The research addresses how solar PV systems are adaptive and effective at different levels of irradiation, integrating with a three-phase grid to maximize renewable energy utilization, thus achieving energy mix through sustainability.

In Case 1, the system performance under an irradiation level of 1000 W/m² through the P&O algorithm and a hybrid approach in voltage as well as current outputs optimisation is tested. Case 2 tests the performance of the systems over a wider range of irradiation values from 0.5 W/m² to 1000 W/m² by comparing the performance of the systems using the P&O algorithm and a hybrid algorithm that combines P&O with the Cuckoo Search Algorithm. Hybrid Improvement Approach on System Enhanced Response Performance with Conversion Detailed evaluation of system performance in response to voltage and current, and harmonic distortion to check the status against specifications and standard lines. In itself, a glimpse into achieving solar PV efficiencies by application - where the job of complex algorithms towards better systems and greener sustainable transitions for greener transitions to sustainable transitions gets a boost.

Case 1: Analysis of the energy system with constant irradiation input (1000W/m^2)

Solar Energy System having P&O Controlled converter system with PI regulators (System 1)

In Case 1, the performance of the solar PV system is assessed under a constant irradiation level of 1000 W/m², which reflects realistic solar energy conditions. The study uses the Perturb and Observe (P&O) algorithm as a converter control technique to optimize the power output by dynamically adjusting the operating point of the PV array in response to changing environmental conditions. This stage introduces more complex settings because non-linear loads usually produce harmonics and electrical distortion within a system. Therefore, this stage includes additional loads in a more realistic scenario.

The key parameters for voltage, current, harmonic distortion, and characteristics of the load line are determined to understand its behaviour under those conditions. This would give indications about the performance, stability, and compliance to the standards, thus giving complete insight into operation in realistic, challenging environments.

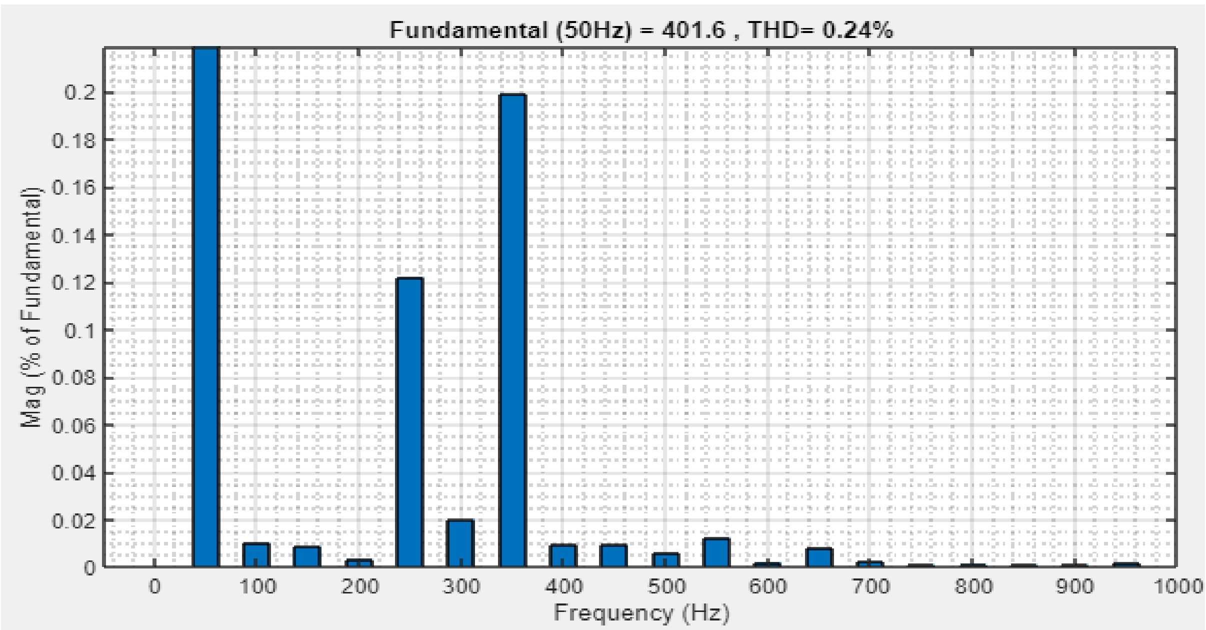

Figure 1: THD% Evaluation of Voltage Output at Non-Linear Load Terminal in system 1 for Case 1

Fig 1 presents Case 1 by showing the harmonic distortion evaluation on the voltage output at the load terminal. THD % shows a measured value of 0.24 %. This graph represents the harmonic distortion level in a voltage signal to assess the electric output quality of the system subjected to non-linear loads.

