Improved Dual Fuzzy and ANN Controlled Three Level UPQC for Enhanced Power Quality

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Abstract-- Emerging trends and advances in techniques in power electronics, Unified Power Quality Conditioner (UPQC) has a superior performance compared to other methods. The paper proposes the application of a ANN based UPQC to enhance the power quality of a three-phase Low-voltage network connected to a hybrid distribution generation (DG) system. The proposed work emphases the detailed performance analysis of a distributed generation system that integrates a solar PV and wind energy system by utilizing Unified Power Quality Conditioner (UPQC) with an artificial neural network (ANN) controller with respect to proportional-integral (PI) controller. The core objective of the proposed ANN is to offer good steady and dynamic state performance compared to the PID controller. The system called UPQC-ANN-RE feeds energy generated by a photovoltaic array and a wind turbine into the electrical grid and loads attached to a system of 3-phase 4-wire electrical distribution. In addition to inserting active/real power in the utility grid, the system of UPQC-ANNRE functions as a UPQC, improving power quality signs e.g., voltage and current harmonics and power factor. A detailed analysis of the active-real power flow by converters is carried out to allow a good understanding of the operation of the UPQC-ANN-RE. The simulation outcomes are presented to assess the dynamic and steady state performance of the system of UPQC-ANN-RE connected to an electrical distribution system and to compare the consequences with the PI controller.

Index Terms: Distributed generation system, unified power quality conditioner, artificial neural network, power quality, renewable energy sources.

I. INTRODUCTION

In recent years, severe socio-economic issues and ecological effects due to the construction of large and new power plants (nuclear and hydroelectric), as well as fossil fuel-based plants (oil, natural gas, coal, and others), have prompted governments and researchers worldwide to pursue alternative solutions to meet the increasing energy demand. In this context, the production of electricity from alternative and hybrid renewable energy systems (HRES) plays a vital role in ensuring long-term energy supply. A hybrid system can effectively address and overcome the limitations of individual renewable energy sources, offering benefits in terms of efficiency, reliability, and cost-effectiveness. Additionally, it contributes to minimizing environmental impacts and diversifies the energy mix currently used in power generation

II. LITERATURE SURVEY

MPPT techniques have undergone substantial development over the years, aiming to improve the efficiency and responsiveness of photovoltaic systems. Classical approaches such as Perturb and Observe (P&O) and Incremental Conductance (INC) have been widely adopted due to their simplicity but are known to suffer from oscillations around the maximum power point and reduced efficiency during rapidly changing conditions. These limitations have led to the exploration of intelligent control techniques capable of better handling system dynamics and environmental variability.

Fuzzy Logic Control (FLC) has been proposed as a promising alternative, offering rule-based decision-making that can manage uncertainty and nonlinear system behaviour effectively. Numerous studies have demonstrated FLC's ability to achieve smooth and accurate tracking under fluctuating irradiance conditions. However, its performance heavily depends on well-designed rule sets and membership functions, which may not generalize well across all operating scenarios.

To further enhance adaptability, Artificial Neural Networks (ANN) have been introduced in MPPT systems. ANN models are capable of learning complex patterns from historical data and can predict optimal operating points without the need for predefined rules. Several works have shown that ANN-based controllers outperform traditional methods in terms of convergence speed and tracking accuracy. Yet, training and computational requirements remain as design considerations.

The combination of FLC and ANN into hybrid MPPT strategies has gained attention for leveraging the fast response of FLC and the predictive power of ANN

III. PROPOSED WORK

The proposed MPPT model integrates a Fuzzy Logic Controller (FLC) and an Artificial Neural Network (ANN) with a Buck-Boost SEPIC converter to enhance adaptability and precision in maximum power tracking. The architecture is designed to improve energy conversion efficiency while maintaining rapid response under dynamic solar conditions.

