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AI-Based Power Quality Enhancement in Grid-Connected Solar PV Systems

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ABSTRACT

The increasing integration of solar photovoltaic (PV) systems into modern power grids has introduced significant challenges in maintaining power quality due to intermittency, nonlinear loads, and grid disturbances. This research presents an advanced Artificial Intelligence (AI)-based approach for power quality enhancement in grid-connected solar PV systems using Artificial Neural Networks (ANN). The proposed methodology focuses on mitigating key power quality issues such as voltage sag, swell, harmonic distortion, and reactive power imbalance. An ANN-based control strategy is developed to optimize the performance of power electronic compensators, such as shunt active power filters (SAPF) under varying environmental and load conditions. The neural network is trained using real-time and simulated datasets to accurately predict system disturbances and generate appropriate compensating signals. The model demonstrates adaptive learning capability, enabling improved dynamic response and robustness compared to conventional controllers such as PI and fuzzy logic systems. Simulation results, carried out in MATLAB/Simulink environment, validate the effectiveness of the proposed ANN-based controller in reducing Total Harmonic Distortion (THD) within IEEE standard limits and maintaining voltage stability at the point of common coupling (PCC). The system also shows enhanced efficiency in reactive power compensation and improved grid synchronization under fluctuating solar irradiance conditions. The findings of this study highlight the potential of ANN-based intelligent control systems in ensuring reliable and high-quality power delivery in renewable energy-integrated grids. This work contributes toward the development of smart and sustainable energy systems by providing a scalable and efficient solution for power quality management in solar PV applications.

Keywords: DSTATCOM, Power Quality, Voltage Sag, Voltage Swell, Harmonics.

I. INTRODUCTION

The growing world needs to access clean and sustainable energy, which has increased the immense movement 'of renewable energy sources, especially solar photovoltaic (PV) systems'. The reason why grid-connected PV installations are popular is that the installations are scalable, the cost has reduced, and it offers a lot of environmental benefits. Among the most significant issues that can be linked to grid-connected PV systems, the quality of power deterioration can be noted. Problems like voltage sags and swells, harmonic distortion due to switching of inverters, frequency variations , and poor dynamic response to grid disturbances can impair system stability and can even cause the disconnection of PV units to the grid [1,2]. These problems of power quality disruption have been widely discussed in the classical and contemporary literature on power systems, with their negative effects on sensitive loads and network stability being the focus. Moreover, the growing infiltration of renewable energy sources has exacerbated these worries, especially within weak grids and large-scale installations. More complex control and modeling methods are thus needed to provide stable operation and improved power quality in the renewable-abundant power systems. This paper presents an ANN-based intelligent control scheme that incorporates a Distribution Static Compensator (DSTATCOM) to improve voltage stability, minimize harmonic distortion, and 'fault ride-through 'operation of 'a grid-connected PV system'. The suggested solution will help to make sure that the updated grid codes will be adhered to and to enhance the general quality of power and dynamic performance considerably [3].

II. RENEWABLE ENERGY SOURCES (RES)

As traditional energy sources are increasingly depleted and have aundesirable impact on the environment, the usage of renewable energy sources (RES) for instance solar-photovoltaic (PV) systems and also wind power systems for electricity generation is becoming increasingly popular. Researchers in academia and industry are now strongly focusing on the network interactions of these RES to improve system performance. RES are more popular than traditional energy sources due to their cost-effectiveness, environmental friendliness, and ease of use [4]. On the other hand, a large number of control equipment, statistics processing equipment, RES, and subtle power electronic equipment (PEE) have been added to the electricity distribution network in recent decades, resulting in a sharp increase in electricity demand, which is accompanying with a substantial increase in PQ problems in the distribution network [2]. PQ is crucial for ensuring the proper operational of connected devices and the overall resilience of decentralized systems. Therefore, power and voltage quality are critical. The authors in [3] described how PQ complications such as voltage sag & swells, harmonics and flickering can cause disturbances, damage delicate equipment and reduce the effectiveness of power systems. Therefore, the use of PQ enhancement methods (PQE) has become increasingly popular as a way to reduce over voltages and power outages. Various tools and procedures have been proposed and employed to progress the stability and performance of power systems and to solve PQ problems [4].