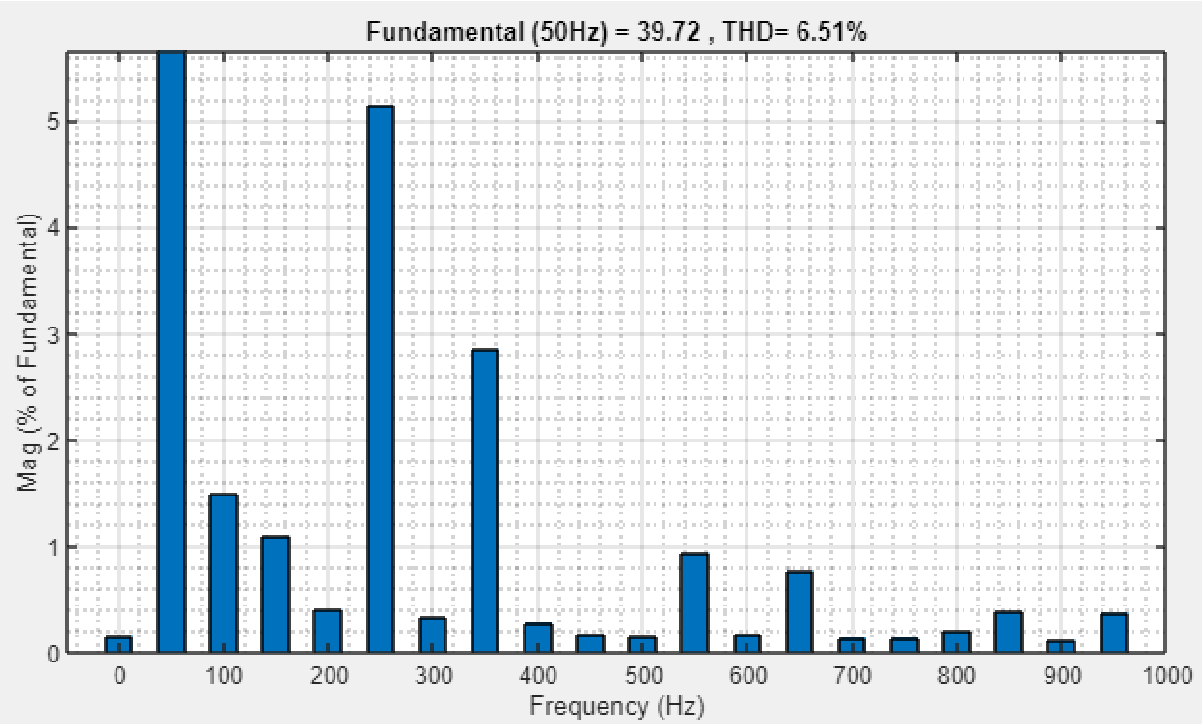

Figure 2: THD% Evaluation of Current Output at Non-Linear Load Terminal in system 1 for Case 1

Figure 2 shows the THD % evaluation of the current output at the non-linear load terminal in System 1 for Case 1, which was measured to be 6.51%. The graph shows the harmonic distortion level in the current signal, thus allowing an evaluation of the quality and stability of the electrical output at the non-linear load terminal.

Solar energy system with Hybrid Control Approach for Converter Control for Quality Enhancement (System 2)

In Case 1 of the system 2 scenario, the value of irradiation is set as 1000 W/m2 and the system under study is exercised to observe behaviour and performance realistically. The power output is optimised using Perturb and Observe (P&O) algorithm in the converter control system along with a Cuckoo Search Algorithm. The researchers will introduce a non-linear load to study the response of the system to such loads and their influence on voltage, current, harmonic distortion, and load line characteristics. These parameters are crucial as they reflect system performance and its compliance with specifications and standards that are desired.

