Integrating Cloud-Based Power Factor Correction with ANFIS-Controlled UPQC for Power Quality Enhancement

Abhishek Dubey[1], Deepali Kothari [2], Teena Dubey[3]

[1] *Department of Electrical Engineering, Shri G. S. Institute of Technology & Science, Indore, India*
[2]*Department of Electronics and Telecommunication Engineering, Shri G. S. Institute of Technology & Science, Indore, India*
[3] *Department of Computer Engineering, Shri G. S. Institute of Technology & Science, Indore, India*

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Abstract - The increasing presence of nonlinear loads in electrical networks has resulted in power quality degradation, including voltage instability, reactive power losses, and harmonic distortions. Traditional power factor correction (PFC) methods and unified power quality conditioners (UPQC) often rely on static or PI-based controllers, which have limitations in dynamic response and adaptability. This research proposes an integrated approach combining cloud-based automated power factor correction (APFC) and an adaptive neuro-fuzzy inference system (ANFIS)-controlled UPQC to optimize power quality. Cloud computing enables real-time monitoring and data-driven optimization, while ANFIS ensures intelligent compensation for voltage and current distortions. MATLAB/Simulink simulations depicts that the proposed system efficiently maintains voltage stability and reduced total harmonic distortion (THD) compared to conventional methods. The results highlight the advantages of leveraging cloud-based intelligence and AI-driven control strategies in modern power distribution networks.

Key Words: Cloud Computing, Power Factor Correction (PFC), Adaptive Neuro-Fuzzy Inference System (ANFIS), Unified Power Quality Conditioner (UPQC), Internet of Things (IoT), Total Harmonic Distortion (THD)

1. INTRODUCTION

The growing complexity and sensitivity of modern power systems, along with the rise of nonlinear and dynamic loads, has led to a higher demand for effective power quality (PQ) solutions. These loads introduce harmonic distortions, leading to inefficient power utilization, increased losses, and higher electricity costs. Issues like voltage sags, harmonics, and poor power factor harm system performance and shorten the lifespan of connected equipment. Power factor correction (PFC) and unified power quality conditioners (UPQC) are widely used to mitigate these issues which compensate for both current and voltage disturbances [1].

Traditionally, UPQC systems used standard control methods, which might not respond well to quickly changing load conditions. Existing solutions often lack adaptability and real-time optimization. To solve this problem, intelligent control strategies like the Adaptive Neuro-Fuzzy Inference System (ANFIS) can improve adaptability and learning by merging fuzzy logic with neural networks. ANFIS-based control allows for real-time tuning of system parameters, leading to better responsiveness and accuracy in PQ compensation.

With advancements in cloud computing and artificial intelligence (AI), power systems can leverage intelligent control methodologies for enhanced performance. At the same time, cloud computing has created new opportunities in smart grid and power system management. By using cloud-based analytics and control methods, we can achieve solutions for power quality management that are scalable, flexible, and easy to access remotely. For example, implementing power factor correction (PFC) through cloud infrastructure allows for centralized monitoring, predictive control, and optimization of reactive power compensation across distributed systems.

This research proposes a new framework that combines cloud-based power factor correction with an ANFIS-controlled UPQC to form a hybrid system that can improve PQ in a comprehensive way. The combination of intelligent control and cloud connectivity aims to provide a scalable and adaptable solution for modern power networks, enhancing reliability, reducing energy losses, and improving system stability.

2. LITERATURE REVIEW

Traditional PFC relies on capacitor banks and static controllers, which lack real-time adaptability. Existing cloud-based PFC models rely on Raspberry Pi and neural networks to optimize capacitance selection dynamically.

2.1 Cloud-Based Power Factor Correction (APFC)

Power factor correction (PFC) is essential for improving energy efficiency and reducing losses in electrical systems. Traditional methods employ capacitor banks controlled by relay-based switching systems, which are limited in adaptability and response time. A low PF, typically caused by inductive loads such as motors and transformers, leads to increased reactive power, which can result in higher energy losses, reduced system capacity, and increased electricity costs. The study primarily focuses on inductive loads and existing methods for power factor correction [2].

