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Artificial Intelligence Integrated Unified Power Quality Conditioner for Renewable Energy Systems

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ABSTRACT: The present study discusses a unified power quality conditioner powered by artificial intelligence (AI) that can provide improved performance regarding the overall power quality of renewable energy systems subjected to varying operating conditions. As more renewable energy sources such as both wind and solar are becoming connected to distribution grids, they introduce harmonic distortion, voltage fluctuations, imbalanced reactive power and intermittent power support. The proposed approach will assist in detecting disturbances, predicting changes in load demand, and real-time generation of adaptive compensation signals by combining an AI control layer and an AI unified power quality conditioner. The intelligent decision-making capabilities of the system will allow for more rapid and accurate responses to disturbances compared to traditional methods of controlling power quality. Improving voltage regulation, mitigating harmonics, correcting power factor, and providing fault tolerant operation are key objectives of this integrated AI-enabled control system, all while maintaining stable operation during periods of volatility in renewable energy supplies. An integrated framework providing cleaner operation of electric grids, increasing reliability, and optimising energy usage is developed based on the results obtained from the evaluation of the performance of AI-controlled power quality compensation devices in renewable energy applications and within future Smart Grid-like interoperability.

KEYWORDS: Artificial Intelligence, Unified Power Quality Conditioner, Renewable Energy Systems, Harmonic Compensation, Smart Grid Control.

I. INTRODUCTION

The global energy sector is witnessing a rapid transformation towards the integration of renewable energy sources into electrical power networks [1]. Solar photovoltaic arrays, wind turbines, hybrid microgrids, and battery-supported systems are indeed widely employed to reduce carbon emissions and dependence on fossil fuels [2]. While these energy sources are environmentally and economically friendly, they present numerous further technical challenges for grid operations [3]. They are often intermittent, nonlinear, and subject to output limits based on the weather and load conditions [4]. This variability is likely to result in transient voltage instability, harmonic distortion, frequency deviation, reactive power imbalance, and one possible reduction in power quality at the point of common coupling [5]. It has become a major research focus that of maintaining stable and aircraft power supply. A unified power quality conditioner is an auspicious device for the taking care of these issues because it is capable of simultaneous compensation for disturbances in both voltage and current [7]. It combines the functions of series and shunt active filters as a fully integrated system, thus allowing correction of sag, swell, harmonic-current, and reactive-power problems-all within one unit [8]. Unfortunately, the conventional control strategies have thoroughly had their limitations with the fast-changing nature of regular generating sources or excessively unpredictable load behavior [9].

In many cases, such controllers do not provide fast enough response times or produce accurate outputs when placed in a nonlinear environment [10]. By integrating a form of artificial intelligence, an adaptive solution can be provided through data-based decision-making [11]. This provides a level of responsiveness and robustness in controlling the unified power quality conditioner (UPQC) through methods such as: recognition of patterns, prediction, and control using learned information [12]. This paper presents an AI-Integrated UPQC specifically designed for use with renewable energy systems [13]. The design of this controller uses three main features: Dynamic compensation, intelligent handling of faults, and enhanced support for the electrical grid [14]. This design, when integrated with AI, provides the opportunity to combine and utilize the fast compensatory abilities of power electronic devices and the adaptability of artificial intelligence [15]. As a result, renewable resources will have a better ability to interact with the



electrical grid, provide improved quality of power, and improve the reliability of the overall system. Therefore, this suggested structure will be an appropriate candidate for implementation in the modern smart grid, distributed generation systems, and energy efficiency applications in the industrial sector.

II. PROBLEM STATEMENT

Standard traditional power quality devices can only work well under specified conditions that are well known. In alternative energy systems, however, voltage and current disruptions occur very suddenly and unpredictably due to both changes in generation and load. Therefore, fixed control strategies are not as effective as you would think. The primary design challenge is developing a compensation system that can intelligently adapt to the dynamic characteristics of renewable energy, maintain constant voltage, minimize harmonics, and transfer power efficiently.

III. LITERATURE REVIEW

Originally filtering methods have been applied as a basic measure of power quality improvement through the renewable energy sector until they evolved into advanced active compensation techniques [1]. Previously, they depended on passive filters, which were both simple and cheap; however lacked a wide range of power quality characteristics, hence making difficult to compensate for many types of disturbances [2]. Once active power filter (APF) was developed to dynamically mitigate harmonics and provide reactive power [3] performance were improved using active power filters; however were subject to the difficulties associated with complexity of tuning and sensitivity to changing operating conditions [4]. A unified power quality conditioner was created to solve the issue by combining current/voltage in one unit and allowing the opportunity to mitigate both voltage sag/swell, harmonic current, reactive power imbalances, and flicker issues in distribution systems [5].