III. RESEARCH MOTIVATION

Renewable sources of energy are more favored in energy production because of the high demand for green electrical energy including the decline of orthodox power sources such as natural gas, oil, coal, or nuclear. The solar PV source is the most notable source for energy production because of its pollution less, waste less, economic, and manageable fabrication. Currently, solar PV energy generation transits from the low to the high-power grid system without any challenge [1]. The burgeoning load requirement and the integration of multiple energy sources take place through the course of transmission lines to control the accumulation, and continuity, diminish the supply power bank demands, and replacement of any traditional sources with non- conventional, green, renewable sources [2], [3]. Lamentably, elevation in unbalanced loads is the cause for more predicaments in harmonics power quality in a disseminated system as opposed to the central grid. Unbalancing is caused because of uneven distribution of either single-phase load voltage or uneven generation level or distribution level voltage. At any given junction in a grid, an unbalanced load will impact different load parameters in the corresponding node [4]. A control method is essential in grid unification. The escalating enormity of the power deficiency pressures and environmental anxieties has rooted for the advancements in the smart grid to grow among urgent subjects researched by present scholars [6]. The association of unconventional renewable sources, like wind, PV, or fuel cells into circulation channels induces a reliable and consumable energy supply. Simultaneously, the occasional inconsistency of principal sources, the expanding employment of the power electrical machines, and the reoccurring un-balanced loads draw about furtive issues of power quality [7], [8].

LC filter can be employed for power conditioning for the minimization of ripples [9]. However, it is expensive because of its high-value inductance for average to large energy demands [10]. Hence, an LCL filter is employed. The lymphoblastoid cell lines LCL design trait has the most crucial position in an all-over system and presents an indispensable role in the stability of the system [11]. The scheme of the LCL filter must take care of expense quandaries, the greater value of capacitance, economical, and the lower value of inductance, which is massive and expensive. Further, the grid's stability is influenced by its impedance, and careful forethought is imperative while designing the LCL filter [12]. The LCL filter's resonant frequency changes as the impedance of the grid changes, which results in the stiffness of the grid. So, for the solar PV system combined with the grid to work, control strategy and synchronization are essential [13]. The control of the reference frame, which is synchronous, is carried out for the synchronization of frequency by employing a phase-locked loop (PLL) [14], [15].

IV. ARTIFICIAL INTELLIGENCE ARCHITECTURE FOR PHOTOVOLTAIC SYSTEMS CONNECTED TO THE GRID

A rundown of all the papers written on artificial intelligence in the electricity grid throughout the last few decades. The data was obtained by referring to the significant articles published in various publications. It is clear that the majority of researchers have been focusing on artificial intelligence methods for optimization and control applications in system design in the last several years. Intelligent photovoltaic (PV) plants are envisioned in [4], with system control achieved by model predictive control and array and energy storage system size optimized using linear programming. Here, AIpowered learning methodologies are made possible by the collected data, allowing the system to detect and respond to a wide range of problems and anomalies within the allotted time. Based on the findings, this procedure can be executed online using reinforcement learning techniques. Data management and categorization allow for precise identification of the many operational phases and characteristics, which is crucial for power system operation, which relies heavily on processing massive volumes of data quickly. Various functioning phases and disruptions in the power system may be identified by monitoring its real-time characteristics, as described in [5]. In addition, the power system employs an expert system analysis to differentiate between various voltage dips and disruptions in [6]. In addition, the data was used to its maximum potential by modifying regression methods for power system power flow analysis, demand side management, and forecasting. To find out how much power to scale up the heterogeneous virtual power plants, the authors of [7] use the K-clustering technique. To accommodate the power system's diverse ESS distribution, this section employs the distributed dynamic clustering technique. By taking power system uncertainty into account, a multi-cluster method is used to optimize ESS sizing for PV production in [8]. Similarly, different power grid linkages are investigated using an ordered clustering spectral approach [9].