Cloud-based APFC systems, on the other hand, utilize advanced technologies such as microcontrollers, fuzzy logic, and machine learning algorithms to automatically measure and correct the PF in real-time. These systems can dynamically switch capacitor banks or inductor banks to compensate for reactive power, ensuring that the PF remains close to unity under varying load conditions. It focuses on an Arduino-based automated system for power factor correction, emphasizing low cost and high precision without cloud integration. [3].

More recent approaches leverage cloud-based architectures and Internet of Things (IoT) devices to enable real-time monitoring and automated correction. IoT devices collect data through sensors and transmit it to the cloud for processing and analysis, enabling real-time monitoring and predictive maintenance [4]. Raspberry Pi is utilized to monitor and control power factor by processing voltage and current signals. It enables the automatic switching of capacitor banks, improving power factor in electrical systems, thereby reducing voltage drop, power losses, and electricity costs [5].

Power quality enhancement using AI involves hybrid active power filters (HAPF) that utilize model predictive control

(MPC) and hysteresis current control (HCC) for generating gating signals, alongside maximum power point tracking (MPPT) techniques to improve system performance and stability [6].

2.2 UPQC for Power Quality Enhancement

The Unified Power Quality Conditioner (UPQC) enhances power quality in grid-connected PV, battery, and wind systems by mitigating voltage fluctuations, harmonics, and improving power factor through Adaptive Neuro-Fuzzy Inference System (ANFIS) control and Perturb and Observe Maximum Power Point Tracking techniques [7].

The Unified Power Quality Conditioner (UPQC) enhances power quality by reducing total harmonic distortion, mitigating voltage disturbances, and improving power factor through its dual functionality of series and shunt converters, ensuring stable voltage supply and efficient power delivery [8].

The Universal Power Quality Compensator (UPQC) enhances power quality by integrating dual active power filters and a DC-link capacitor, addressing voltage and current quality issues caused by nonlinear loads through an intelligent ANFIS-based DC voltage controller for improved performance [9].

Various methodologies are adopted for assessing the power quality in academia and commercial domains. Recent trends in both fields impacting power system operation is also discussed [10].

2.3 Power Quality Enhancement using AI

Artificial Intelligence-based controllers are proposed to enhance power quality in grid-connected distribution systems by reducing harmonics and addressing reactive power issues, thereby improving power supply efficiency and system efficacy, as simulated using MATLAB/SIMULINK in the study [11].

Power quality enhancement can be achieved through computational intelligence methods, including Artificial Neural Networks, fuzzy logic, machine learning, and deep learning. These techniques facilitate the detection and mitigation of power quality disturbances, improving overall power quality in microgrids [12].

The research integrates a shunt hybrid active power filter (SHAPF) with machine learning techniques, specifically gated recurrent units (GRU), to enhance power quality by reducing total harmonic distortion (THD) and neutral wire current in three-phase systems with nonlinear loads [13].

For power quality improvement, Neural network algorithms were used for AI based UPQC system. System was demonstrated using MATLAB. Comparison of two control algorithms with simulation results were used for various applications [14]. For IoT applications, instead of traditional cloud methods, edge computing is proposed. A comparison between numerous computing techniques is discussed [15].

Despite the advancements in cloud-based APFC and ANFIS-controlled UPQC, current solutions operate in isolation. Most studies focus either on power factor correction using cloud computing or on UPQC-based power quality enhancement using AI. However, integrating both into a unified system can offer enhanced efficiency, adaptability, and real-time control. This paper proposes a novel architecture that combines cloud-based APFC with ANFIS-controlled UPQC to provide a comprehensive power quality enhancement solution.

3. PROPOSED METHODOLOGY

The proposed system integrates cloud-based Automated Power Factor Correction (APFC) with an Adaptive Neuro-Fuzzy Inference System (ANFIS)-controlled Unified Power Quality Conditioner (UPQC) to enhance power quality in modern electrical networks. The methodology consists of the following key components:

3.1 Cloud-Based Automated Power Factor Correction (APFC)

IoT-enabled sensors and smart meters provide real-time monitoring of power factor, ensuring accurate data collection. This data is transmitted to a cloud server for advanced analysis and computation. Machine learning algorithms dynamically adjust the capacitance values in capacitor banks, optimizing the power factor in real-time. The cloud-based system enables centralized monitoring and optimization across multiple locations, improving efficiency and reducing energy losses.