Several intelligent control techniques have increased the performance of compensation [7]. The use of fuzzy logic, neural networks, adaptive control, and optimization algorithms have improved the ability to detect disturbances and produce control signals [8]. Comparing these methods to classical proportional-integral control they result in superior performance in the nonlinear and uncertain operating conditions [9]. Renewable energy has made intelligent control systems an essential tool in managing grid connectivity of solar and wind sources, which produce variable power injection and can cause instability in the grid [10]. AI techniques can learn the patterns of disturbances to provide estimates of compensation and respond more quickly to transient events [11]. Also, machine learning approaches can revise controller parameters continuously based on the current operating conditions of the system, thus improving dynamic stability and accuracy of the compensation [12].

There have been several current studies focused on advancements in digital signal processing technology, real-time monitoring technology, and hybrid control strategies for performance improvement of unified power quality conditioner (UPQC) [13]. Frameworks have been developed that leverage machine learning techniques for fault identification, load identification, and voltage sag detection, as well as predictive models to anticipate power variations prior to impacting the grid. Although these methods are advancing the state of art, a number of methods are still limited by conditions that exist a priori and require considerable computation time, thus affecting their ability to be used effectively in rapidly changing renewable plants. There is now increasing interest in researching digital signal processing, real-time monitoring, and hybrid control approaches to improve the performance of unified power quality conditioner systems [14].

There are some systems that have used machine learning for the purpose of fault identification, load type classification, and voltage sag detection, while others have developed predictive models to predict power fluctuations before they impact the grid. Additionally, remote monitoring and faster fault diagnosis in renewable energy systems have also been enhanced through the use of cloud-based monitoring and sensing technologies utilizing IoT. Although many of these new technologies show considerable promise, the majority of the methods are based on pre-established conditions or require a substantial amount of computation time. These two limitations severely restrict the practical application of these technologies in renewable energy systems that change rapidly. Therefore, in order to greatly enhance the stability, power factor, harmonic suppression, efficiency of converters, and overall reliability of the continuous renewable energy industry, a more adaptive, efficient, and intelligent unified power quality conditioner needs to be developed [15].



IV. METHODOLOGY

Figure 2 illustrates the overall methodology of the proposed artificial-intelligence-enabled integrated unified power quality conditioner for renewable energy systems. The design framework is structured to detect disturbances, learn the behaviour of the system, and inject appropriate compensation signals in real time. The methodology begins with renewable energy generation, where fluctuations in output power occur because of varying environmental conditions and changing load demand. The generated power is supplied through a power electronic inverter and connected to the grid using the integrated UPQC framework. Different sensing units continuously monitor electrical parameters such as voltage, current, harmonic distortion, reactive power, and power factor. These measured signals are transmitted to the AI-based control module for further analysis and decision-making. The intelligent controller identifies abnormal operating conditions, predicts disturbances, and generates suitable compensation signals for the series and shunt converters of the UPQC. The compensation process helps regulate voltage, reduce harmonics, improve power factor, and maintain stable current flow under dynamic operating conditions. Therefore, the proposed methodology ensures improved power quality, better system reliability, and effective renewable energy integration in smart grid environments.

Step 1: System Modelling and Data Acquisition

The renewable energy source has modelled variability in output characteristics to simulate output fluctuation caused by sunshine or wind. Continuous measurements of Voltage, Current, Active Power, Reactive Power, and Harmonic Content are taken at the point of common coupling. The measuring layer collects real-time operational data and transmits the operational data back to the controller. The data will serve as a foundation for analysis of disturbances and assist artificial intelligence (AI) in decision making. In addition, the model provides the ability to identify normal operational characteristics and abnormal variations so that corrective action can be triggered immediately when needed.

Step 2: AI-Based Disturbance Detection and Prediction

The AI system analyses ongoing system measurements so that it can identify problems relating to voltage (voltage sag, voltage swell), harmonic distortion and reactive power (reactive power imbalance). A trained neural net predicts the characteristics of some type of disturbance by comparing current measured conditions with what those conditions would typically be for an operationally healthy electrical system. This is an important step since renewable energy systems can change rapidly, making fast problem detection essential to improve the effectiveness of compensation. The AI will also forecast upcoming load and generation variability so the controller can take action in advance rather than waiting until it is too late to respond.