V. USING AI TO DESIGN POWER SYSTEMS

The existing status of artificial intelligence (AI) application in PV system design and optimization with respect to energy yield, costs, and permits is presented in this section. Solar panel equivalent circuit model-based numerical simulations for system operational performance description have long been the subject of discussion [10-11]. Through analytical or numerical methods, the parameters of these models are discovered. The problem with using analytical techniques is that they rely on a lot of assumptions and approximations, which might lead to inaccurate models. In contrast, numerical approaches have consistently shown superior results [12-13]. Despite its computational demands, these approaches include pattern search, non-linear least squares optimization, and the Newton-Raphson method. Also, by using Markov chains, parameter identification was successfully achieved [14]. Conventional approaches cannot be used if data covering a broad time range is not accessible, since these methods rely on this data. When modeling and simulating the PV system, as well as when diagnosing faults, parameter identification is crucial. A method for estimating currents and shunt resistance based on the temperature dependence of diode voltages has been devised. The top performers from the last generation are selected based on how closely they follow the experimental I-V curve with excellent convergence. When compared to other approaches found in the literature, the findings demonstrate that the created strategy performs the best in terms of RMSE. A similar approach is used in [15] to identify parameters of the solar cell's single and double diode models using an artificial bee colony. Compared to the previous algorithms, the one that was designed converges more quickly and with better accuracy (lower RMSE). In addition to heuristic search methods, other popular techniques include neural networks [16-17] and parameter identification methods based on the adaptive neuro fuzzy inference system (ANFIS) [18]. These methods have shown promising outcomes when used to solar panels whose parameters are not known. Figure 5 provides a high-level overview of how the ANFIS technique may be used to perform parametric identification. Table 1 also provides a highlevel summary of the many traditional and AI-based parameter identification methods, with the goal of determining which methods are more accurate.

VI. PROPOSED METHODOLOGY

1. Detailed System Modeling of Grid-Connected PV System

The proposed work begins with accurate modeling of a grid-connected solar PV system in MATLAB/Simulink. The PV array is modeled considering irradiance and temperature variations to replicate real environmental conditions. A DC-DC boost converter is used to regulate and maintain a constant DC-link voltage, while a Voltage Source Inverter (VSI) enables grid interfacing. Nonlinear loads are connected at the Point of Common Coupling (PCC) to intentionally introduce harmonics and disturbances. This realistic modeling ensures that the system reflects practical challenges such as voltage fluctuation, harmonic injection, and reactive power imbalance, forming a strong base for testing the proposed AI controller.

2. Intelligent Data Acquisition and Feature Extraction

In this stage, real-time electrical parameters such as grid voltage, load current, inverter current, and DC-link voltage are continuously measured. These signals are processed to extract meaningful features like Total Harmonic Distortion (THD), voltage deviation, and reactive power demand. Advanced signal processing techniques are applied to convert raw data into structured inputs suitable for the ANN. This step is crucial because the performance of the ANN depends heavily on the quality and relevance of input features, ensuring accurate detection and classification of power quality disturbances.

3. Design and Training of ANN-Based Controller

An Artificial Neural Network (ANN) is developed to perform intelligent control actions by learning nonlinear relationships between system disturbances and required compensations. The

ANN architecture typically consists of multiple hidden layers with optimized neurons to improve learning capability. It is trained using supervised learning, where input-output datasets are generated from various operating conditions such as load switching, faults, and irradiance variations. The backpropagation algorithm is used to minimize error and improve prediction accuracy. Once trained, the ANN can quickly predict the required compensating signals, offering faster and more adaptive performance compared to conventional controllers.

4. Real-Time Control and Compensation Mechanism

The trained ANN controller is integrated with a power electronic compensator such as a Shunt Active Power Filter (SAPF) or Unified Power Quality Conditioner (UPQC). Based on real-time inputs, the ANN generates reference currents or voltages required to eliminate disturbances. These reference signals are fed into a PWM-based switching scheme to control the Voltage Source Inverter (VSI). The inverter injects compensating currents into the grid, effectively reducing harmonics, stabilizing voltage, and balancing reactive power. This closed-loop control ensures continuous monitoring and correction, maintaining high power quality under dynamic conditions.

