

AI-Based Control Strategy for UPQC in Smart Grid Applications

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Abstract- This paper presents a simplified control technique for This paper presents an advanced AI-based control strategy for Unified Power Quality Conditioner (UPQC) in smart grid applications using a DC-link capacitor without photovoltaic (PV) integration. The UPQC consists of a series and shunt active filter designed to mitigate power quality issues such as voltage sag, swell, harmonics, and unbalance in modern distribution systems. Unlike conventional control methods such as PI and hysteresis controllers, the proposed system incorporates Artificial Intelligence (AI)-based adaptive control, enabling real-time decision-making and improved dynamic response under varying load conditions. The DC-link capacitor acts as the primary energy storage element, ensuring stable power exchange between series and shunt converters. The AI controller continuously monitors system parameters such as voltage, current, Total Harmonic Distortion (THD), and load variations, and generates optimized switching signals for Voltage Source Inverters (VSI). This results in enhanced compensation capability, reduced THD, faster response time, and improved system stability.

Key Words-Power Quality, UPFC, Dc Link Capacitors, Facts, UPQC & Dstatcom, VSI, Hysteresis PWM

I. INTRODUCTION

The economy invested in the Distribution System is large enough to take into account the concept of equipment protection against various disturbances that affect the reliability of not only the distribution system but the entire power system incorporation Generation and Transmission too. The wide acceptance of sophisticated electronic device at the utility end deteriorates the quality of supply and utility is suffering from its bad effects on large scale. The various Power quality problems Simulation results demonstrate that the proposed AI-based UPQC significantly outperforms conventional

controllers in terms of power quality improvement and reliability in smart grid environments. sinusoidal references. In this paper, the proposed design control, power flow analysis, and experimental results of the developed prototype are presented. The UPQC which can be used at the PCC for improving Power quality is modeled and simulated using proposed control strategy and the performance are compared by applying it to a distribution system without compensation, shunt compensation, series compensation and with UPQC. The performance of this UPQC has been evaluated with a typical industrial load with realistic parameters supplied by polluted distribution network. [1] encompass the voltage sags, voltage dips and voltage swells, flickers, harmonics and transient accompanied by unbalanced power, which are results of various faults with three phase fault being the most severe among all, starting of induction motor which is most often used due to its rugged construction, switching off large loads and energizing of capacitor bank. The higher index of reliability and power quality [2] to satisfy the customer has reflected the need for the development and application of compensation systems. Compensating systems [3] also known as switching off large loads and energizing of capacitor bank. The higher index of reliability and power quality [2] to satisfy the customer has reflected the need for the development and application of compensation systems. Compensating systems [3] also known as the custom power devices [CPD] offer a handful protection and security to the system under observation. They tend to absorb the various disturbances by injecting appropriate voltage, current or both into the system, thereby relieving the main source from meeting the reactive power demand of the load. This dissertation attempts to explain the

various control strategies providing a reliable solution to the faulted system with the help of UPQC (Unified Power Quality Controller). This series conditioner device is capable of generating or absorbing real and reactive power with the help of its essential components, namely power circuit and control circuit. Various control techniques are available to obtain a controlled output voltage, to be injected into the system. There are known as linear and non-linear techniques. A PI controller with a linear structure offers satisfactory performance over a wide range of operation [5]. The problem encountered by the controller is the setting of PI parameters i.e. the gains (K_p , K_i) in the influence of varying parameters and operating conditions, the fixed gains of linear controller don't adapt accordingly to give good dynamic response. To overcome the problems faced by a linear technique, non-linear technique is an effective solution [10]. The recommended system use the PI, Hysteresis [20] [21] [22] and Hybrid PI- Hysteresis [28] controllers to the investigate the performance level of various controllers in a regard to increase capability of the existing system by creating immunity.

II. SCOPE OF WORK

Power Quality gains its importance with the introduction of sophisticated electrical gadgets.

Nowadays, a non-linear load causes the distortion of sinusoidal waveform which adversely affect the Power Quality performance. Switching of heavy loads, capacitors, Transformers and unbalance loads on a three phase system are some of the sources that contribute to voltage sag. Due to this voltage sags, the performance and the life of the equipments deteriorate considerably. This calls for the introduction and usage Custom Power Devices (CPD) with philosophy of improvement of the power quality. As per the literature review, the UPQC provides excellent voltage regulation capabilities in the influence of various power quality problems.

Objective of the proposed dissertation

The objective of the proposed dissertation is to enhance power quality and reliability in smart grid distribution systems through the development of an AI-based control strategy for Unified Power Quality

Conditioner (UPQC) using a DC-link capacitor configuration. The proposed system aims to overcome the limitations of conventional control techniques such as PI and hysteresis controllers by implementing an intelligent and adaptive control mechanism.

The system focuses on the design and implementation of an automated compensation technique that utilizes an H-bridge inverter and series injection transformer to mitigate voltage sag and other power quality disturbances in real time. The integration of ATmega8 microcontroller for signal acquisition and ESP32 module for AI-based decision-making and IoT monitoring enhances the overall system intelligence and responsiveness.