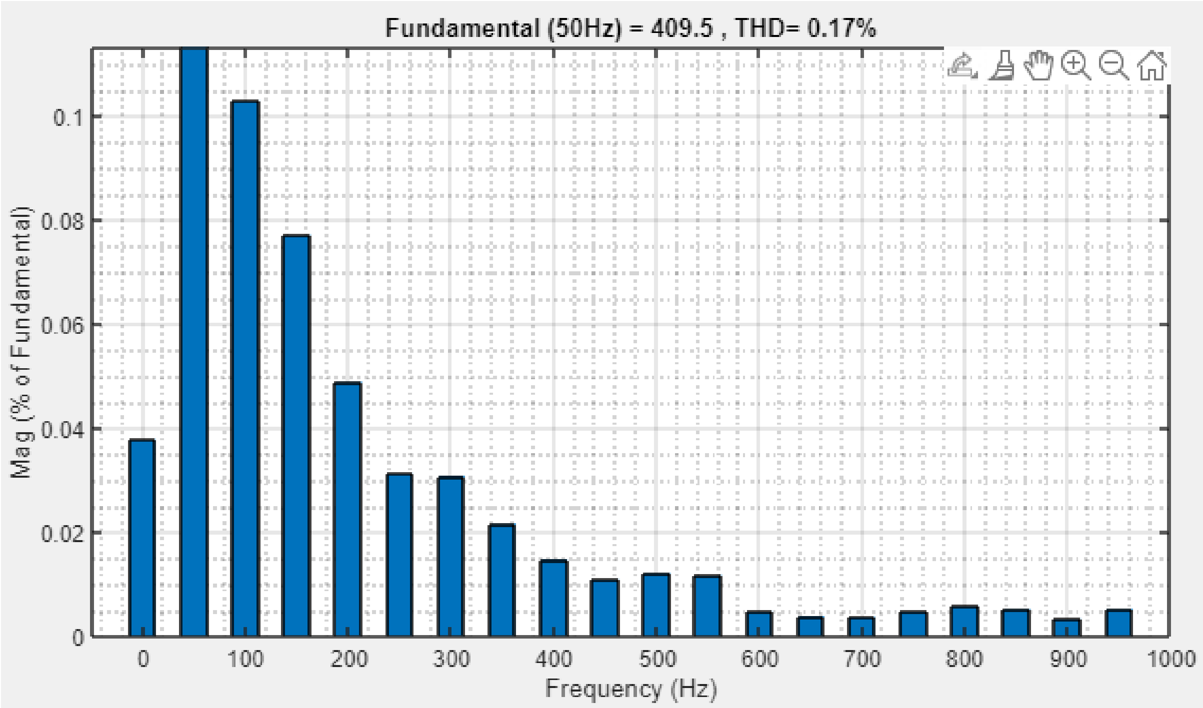

Figure 3: THD% Evaluation of Voltage Output at Non-Linear Load Terminal in system 2 for Case 1

Figure 3: Case 1 evaluation of THD % in the voltage output at the non-linear load terminal: measured value of 0.17%. The graph provides information on the amount of harmonic distortion present in the voltage signal and allows for the assessment of the quality and stability of the electrical output of the system when under non-linear loads.