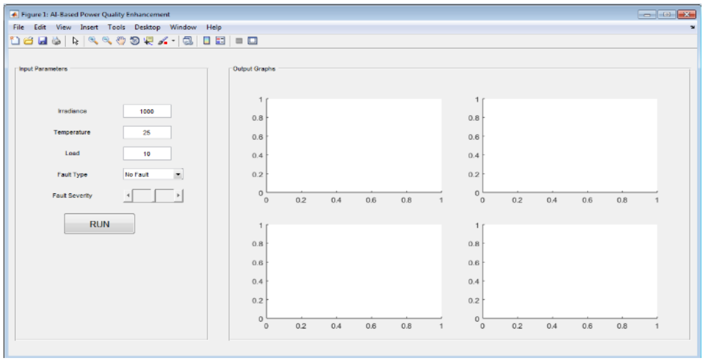
5. Performance Evaluation and Comparative Analysis

The effectiveness of the proposed ANN-based system is validated through extensive simulations in MATLAB under varying operating scenarios such as fluctuating solar irradiance, nonlinear loads, and fault conditions. Key performance metrics include Total Harmonic Distortion (THD), voltage regulation, and power factor improvement, evaluated according to IEEE standards. The results are compared with traditional PI and fuzzy logic controllers to demonstrate the superiority of the ANN approach in terms of faster response, higher accuracy, and better adaptability.

VII. RESULT AND SIMULATION

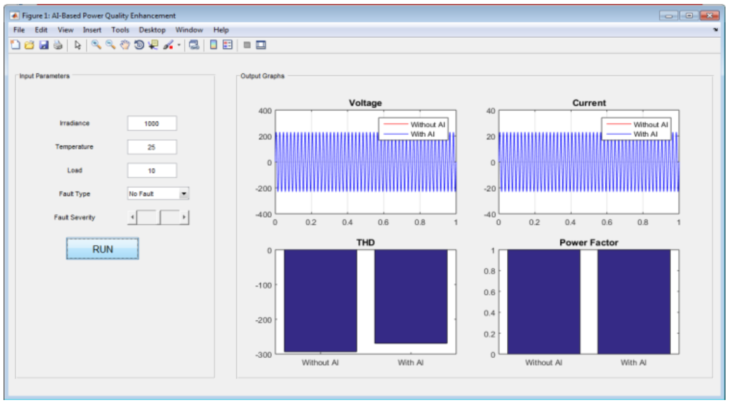
The simulation of the proposed AI-based power quality enhancement system was carried out using MATLAB R2015a environment. A grid-connected solar photovoltaic (PV) system was modeled with nominal voltage of 230 V and frequency of 50 Hz. Various power quality disturbances such as voltage sag, voltage swell, harmonic distortion, and line faults were artificially introduced into the system to evaluate performance under abnormal operating conditions. The disturbance severity was varied dynamically to analyze system robustness.

An artificial neural network (ANN) based compensator was designed using a feedforward architecture with Levenberg–Marquardt training algorithm. The ANN was trained using distorted voltage signals as input and corresponding ideal sinusoidal voltage as the target output, enabling the network to learn nonlinear compensation characteristics. The simulation time was set to 1 second with a sampling interval of 0.001 seconds to capture transient behavior accurately.



Irradiance: 1000
Temperature: 25
Load: 10
Fault Type: No Fault
Fault Severity

Fig.7.1 Matlab Simulation GUI.



Irradiance: 1000
Temperature: 25
Load: 10
Fault Type: No Fault
Fault Severity

Fig.7.2 No Fault condition THD and Power Factor.