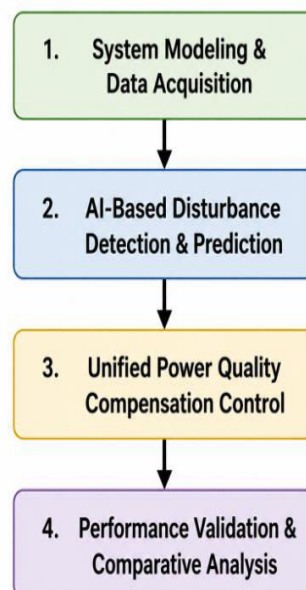


Fig.1. Proposed Methodology Flow Diagram for AI-Integrated UPQC in Renewable Energy Systems



Step 3: Unified Power Quality Compensation Control

The UPQC will generate compensation when there is a disturbance detected (i.e., something changing from its original state). The series converter produces corrective voltage to help keep load side voltage quality (this helps keep load voltage waveform under control), while supplying harmonic/reactive current compensation to the grid at the same time. The AI-based controller knows how much and when to produce the compensating signals to be injected into the load and grid. This is an improvement for faster response time and decreased overshoot. The coordination of the prediction and compensation of these signals increases the stability of the overall system as renewable injections fluctuate and non-linear loads vary from one situation to another.

Step 4: Performance Validation and Comparative Analysis

The last step of evaluation involves assessing the system while operating under the various conditions of normal operation, an instant change in load, renewable energy source fluctuations, and grid disturbances. There are several key performance indicators used to evaluate these systems including total harmonic distortion, voltage regulation, response time, power factor, and time recovery from transients. The AI integrated systems are compared to traditional control systems so that the advantages of intelligent systems can be illustrated and then the results are analyzed to see if intelligent systems improve reliability, adaptability, and quality of power in renewable energy systems.

V. RESULT AND DISCUSSION

Total Harmonic Distortion (THD) results in a variation of the THD level with the amount of load being applied as shown in Figure 2. The THD level increases from the normal load to become a maximum under heavy load operation because of an increased non-linear load demand as well as variability in generation of renewable power. The maximum THD observed under heavy load is due to an increase in the strain on the electrical network. In the case of all disturbance conditions, the AI-Powered UPQC reduces the total harmonic distortion (THD) and provides harmonic suppression. The intelligent controller is capable of rapid detection of abnormal operating conditions and will automatically implement corrective compensation in order to maintain power quality. This data demonstrates that the AI-Powered UPQC can improve harmonic mitigation, provide stable performance and be easily adapted for a range of loads and renewable energy sources, making it suitable for current smart grid applications.

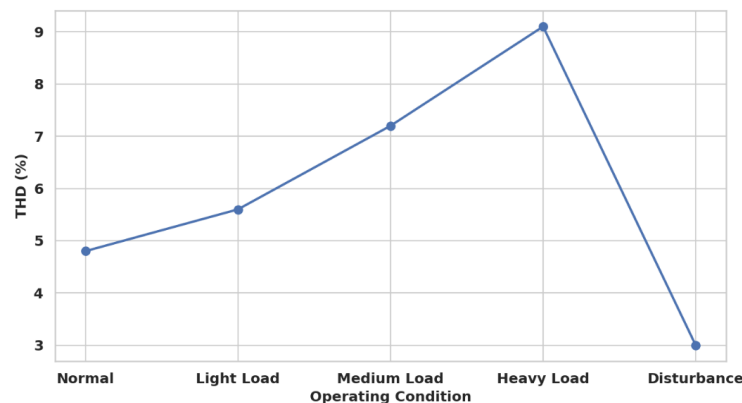


Fig. 2 Harmonic Distortion Reduction Using AI-Integrated UPQC

Figure 3 shows a comparison of the traditional UPQC with the smart UPQC by looking at the harmonic distortion, how fast the device can deliver power, how much reactive power the device can compensate for, and how much improvement can be made to the power factor. The results indicate that the smart UPQC controller will produce fewer harmonics and will recover faster than a conventional UPQC controller. In addition, the smart UPQC can provide better management of the reactive power produced, as well as maintain a higher power factor, which contributes to the overall efficiency of the entire system, by being able to adapt quickly to disturbances in the system and changes in the operating conditions without the need for major retuning. The improvements made to the system due to the use of Artificial Intelligence have increased the speed, accuracy, and flexibility of the smart UPQC system. For these reasons, the new controller has a better ability to compensate for renewable energy and distributed generation.