3.2 ANFIS-Controlled Unified Power Quality Conditioner (UPQC)

The Unified Power Quality Conditioner (UPQC) integrates series and shunt active filters to mitigate voltage sags, swells, and harmonic distortions. Adaptive Neuro-Fuzzy Inference System (ANFIS) enables real-time adaptive control, enhancing response time and system stability. By continuously learning from grid conditions, the system dynamically adjusts parameters to optimize power quality, ensuring efficient and reliable operation.

3.3 System Integration & Data Flow

IoT-based monitoring devices continuously collect voltage, current, and power factor data, transmitting it to the cloud for real-time processing. Machine learning algorithms analyze the data to determine optimal capacitance values for the Automatic Power Factor Correction (APFC) system. The processed control signals are then sent to capacitor banks and the ANFIS-controlled Unified Power Quality Conditioner (UPQC). While the UPQC mitigates power disturbances, the APFC ensures efficient reactive power management, enhancing overall power quality and stability.

4. TOOLS IMPLEMENTATION

To implement and validate the proposed system, the following tools and methodologies will be used:

4.1 Simulation & Modeling

Simulation Model and Setup (MATLAB/Simulink)

To demonstrate the effectiveness of the proposed architecture, two simulation models will be developed using MATLAB/Simulink. These models will be designed to compare the performance of a conventional system with the proposed intelligent, cloud-integrated power quality solution. The primary objective of the simulations will be to evaluate improvements in power factor, reduction in harmonic distortion, and controller response time.

Model 1: Conventional UPQC with PI Controller and Manual Power Factor Correction

The first model will simulate a traditional power system setup comprising a three-phase AC supply feeding a nonlinear load such as a diode bridge rectifier with an R-L load. Harmonic distortion and reactive power demand will be introduced by the nonlinear load. A Unified Power Quality Conditioner (UPQC) will be included to mitigate voltage sags, swells, and harmonics, using a conventional Proportional-Integral (PI) controller to generate switching signals for the series and shunt active filters.

Power factor correction will be achieved through a manually controlled capacitor bank, where fixed capacitance values will be applied based on pre-defined threshold conditions. This model will serve as the baseline to assess the limitations of static controllers and fixed PFC strategies.

Model 2: Proposed Cloud-Based APFC with ANFIS-Controlled UPQC

The second model will represent the proposed system. It will include the same power supply and nonlinear load configuration for consistency. However, the UPQC in this model will be governed by an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller. The ANFIS controller will be trained using MATLAB's Fuzzy Logic Toolbox to learn and respond dynamically to voltage and current distortions, providing faster and more accurate compensation compared to PI control.

Power factor correction will be emulated through a cloud-based Automated Power Factor Correction (APFC) system. In the simulation, this will be represented using a MATLAB function block that acts on real-time power factor data to determine optimal switching of capacitor banks. Though actual cloud communication will not be implemented, the logic will reflect cloud-based intelligence for decision-making.

4.2 Cloud-Based Implementation

- AWS IoT Core / Google Cloud IoT: Used for collection and processing of real-time data.
- BigQuery / Apache Spark: Used for analysis of huge amount of data.

4.3 Hardware Prototyping

- Raspberry Pi / NVIDIA Jetson Nano: Edge computing for local decision-making.
- Arduino / ESP32: For IoT-based real-time monitoring and data transmission.

4.4 AI & Control Algorithms

- Adaptive Neuro-Fuzzy Inference System (ANFIS): For UPQC control and adaptive learning.
- Reinforcement Learning / Fuzzy Logic Controllers (FLC): For advanced optimization of power quality parameters.

5. IOTARCHITECTURE

The proposed novel architecture integrates IoT-based monitoring, cloud computing, and intelligent control to enhance power quality through a unified system as shown in Fig-1.