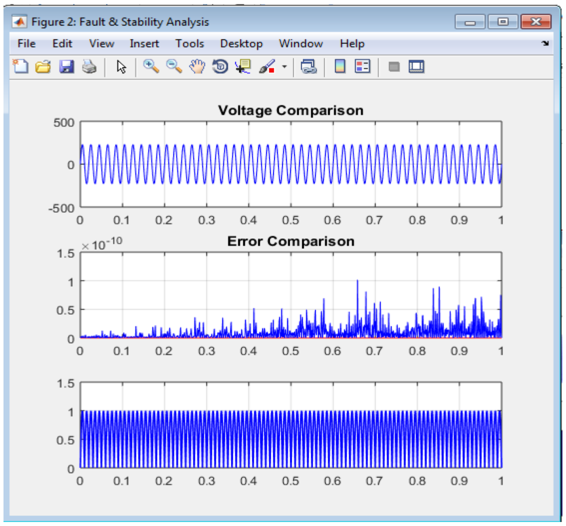
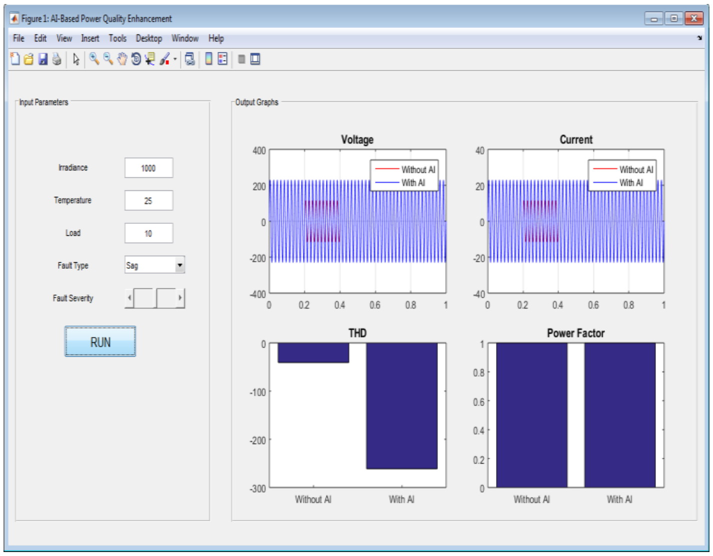


Fig.7.3 No Fault condition Voltage Comparison, Error and Profile index.



Irradiance 1000
Temperature 25
Load 10
Fault Type Sag
Fault Severity

Fig.7.4 Sag Fault condition THD and Power Factor.

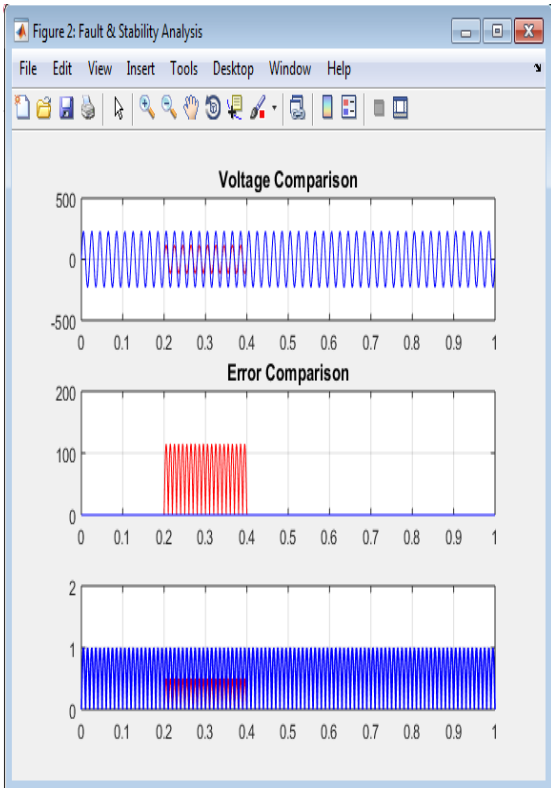
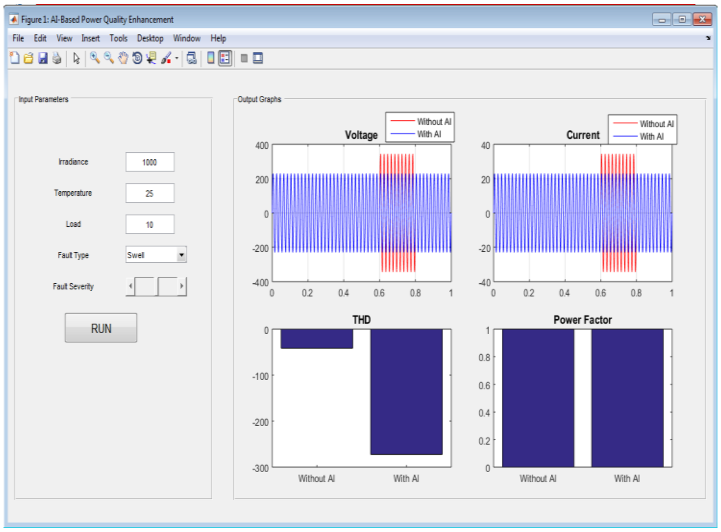


Fig.7.5 Sag Fault condition Voltage Comparison, Error and Profile index.