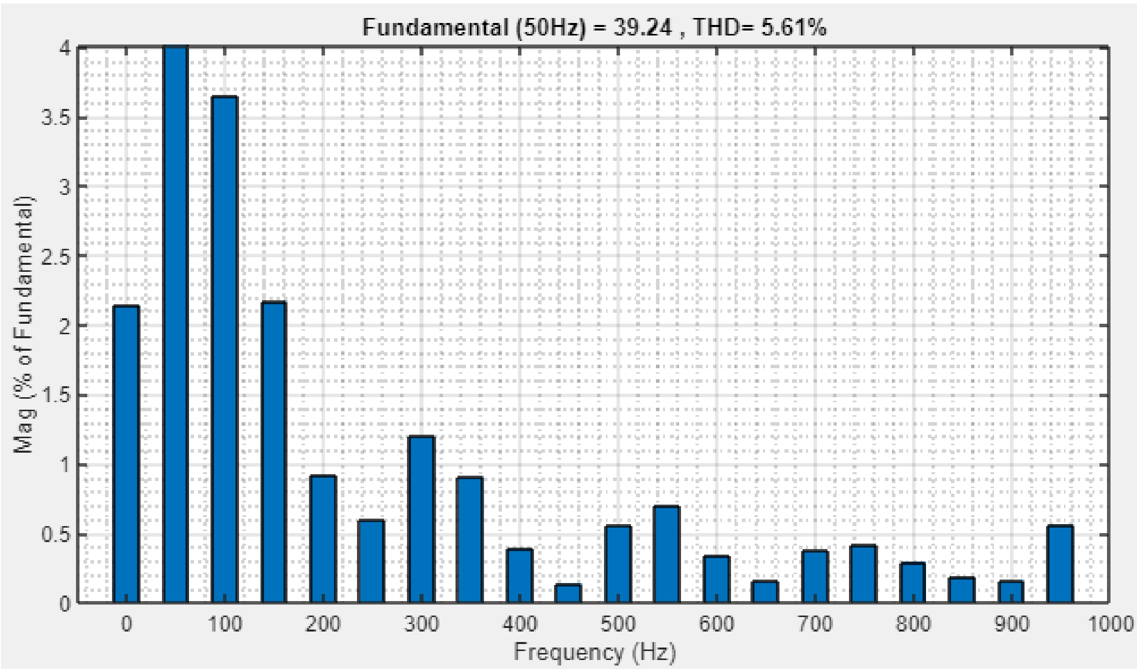

Figure 4: THD% Evaluation of Current Output at Non-Linear Load Terminal in system 2 for Case 1

The Fig. 4 illustrates the computation of THD % in the output current of System 2 for Case 1 at the nonlinear load end. The obtained measurement is about 5.61%. This figure reveals the percentage level of the distortion in the current signal which could be interpreted in terms of quality and steadiness of electrical output at the nonlinear load terminal of the system.

Comparative Analysis of System 1 and System 2 for Case 1

The comparative analysis of System 1 and System 2 in Case 1 involves evaluating their performance under a set irradiation level of 1000 W/m2. The analysis assesses the effectiveness of the Perturb and Observe algorithm as the control technique for System 1, while System 2 utilizes a hybrid algorithm. DC link voltage is analyzed to compare the performance and efficiency of the two systems.

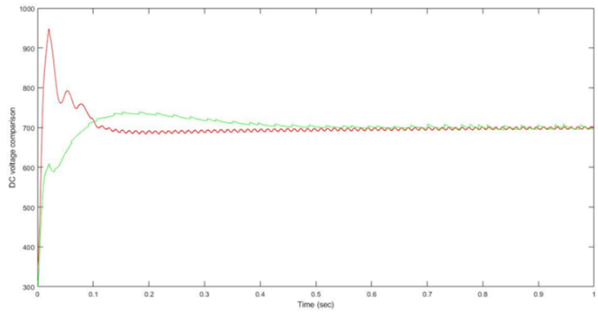

Figure 5: Comparative Analysis of System 1 and System 2 for Case 1

This graph illustrates that both systems exhibit voltage stability at 700V, and as it seen clearly that positive spikes are reduced at initial stage in system 2. During constant value of irradiation levels, it is observed that value of positive spikes is reduced in system 2. This shows that performance of system 2 in case 1 is much better than system 1 with respect to quality enhancement.

Case 2: Analysis of the energy system with variable irradiation input (500 -1000W/m^2)

Solar Energy System having P&O Controlled converter system with PI regulators (System 1)

In Case 2 of System 1, a range of variable irradiance values from 0.5 W/m2 to 1000 W/m2 was selected to study the system's behaviour and performance under diverse environmental conditions. The objective of this work is to assess the adaptability and efficiency of the PV system by the Perturb and Observe (P&O) algorithm, which adjusts the operating point of the PV array to optimize power output. A non-linear load was introduced in the system, and the effects of this on the system operation were examined in terms of parameters such as voltage, current, harmonic distortion, and load line characteristics. The analysis of these parameters is essential in assessing the performance of systems and ensuring compliance with given standards and specifications.