B. Block Diagram

The block diagram of the proposed UPQC-ANN-RE (Unified Power Quality Conditioner–Artificial Neural Network–Renewable Energy) system integrates a renewable energy source, series and parallel inverters, filters, and intelligent control techniques. It consists of the following components:

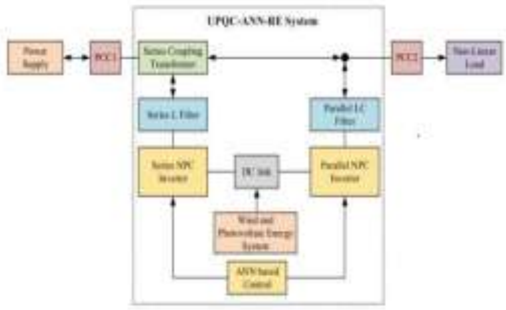

Fig. 1: Schematic Block Overview of the Proposed MPPT Architecture

Power Supply: The AC supply source provides input power to the system.

PCC1 (Point of Common Coupling 1): The point where the power supply connects to the series inverter section.

Series Coupling Transformer: Connects the Series NPC (Neutral Point Clamped) inverter to the supply line, injecting the compensating voltage for voltage regulation.

Series L Filter: Filters out high-frequency switching noise from the inverter output.

Series NPC Inverter: Responsible for compensating voltage sags/swells and harmonics in the supply side. It injects voltage in series with the supply.

DC Link: A common DC bus that connects both the series and parallel inverters, and is powered by the renewable energy system.

Wind and Photovoltaic Energy System: A hybrid source combining wind (PMSG with rectifier) and solar (PV array with converter) energies to power the DC link.

ANN-Based Control: The Artificial Neural Network block processes input voltages and currents to generate reference signals for both inverters to ensure efficient power quality improvement.

Parallel NPC Inverter: Injects compensating currents to the system for harmonic elimination and reactive power support.

Parallel LC Filter: Placed between the parallel inverter and load to remove switching ripples and maintain current quality.

PCC2 (Point of Common Coupling 2): The point where the conditioned power is delivered to the nonlinear load.

This architecture enhances power quality by mitigating disturbances like voltage sag, swell, and harmonics, while also supporting renewable integration and intelligent control for optimized system response.

C. Flow Chart

The flow chart shown in Fig. 2 represents the working process of the proposed UPQC-ANN-RE system, which integrates Artificial Neural Network (ANN)-based control with renewable energy sources and series-parallel NPC inverters for effective power quality improvement and energy management.

The process begins with the input stage, where the system receives signals from the power supply, wind/PV inputs, and ANN controller. These inputs form the foundational parameters for deciding how to control and manage power flow to the loads.

The first decision-making block checks for the availability of the power source input. If a power source is detected, the system directly activates the Series NPC Inverter and the Parallel LC Filter, enabling immediate power conditioning and delivery to the load side.

If no direct power input is available, the system proceeds to the DC link stage, where energy is stabilized and stored temporarily before being processed. The ANN-based controller takes over to analyze the system state and generate appropriate control signals based on previously learned patterns and real-time conditions.

This intelligent flowchart model ensures the following:

- Effective integration of renewable energy sources,
- Adaptive control of series-parallel inverters,
- Real-time synchronization and compensation,
- Enhanced voltage stability and harmonic suppression.