Irradiance 1000
Temperature 25
Load 10
Fault Type Swell

Fig.7.6 Swell Fault condition THD and Power Factor.

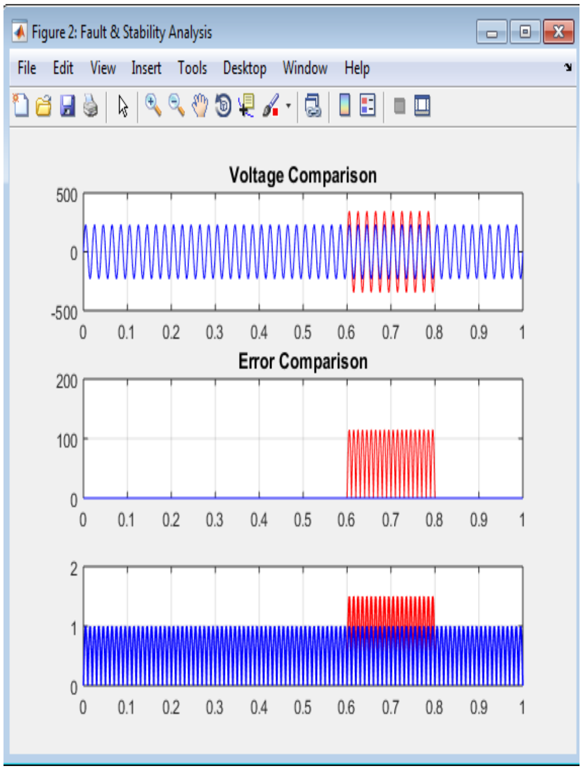
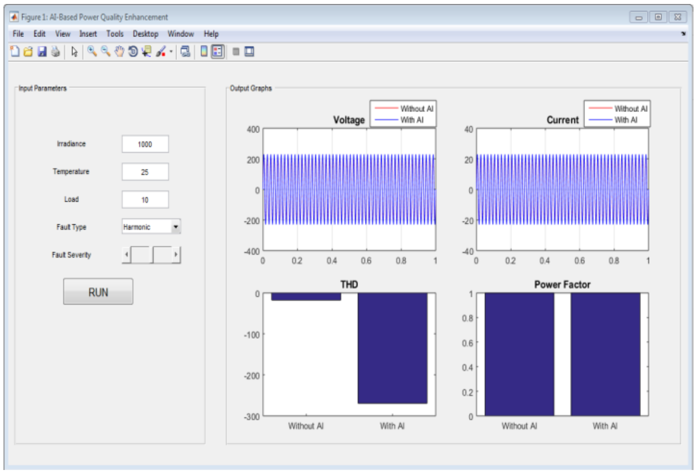


Fig.7.7 Swell Fault condition Voltage Comparison, Error and Profile index.



Irradiance 1000
Temperature 25
Load 10
Fault Type Harmonic
Fault Severity

Fig.7.8 Harmonics Fault condition THD and Power Factor.