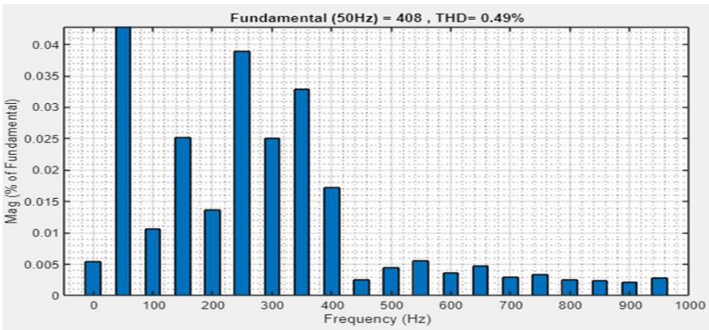

Figure 6: THD% Evaluation of Voltage Output at Non-Linear Load Terminal in system 1 for Case 2

Figure 6 plots the THD % evaluation of the voltage output at the non-linear load terminal for Case 2, where a measurement of 0.49% was taken. This graph shows the amount of harmonic distortion existing in the voltage signal and may be used for an evaluation of the electrical quality and stability of the system while operating with nonlinear loads.

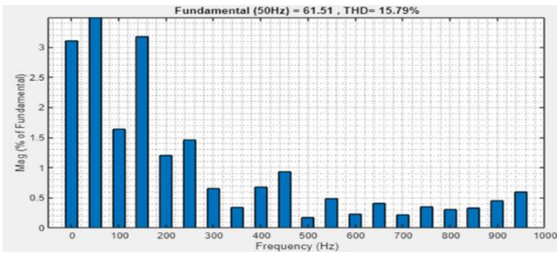

Figure 7: THD% Evaluation of Current Output at Non-Linear Load Terminal in system 1 for Case 2

Figure 7 shows the measurement of THD % in the current output at the non-linear load terminal in System 1 for Case 2, which is measured to be 15.79%. This graph gives an idea of the amount of harmonic distortion present in the current signal and thus allows for an assessment of the quality and stability of the electrical output of the system at the non-linear load terminal.

Solar energy system with Hybrid Control Approach for Converter Control for Quality Enhancement (System 2)

In Case 2 of this research work, different systems were studied with a different range of irradiation values. The irradiation range set from 0.5 W/m2 to 1000 W/m2. This wider range of irradiation levels was chosen to study the system's performance across a broader spectrum of environmental conditions. This hybrid approach aims to improve efficiency and effectiveness in the process of a converter system by combining the hybrid Perturb and Observe (P&O) algorithm with the Cuckoo Search Algorithm. Hence, this hybridization was integrated in order to take the advantage of both algorithms to enhance tracking performance for maximum power point tracking. As already mentioned, the P&O algorithm changes the operating point of the PV array to optimize power output. Integration of the Cuckoo Search Algorithm, which is a nature-inspired optimization algorithm, is used to provide additional exploration and exploitation capabilities to the converter process. The Cuckoo Search Algorithm may also provide a better exploration of the solution space and possibly lead to improved convergence and optimization results.

In Case 2, simulation of both systems was done and results obtained were in terms of parameters like voltage, current, harmonic distortion, and load line characteristics. This result could analyze the system's performance for different irradiation levels within the given range. The researchers combined the P&O and Cuckoo Search algorithms in the converter process and considered a wide range of irradiation values to test the adaptability, robustness, and efficiency of the system under various environmental conditions. The results from this research work may be very useful for optimizing and designing solar PV systems for better performance and energy yield.