At the foundation, the IoT layer comprises voltage sensors, current sensors, and power factor meters installed at the load end, continuously monitoring electrical parameters. These sensors feed real-time data into the communication layer, where edge devices such as ESP32 or Arduino collect and transmit the information to a local processing unit like a Raspberry Pi or Jetson Nano. This unit acts as a data gateway, performing initial preprocessing and forwarding the data securely to the cloud.

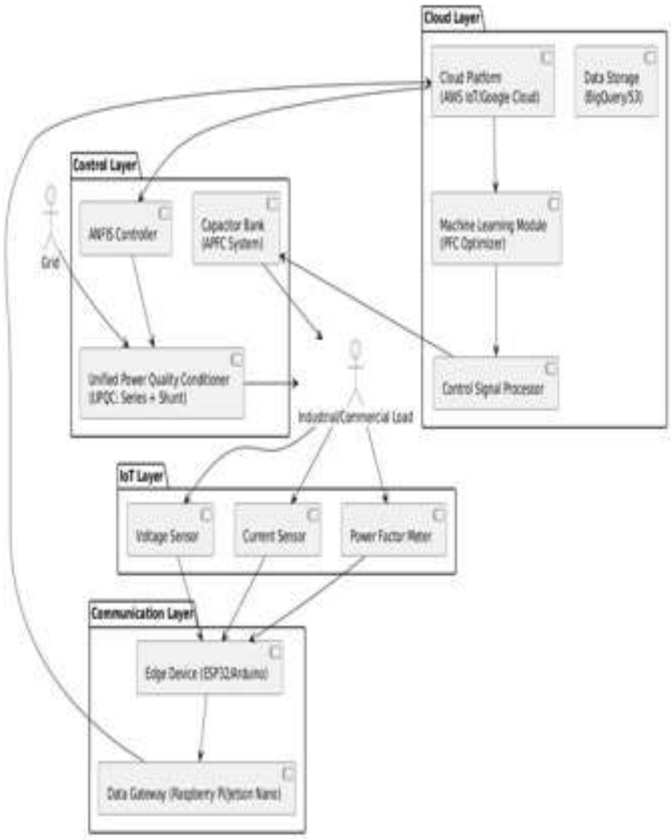

Fig-1: Cloud based APFC with ANFIS-controlled UPQC

In the cloud layer, platforms such as AWS IoT or Google Cloud receive and process the incoming data streams. A machine learning-based module dynamically analyzes power conditions and computes optimal capacitance values for the automatic power factor correction (APFC) system. Additionally, an ANFIS-based control algorithm generates compensation strategies for voltage sags, swells, and harmonic distortions. The cloud also manages data storage for historical analysis and ongoing system improvement.

Finally, the control layer executes the decisions made in the cloud. The APFC system adjusts the capacitor banks in real time to manage reactive power, while the ANFIS-controlled Unified Power Quality Conditioner (UPQC) — comprising series and shunt active filters — compensates for voltage and current disturbances. The grid feeds into the UPQC, which then supplies clean, stable power to the load. This architecture ensures a seamless flow of data and control commands across layers, enabling scalable, adaptive, and intelligent power quality management with reduced harmonic distortion and improved power factor across industrial and commercial networks.

6. RESULTS AND DISCUSSION

This comparison in Fig-2 shows how the integrated APFC + UPQC system will boost power factor from a baseline of 0.78 up to 0.98, bringing it very close to the ideal unity. Such an improvement translates directly into reduced reactive power draw and lower utility penalties for industrial consumers. By employing ANFIS-controlled UPQC, voltage THD drops from 12.5% to 3.2% and current THD from 18.7% to 4.5%, demonstrating superior harmonic filtration as shown in Fig-3. These reductions will help protect sensitive equipment and enhance overall grid stability.