The proposed work aims to analyze and improve key power quality parameters such as voltage stability, harmonic distortion (THD), and reactive power compensation under both linear and non-linear load conditions. The effectiveness of the AI-based UPQC system is evaluated using MATLAB/SIMULINK simulations, where different disturbance scenarios are applied to the distribution network.

Furthermore, the objective includes demonstrating that the proposed AI-based control strategy provides faster dynamic response, better adaptability, and improved compensation performance compared to traditional control methods. The system is expected to achieve reduced THD, minimized voltage fluctuations, and enhanced overall efficiency, making it highly suitable for modern smart grid applications.

The users demand higher power quality to use more sensitive loads to automate processes and improve living standards. Some basic criteria for power quality are constant RMS value, constant frequency, symmetrical three-phase, pure sinusoidal wave shape and limited THD. These values should be kept between limits determined by standards if the power quality level is considered to be high. The economic losses due to power interruptions and disturbances can be quite high as a result of the important processes controlled and maintained by the sensitive devices.

III. PROPOSED SYSTEM

The proposed system presents an advanced Artificial Intelligence (AI)-based control strategy for the Unified Power Quality Conditioner (UPQC) in smart grid applications using a DC-link capacitor as the primary energy storage element, without the use of photovoltaic (PV) sources. The system is designed to enhance power quality by mitigating disturbances such as voltage sag, swell, harmonics, and load imbalance through intelligent and adaptive control.

The UPQC consists of two major components: a series active filter and a shunt active filter, interconnected through a common DC-link capacitor. The series compensator is responsible for injecting appropriate voltage into the system to correct voltage-related disturbances, while the shunt compensator injects current to eliminate harmonics, compensate reactive power, and maintain load balance.

In this proposed architecture, a combination of ATmega8 microcontroller and ESP32 module is utilized to implement an efficient and intelligent control system. The ATmega8 microcontroller is primarily responsible for real-time signal acquisition, sensor interfacing, and basic control operations. It collects data from voltage and current sensors, processes analog signals, and performs initial conditioning required for compensation control.

The ESP32 module serves as the high-level processing and communication unit. It is used to implement the AI-based control algorithm, enabling adaptive and real-time decision-making. The ESP32 processes system parameters such as voltage variations, current harmonics, and Total Harmonic Distortion (THD), and generates optimized control signals for the Voltage Source Inverters (VSI). Additionally, the ESP32 enables IoT-based monitoring, allowing real-time data visualization and remote supervision through a web-based dashboard.

The AI-based controller replaces conventional PI and hysteresis controllers by providing dynamic tuning capability and improved response under varying load conditions. Based on trained models or rule-based logic, the controller determines the required

compensation strategy and generates precise PWM signals for both series and shunt converters.

The DC-link capacitor ensures a stable DC voltage level and facilitates effective power exchange between the converters. It plays a crucial role in maintaining system stability and ensuring continuous compensation without relying on external energy sources.

Overall, the proposed system provides a smart, adaptive, and efficient UPQC solution, capable of significantly improving power quality in modern smart grid environments. The integration of AI, ATmega8, and ESP32 enhances system intelligence, reduces harmonic distortion, improves voltage regulation, and ensures reliable operation under dynamic conditions.

“Custom Power”. It focuses on reliability and quality of power quality.

Custom power technology, the low-voltage counterpart of the more widely known flexible ac transmission system (FACTS) technology, aimed at high-voltage power transmission applications, has emerged as a credible solution to solve many of the power quality problems relating to continuity of supply at the end-user level. Mitigation is in the harmonic context which is often seen as reduction of harmonic voltage or current distortion.

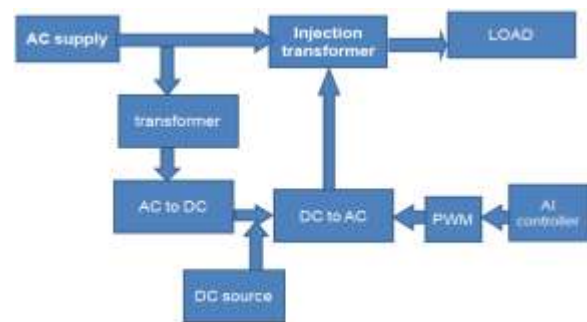


Figure.2. Proposed block diagram

IV. WORKING

However the problem can also be mitigated by improving the immunity of equipment. The mitigation methods include reducing the number of faults, faster fault clearing, improved networks

design and operation, improved end-user equipment [5]. The higher index of reliability and power quality to satisfy the customer has reflected the need for the development and application of compensation systems. Compensating systems also known as the custom power devices offer a handful of protection and security to the system under observation. A custom power device is a reliable and flexible solution to the consumers regarding the power supply. They tend to absorb the various disturbances by injecting appropriate voltage, current or both into the system, thereby relieving the main source from meeting the reactive power demand of the load. Various custom power devices covering a wide range of flexible controllers and capitalize on evolution of power electronic controllers are widely used to compensate voltage sag / swells in the system [3]. The custom power devices used for transmission system includes static synchronous compensator (STATCOM), The proposed AI-based UPQC system operates by continuously monitoring the supply voltage and load conditions to detect power quality disturbances such as voltage sag, swell, harmonics, and unbalance. The sensing unit, interfaced through the ATmega8 microcontroller, acquires real-time voltage and current signals from the distribution system. These signals are conditioned and transmitted to the ESP32 module, where advanced AI-based analysis is performed to identify abnormalities in the power system.