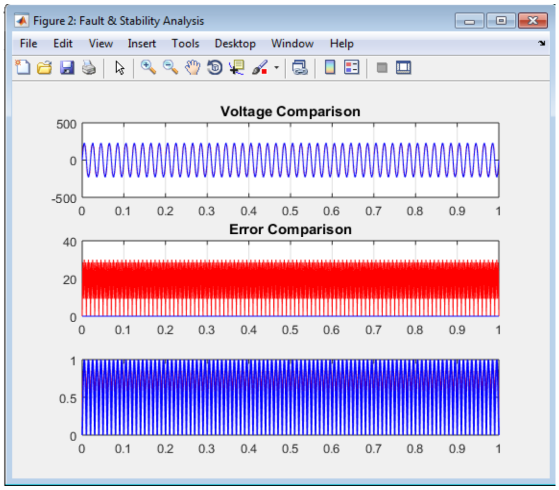
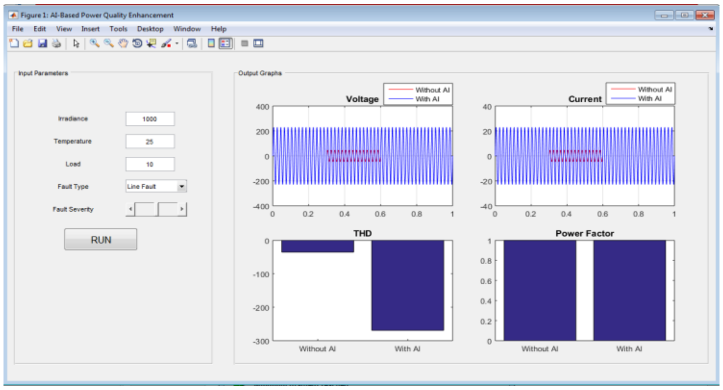


Fig.7.9 Harmonics Fault condition Voltage Comparison, Error and Profile index.



Irradiance 1000
Temperature 25
Load 10
Fault Type Line Fault
Fault Severity

Fig.7.10 Line Fault condition THD and Power Factor.

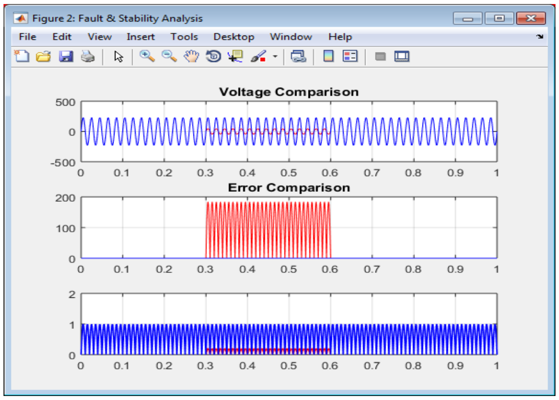


Fig.7.11 Line Fault condition Voltage Comparison, Error and Profile index.

The simulation results demonstrate the effectiveness of the proposed ANN-based approach in enhancing power quality under various fault conditions. In the absence of compensation, the system exhibited significant voltage distortions, increased total harmonic distortion (THD), and reduced power factor due to the presence of nonlinear disturbances. However, upon applying the ANN-based compensator, the output voltage waveform was restored closer to the nominal sinusoidal profile.

A substantial reduction in THD was observed, aligning with the limits prescribed by IEEE 519 Standard, thereby ensuring improved waveform quality. Additionally, the power factor improved significantly, approaching unity, which indicates efficient utilization of electrical power. The voltage sag and swell conditions were effectively mitigated, as evidenced by the reduced deviation from nominal voltage levels.

Furthermore, the Voltage Stability Index (VSI) analysis revealed that the system maintained values closer to unity when controlled by the ANN, indicating enhanced voltage stability under dynamic fault conditions. The comparative analysis between compensated and uncompensated cases clearly validates the capability of the proposed method to act as an intelligent active power filter.

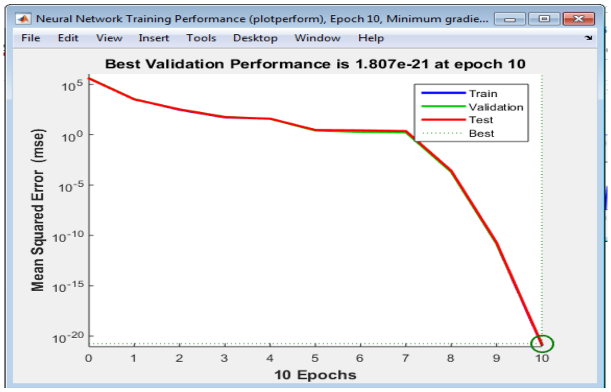


Fig.7.12 MSE.