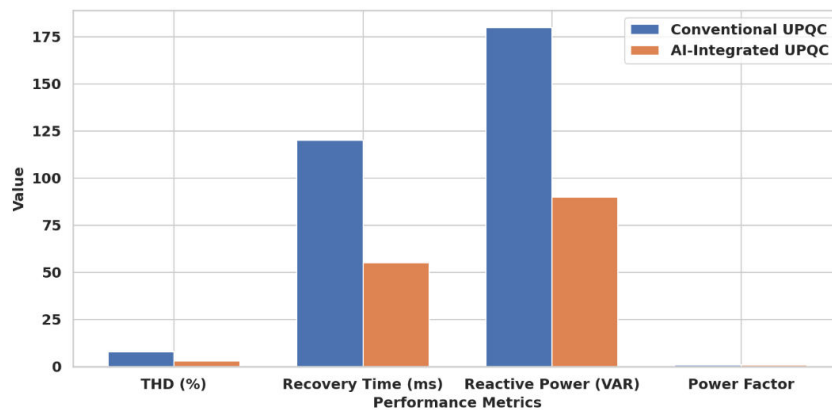


Fig. 3 Performance Comparison of Conventional and AI-Integrated UPQC

Figure 4 shows the voltage sag compensation capabilities of the traditional UPQC and the AI-enabled UPQC when responding to a disturbance in the electrical system. Both types of UPQC systems initially operate at normal voltage levels; however, during the voltage sag period the traditional UPQC will experience a larger reduction in voltage and will take longer to return to steady state conditions than does an AI-enhanced system. In addition, an AI-enhanced system will limit the amount of dropped voltage and will return to nominal voltage levels much quicker than a traditional UPQC system. The faster response time of the AI-enhanced comparative versus the traditional UPQC case is attributable to predictive analysis and intelligent control strategies, which enable an earlier response to system disturbances. Furthermore, the smoother recovery profile shown in Figure 4 demonstrates that AI-enhanced UPQCs operate with greater stability during transient conditions when compared to the traditional UPQC. The findings of this study support the conclusion that an AI-based controller improves voltage regulation, transient response performance, and operational reliability for renewable energy and smart grid systems when compared to conventional UPQC controllers.

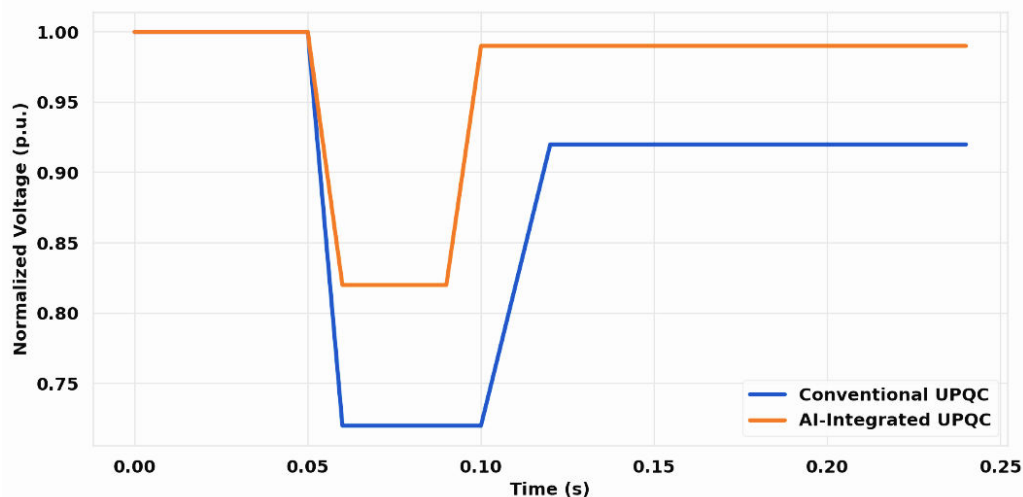


Fig. 4 Voltage Sag/Swell Compensation Response

In Fig 3, Throughput of sending bits Vs Maximal simulation jitter. Jitter is the undesired deviation from true periodicity of an assumed periodic signal. Jitter period is the interval between two times of maximum effect (or minimum effect) of a signal characteristic that varies regularly with time.



VI. CONCLUSION

The article presents a new control system that incorporates AI with a UPQC or Power Quality Correction Device. The purpose is to provide an enhanced level of power quality in RE systems since RE generation often leads to degraded power quality due to the non-linear characteristics of RE loads and their use of intermittent generation resources. The authors will propose a method that allows the real-time detection of disturbances caused by the operation of RE resources on the power grid and provide the real-time predictive capability to respond appropriately to disturbances once detected by using AI integrated with a UPQC to develop a comprehensive method of controlling power factors, voltage fluctuations, harmonics and other forms of power quality issues associated with the use of RE generation sources through integrated compensation techniques.