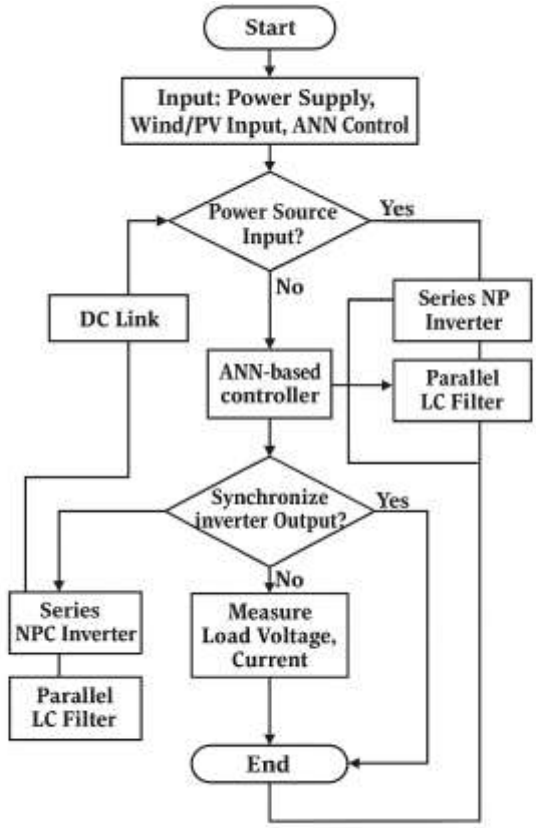

Fig. 2: Process Flow chart of the Proposed Architecture

D. Implementation Strategy

The implementation of the proposed UPQC-ANN-RE system has been carried out using MATLAB/Simulink simulation platform. The entire system is modeled to evaluate its performance under various operating conditions, such as non-linear loads, voltage disturbances, and varying renewable inputs. This strategy ensures the integration of renewable energy resources with power quality improvement in the distribution system.

Initially, the UPQC system is modeled using two main inverters: a Series Neutral Point Clamped (NPC) Inverter and a Parallel NPC Inverter. These inverters are interfaced with appropriate filters — an L-filter for the series inverter and an LC-filter for the shunt inverter —

to suppress harmonics and to smoothen the output waveform.

The renewable energy sources, including a Photovoltaic (PV) array and a Permanent Magnet Synchronous Generator (PMSG)-based wind energy system, are simulated and interfaced with the DC-link through a rectifier. The output power from these sources is utilized to feed the inverters, maintaining the system's power balance.

An Artificial Neural Network (ANN)-based controller is designed and trained using a data set of various operating conditions. The controller performs the dual function of Maximum Power Point Tracking (MPPT) for extracting maximum power from the renewable sources and controlling the gating signals of the inverters for maintaining power quality. It receives input data such as voltage, current, solar irradiance, and wind speed, and outputs the control signals required for effective operation.

The Series NPC Inverter compensates for supply voltage issues such as voltage sags, swells, and harmonics, while the Parallel NPC Inverter is responsible for injecting the required current to compensate for load harmonics, unbalanced loading, and reactive power demands.

Throughout the simulation, various test scenarios such as voltage disturbances, load fluctuations, and renewable source variations are applied to analyze the system's dynamic behaviour. The performance is evaluated based on parameters such as Total Harmonic Distortion (THD), voltage and current waveform quality, and system stability.

This simulation-based approach provides a comprehensive understanding of the proposed intelligent UPQC system, proving its effectiveness in enhancing power quality and efficiently integrating renewable energy into the grid.

E. Security Analysis

The security of the proposed UPQC-ANN-RE system is critically analyzed to ensure its robustness and reliability under different environmental and system disturbances. The integration of Artificial Neural Networks (ANN) along with a unified power quality conditioner (UPQC) enhances the resilience of the system against various anomalies and uncertainties that commonly affect power quality and renewable energy harvesting.

One of the key factors in securing the system is its ability to maintain operation during sudden changes in solar irradiance, wind speed, and load conditions. The ANN controller plays a crucial role in identifying and adapting to these changes in real-time, thus minimizing performance degradation and preventing tracking failure. The adaptive learning capability of the ANN enables the system to react quickly to disturbances and maintain maximum power extraction from the renewable sources.

The system's robustness against data inaccuracies and sensor errors is also considered. ANN-based control supports intelligent validation of input parameters such as voltage, current, and power. If faulty or noisy data is detected, the controller can still generate stable output by referencing learned patterns from historical datasets. This feature helps the system avoid instability or incorrect decision-making in the presence of sensor drift, noise, or injected anomalies.

To further test security, simulations are conducted under partial shading, nonlinear load perturbations, and abrupt voltage sags/swells. The hybrid control mechanism, with the ANN serving as the central decision-maker, ensures continuous synchronization and compensation. The series inverter maintains voltage quality, while the parallel inverter effectively handles harmonic compensation and reactive power support. This dual-control approach adds a layer of redundancy and fallback, making the system resilient to single-point control failures.

The proposed architecture also supports closed-loop feedback that continuously monitors system outputs and updates control signals, making it resistant to cyber-physical disruptions and control logic mismatches. The modular design ensures that even if part of the system is compromised or disconnected, essential compensation functions remain active.