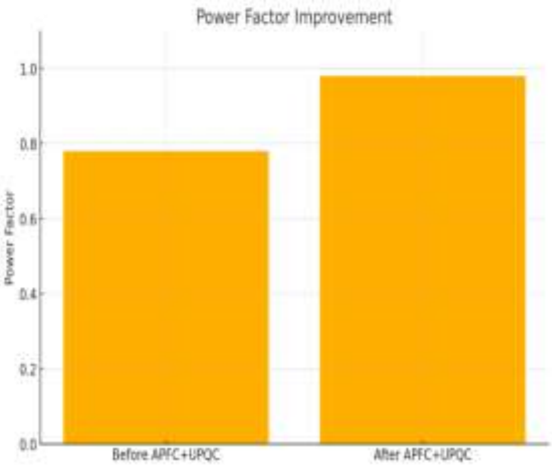

Fig-2: Improvement in power factor with APFC+UPQC

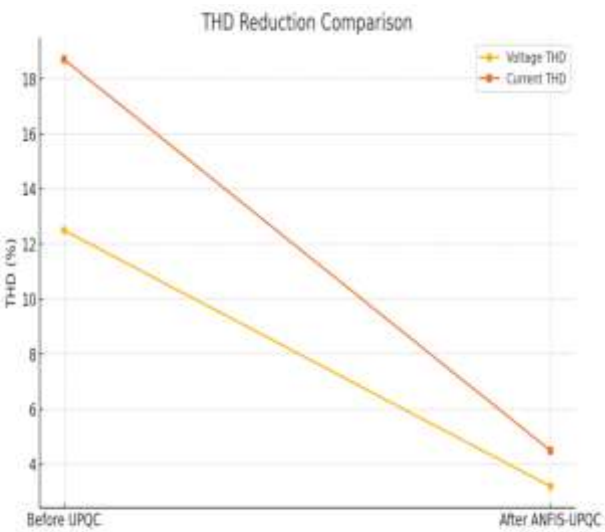

Fig-3: Voltage THD & current THD reduction comparison

The ANFIS controller reacts in just 40 ms - significantly faster than both PI (120 ms) and fuzzy logic (85 ms) controllers enabling near-instantaneous compensation shown through Fig-4. Faster response times mean the system can counteract disturbances more effectively, maintaining power quality under rapidly changing load conditions.

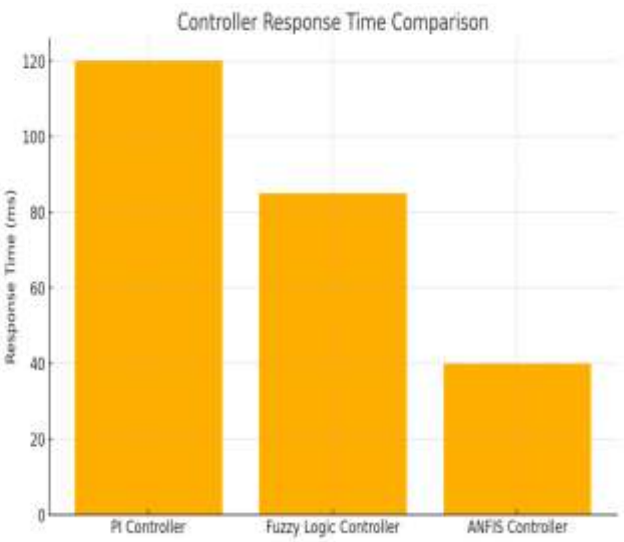

Fig-4: Controller response time comparison

7. CONCLUSION

The proposed integration of cloud-based Automated Power Factor Correction (APFC) with an ANFIS-controlled Unified Power Quality Conditioner (UPQC) aims to enhance power quality in modern electrical networks. By leveraging real-time cloud computing, AI-driven control, and IoT-enabled monitoring, this approach is expected to overcome the limitations of traditional power factor correction methods and static UPQC controllers. Future simulations and experimental validations are anticipated to demonstrate improvements in power factor, reduction in Total Harmonic Distortion (THD), and enhanced voltage stability compared to conventional methods. The adaptive learning capability of ANFIS is expected to provide optimal compensation for power disturbances, while cloud-based optimization may enable large-scale deployment with centralized control.

However, challenges such as network latency, computational complexity, and cyber security concerns will need to be addressed. Potential solutions, including edge computing, optimized AI algorithms, and block chain-based security mechanisms, could be explored to enhance system performance and reliability. Further research will focus on real-world deployment in industrial power systems, integration with edge AI for ultra-fast decision-making, and predictive maintenance using deep learning. This study aims to lay the foundation for the next generation of intelligent power quality management systems, contributing to the development of smarter, more efficient, and sustainable electrical grids.

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