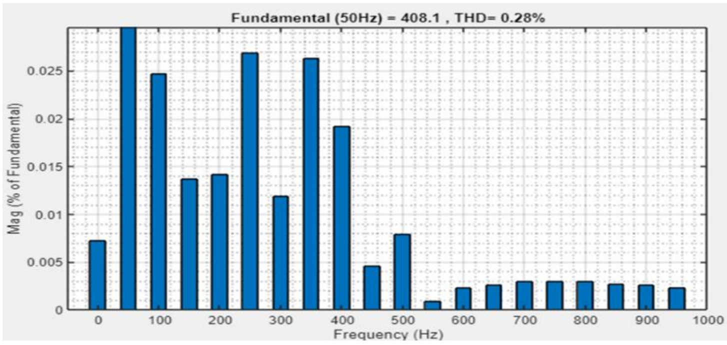

Figure 8: THD% Evaluation of Voltage Output at Non-Linear Load Terminal in system 2 for Case 2

Figure 8 demonstrates the THD % of the voltage output at the terminal of the non-linear load in Case 1. The measured value is 0.28%. This graph will be useful for determining the amount of harmonic distortion in the voltage signal, allowing for an evaluation of the electrical output quality and stability of the system under the influence of non-linear loads.

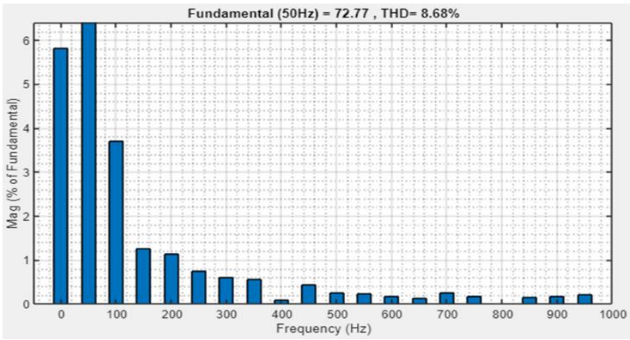

Figure 9: THD% Evaluation of Current Output at Non-Linear Load Terminal in system 2 for Case 2

Figure 9 depicts the THD % evaluation in the current output of the non-linear load terminal for System 2 in Case 2, at 8.68%. The current signal can then be assessed about the quality and stability of the system's electrical output at the non-linear load terminal from this graph in terms of the harmonic distortion level.

Comparative Analysis of System 1 and System 2 for Case 2

In Case 2, the comparison of System 1 and System 2 is done on the basis of their performance in a given set irradiation level ranging from 500 - 1000 W/m2. Here, the efficiency of the Perturb and Observe algorithm used as the control technique for System 1 has been analyzed while the hybrid algorithm is used in System 2. DC link voltage is analyzed to compare the performance and efficiency of the two systems.

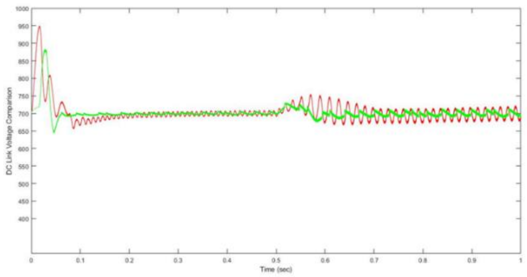

Figure 10: Comparative Analysis of System 1 and System 2 for Case 2

This graph illustrates that both systems exhibit voltage stability at 700V, and as it seen clearly that positive spikes are reduced at initial stage in system 2. During variation of irradiation levels also, it is observed that value of positive spikes is reduced. This shows that performance of system 2 in both the cases is much better than system 1 with respect to quality enhancement.

VI. CONCLUSION

The study emphasizes the significance of solar PV systems in today's power grid, especially the integration of such systems with three-phase systems for better power quality and energy efficiency. Advanced hybrid control algorithms used in this research successfully address the challenges of harmonic distortion and voltage stability under different environmental conditions. Comparing the two, conventional and hybrid methods, show better performance with reduced harmonic distortion in hybrid approaches as well as good adaptability with non-linear loads. In such a context, integration of UPQC and the use of LCL filters improve the feasibility for successful integration of solar PVs with existing grids with respect to worldwide energy standards. These findings open up new avenues for the creation of sustainable energy solutions, toward the goals of decarbonization and resilience in power systems.

Conflict of Interest: The corresponding author, on behalf of all authors, confirms that there are no conflicts of interest to disclose.

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