When a voltage sag is detected, the system automatically activates the compensation mechanism without any manual intervention. The AI controller determines the magnitude and duration of the sag and generates appropriate control signals. These signals are used to drive an H-bridge inverter, which converts the DC-link capacitor voltage into a controlled AC output.

The output of the H-bridge inverter is fed through a series injection transformer, which injects the required compensating voltage into the distribution line. This injected voltage effectively restores the load voltage to its nominal value, ensuring uninterrupted and stable operation of sensitive equipment. The transformer also provides electrical isolation and ensures safe integration of the compensation voltage with the main supply.

Simultaneously, the shunt active filter operates to eliminate current-related issues such as harmonics and reactive power demand. The AI controller continuously adjusts the switching pattern of the inverter to maintain a sinusoidal waveform and minimize Total Harmonic Distortion (THD). The coordination between series and shunt compensators ensures comprehensive power quality improvement.

The DC-link plays a vital role in maintaining a constant DC voltage, enabling smooth energy transfer between the series and shunt converters. During compensation, energy is either supplied or absorbed by the DC link depending on system requirements, ensuring balanced operation.

The entire process is fully automated and adaptive due to the integration of AI-based control using the ESP32. The system responds rapidly to dynamic changes in load and supply conditions, providing high-speed compensation and improved stability. As a result, the proposed system effectively mitigates voltage sag and other disturbances, ensuring enhanced power quality and reliable operation in smart grid applications.

V. APPLICATION OF UPQC

The First UPQC was installed in North America in 1996- a 12.47 KV system located in Anderson, South Carolina [13]. Practically, the capability of injection voltage by UPQC system is 50% of nominal voltage. This allows UPQCs to successfully provide protection against sags to 50% for duration of up to 0.1 Seconds. Furthermore, most voltage sag rarely reach less than 50%. The Dynamic Voltage Restorer is also used to mitigate the damaging effect of voltage swells, voltage unbalance and other waveform distortions.

UPQCs of capacities up to 50 MVA have seen applications to critical loads in food processing, semiconductor and utility supply. Cost and installation constraints limit these to where there is clear need for constant voltage supply

VI. RESULT

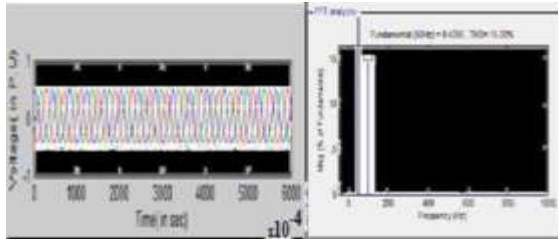


Figure.3. Load Voltage Wave form and its Frequency Spectrum when compensated using AI controller based UPQC.

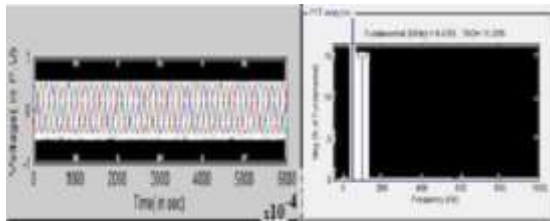


Figure.4. Load Voltage wave form and its frequency spectrum when compensated using AI controller based UPQC.

VII. CONCLUSIONS

In this work, cost effective and reliable custom Power concept, Dynamic Voltage Restorer is used to medicate the voltage sags in the distribution System, thereby improving the performance of the system. The various control strategies are employed and tested for 11KV distribution system. The PI controller based UPQC, Hysteresis controller based UPQCs and PI Hysteresis controller based are connected step by step in the compensated feeder to compare their performances. The effectiveness of different controller techniques based UPQCs for static linear and static non-linear loads have been investigated. As seen from the load voltage wave form and frequency spectrum of uncompensated system in fig 5.3, the THD level is reduced effectively from 25% to a much less value of 16.68% as in fig 5.11. load voltage waveforms and frequency spectrum of hybrid control scheme for static non-linear loads in fig5.11 depicts that the harmonics are effectively reduced to a less value as compared to 23.70% with PI controller in fig 7 and 17.49% with hysteresis controller in fig 9/ simulation results indicate that the non-linear control techniques provide better compensation to the system as

compared to the linear PI technique based UPQC connected to the feeder during static non-linear loads

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