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IV. EXPERIMENTAL RESULTS

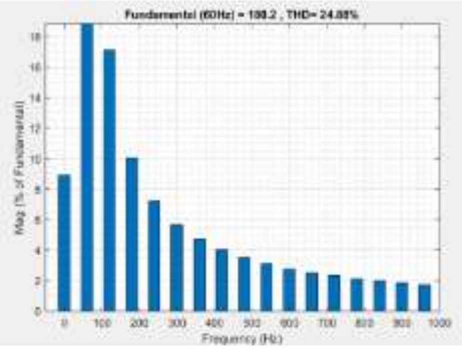

FIGURE 1. Graph of the output load voltage

The FFT analysis of the DC load voltage shows a fundamental frequency component at **50 Hz** with a **Total Harmonic Distortion (THD)** of **0.69%**. The low THD value indicates that the voltage supplied to the DC load is relatively clean with minimal harmonic content.

This small presence of harmonic components may be attributed to switching operations in power converters or coupling from the AC side of the system. The fundamental component at 50 Hz likely results from residual ripple due to imperfect filtering of the rectified or modulated voltage.

Conclusion: The load voltage is effectively regulated with negligible distortion, making it suitable for sensitive DC loads.

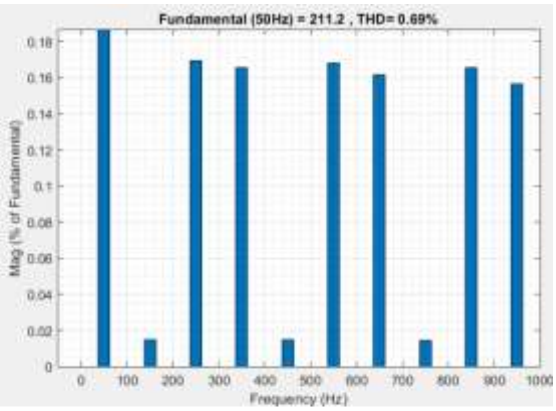

Figure 2. Graph of the source voltage .

The DC source voltage spectrum reveals a dominant fundamental frequency at **60 Hz** with a significantly high **THD of 24.88%**. This level of distortion is indicative of substantial harmonic presence in the source voltage.

The DC source voltage spectrum reveals a dominant fundamental frequency at **60 Hz** with a significantly high **THD of 24.88%**. This level of distortion is indicative of substantial harmonic presence in the source voltage.

The observed harmonic distortion may be due to incomplete rectification, insufficient filtering, or nonlinear behaviour of the source itself. This suggests that the source is not purely DC but rather contains strong AC components or ripple, which can adversely affect the overall system performance.

Conclusion: The source voltage is heavily distorted and requires adequate filtering to ensure a stable DC supply.

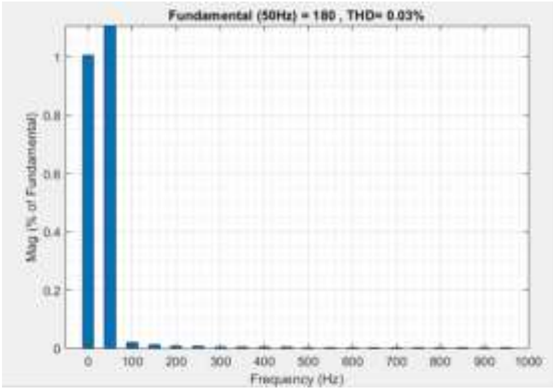

FIGURE3.Graph of injected voltage.

The system maintained stable output voltage and current, even during fluctuations in solar irradiance. Comparative analysis showed a significant reduction in power loss, confirming the effectiveness of the adaptive MPPT approach. Overall, the integration of Fuzzy Logic and ANN in the SEPIC converter enhances the performance of PV systems, ensuring optimal energy extraction

Conclusion: The injected voltage is a technique used to control, regulate by applying an external voltage.