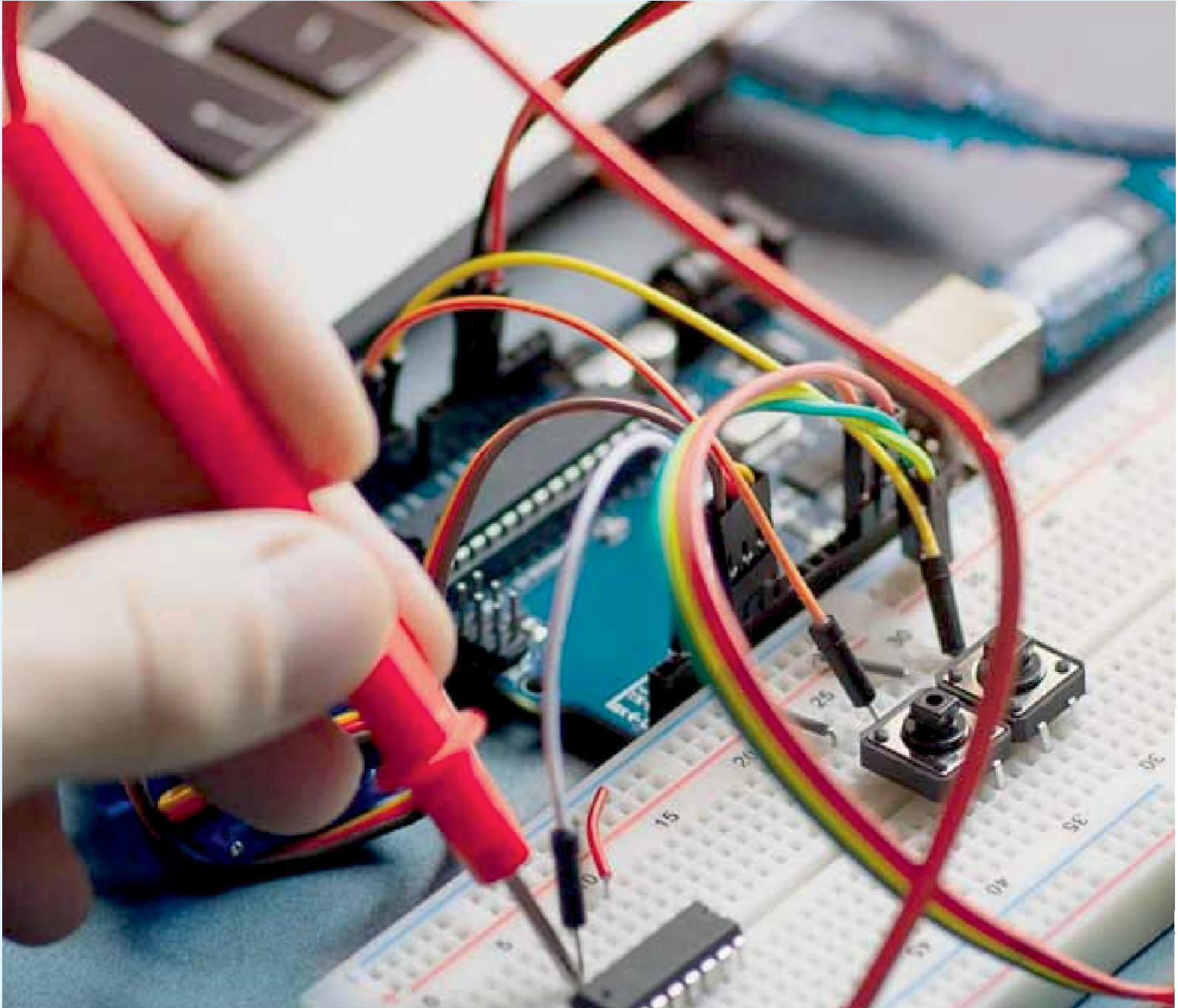
This paper discusses how the incorporation of AI into the UPQC improves the responsiveness of the control processes used within the UPQC and strengthens the performance of the UPQC in managing these power quality issues. The discussion focuses on the adaptability of traditional controllers used in power grids and how AI integrated with a UPQC provides enhanced learning capabilities for adaptive control management along with a more rapid response time and improved overall system stability than conventional controllers utilized in traditional grid control systems. The integration of AI with the UPQC to improve the management of power quality issues is particularly necessary in a world where additional RE resources are being connected to power grids and where intermittent generation continues to be utilized in substantial volumes. Consequently, the combined effects of the operation of RE generation resources and intermittent generation leads to a considerable requirement for the effective coordination of series and shunted accomplished through the use of a UPQC. In conclusion, the proposed AI-integrated UPQC will provide an effective and innovative method of providing improved power quality in a method that supports effective grid interactions, enhances load protection and improves energy efficiency for REs used in modern power grids..

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