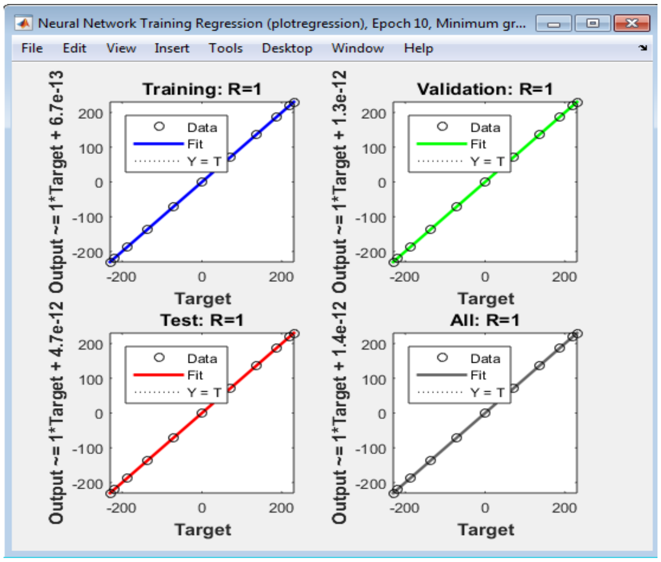


Fig.7.13 Regression Curve.

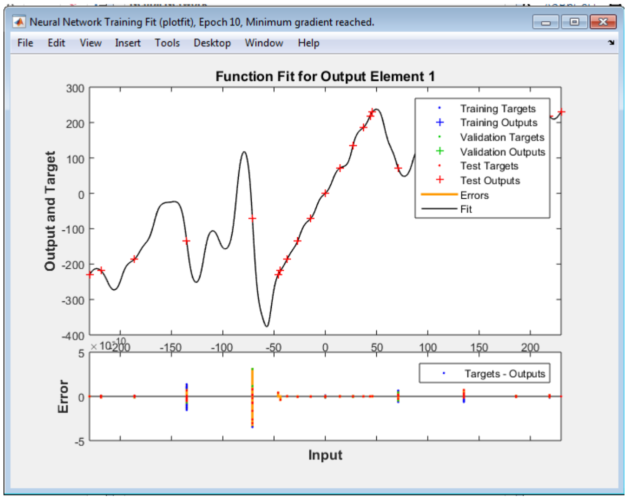


Fig.7.14 Plot Fit curve.

Overall, the ANN-based power quality enhancement technique demonstrated robust performance in mitigating multiple power disturbances in grid-connected PV systems. The proposed model effectively reduced harmonic distortion, improved voltage stability, corrected power factor, and minimized the impact of voltage sag and swell. These results confirm that intelligent AI-based controllers can significantly enhance the reliability and stability of modern power systems, making them suitable for integration in smart grid environments.

VIII. CONCLUSION

This research successfully presents an intelligent approach for enhancing power quality in grid-connected solar photovoltaic (PV) systems using an Artificial Neural Network (ANN)-based control strategy. The increasing penetration of renewable energy sources, particularly solar PV, introduces significant challenges such as harmonic distortion, voltage instability, and reactive power imbalance. The proposed ANN-based methodology effectively addresses these challenges by providing adaptive and real-time compensation under varying operating conditions.

The developed system, modeled and simulated in MATLAB/Simulink, demonstrates superior performance in mitigating power quality disturbances compared to conventional control techniques. The ANN controller efficiently learns the nonlinear behavior of the system and generates precise compensating signals for the power electronic interface. As a result, significant reduction in Total Harmonic Distortion (THD) is achieved, maintaining it within permissible limits defined by IEEE standards. Additionally, the system ensures improved voltage regulation, enhanced power factor, and effective reactive power compensation at the Point of Common Coupling (PCC).

The comparative analysis confirms that the ANN-based controller outperforms traditional PI and fuzzy logic controllers in terms of faster dynamic response, higher accuracy, and robustness against uncertainties such as fluctuating solar irradiance and nonlinear load variations. The adaptive learning capability of ANN enables the system to maintain stable operation even under disturbed grid conditions, making it highly suitable for modern smart grid applications.

Overall, this research contributes to the advancement of AI-driven energy management systems by providing a scalable, efficient, and reliable solution for power quality enhancement in renewable energy-integrated grids. The proposed methodology not only improves system performance but also supports the transition toward sustainable and intelligent power systems.

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