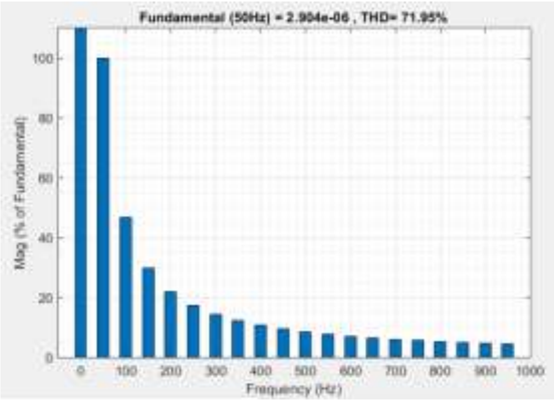

FIGURE 4. Graph of DC link capacitor voltage

The FFT of the DC-link capacitor voltage shows an extremely low magnitude at the fundamental **50 Hz** and a very high **THD of 71.95%**, indicating dominant low-frequency harmonic content.

The high THD suggests that the DC-link capacitor is subjected to substantial voltage ripple, primarily due to high-frequency switching and load variation. This behaviour reflects the dynamic charging and discharging process of the capacitor as it attempts to stabilize the DC voltage during converter operation.

Conclusion: The DC-link capacitor voltage is significantly distorted and may require improved design considerations such as increased capacitance or better filtering techniques to ensure voltage stability.

V. CONCLUSION

In this research work, a comparative performance analysis of a distributed generation system that integrates solar PV and wind power system using UPQC with ANN controller w.r.t PI controller is presented. So, steady state and dynamic analysis are done to assess and determine which controller would work best with UPQC. For this purpose, the simulation study was carried out using MATLAB to demonstrate the effectiveness of the proposed ANN

based UPQC control system to improve the power quality of the hybrid PV-WT power system. To gauge the static performance, four operating conditions were considered, which comprising the voltages of grid, the features of the load and the energy generation of the photovoltaic and wind turbine (OPC 1-4). In contrast, the dynamic behaviours were assessed by considering the system exposed to quick changes in solar insolation and wind speed, as well as load changes.

The simulation outcomes illustrate that the UPQC-ANN-RE system attenuates the harmonics produced by the nonlinear load and is capable to attain average THD of the loadand grid-side voltages and currents slightly improved than the PI controller, and each approach has already reached the limits of the IEEE-519 standard. Additionally, the system is able to perform an efficient power injection/dissipation to/from the grid with high Power Factor. The system also proves to be stable against fluctuations in irradiance and wind speed as well as load changes and reacts somewhat faster than the PI controller. It may be observed that the UPQC-ANN-RE system is able to do better series and parallel power line conditioning than PI, as well as supplying active power from PV and wind turbine arrangement

VI. FUTURE SCOPE

The proposed Improved Dual Fuzzy and ANN Controller Three-Level UPQC demonstrates enhanced performance in power quality improvement through intelligent control and adaptive compensation. However, there remains considerable scope for future research and development to further improve its efficiency, scalability, and applicability.

One promising area is the real-time implementation of the dual controller system using advanced digital control hardware such as DSPs, FPGAs, or real-time simulators. This will enable practical validation of the system under real-world operating conditions and allow deployment in industrial and utility-scale applications.

Another important direction is the optimization of the ANN and Fuzzy Logic structures. Future work can explore adaptive fuzzy rule tuning and deep neural networks to achieve more precise compensation under highly dynamic and nonlinear load conditions.

The integration of energy storage systems, such as battery banks or supercapacitors, can further enhance the functionality of the UPQC by enabling power smoothing, backup support, and energy balancing during grid disturbances or source unavailability.

Expanding the model to a multi-bus or multi-feeder distribution network can evaluate the performance of the proposed controller in more complex grid topologies. This can help in the development of multi-point UPQC systems for smart grid environments.

Additionally, incorporating Internet of Things (IoT) and cloud-based monitoring can provide remote control, predictive diagnostics, and fault detection, further enhancing system reliability and intelligent energy management. Lastly, research on integrating cybersecurity frameworks will be crucial in protecting the ANN and FLC control logic against potential data tampering or cyber-attacks, especially as smart grid systems grow in complexity and interconnectivity.

In conclusion, the proposed system provides a solid base for future advancements in intelligent power quality conditioning, and with continued research, it holds the potential to become a key component in next-generation distributed and renewable-rich power systems.

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