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ENHANCING POWER QUALITY IN INDUSTRIAL AND COMMERCIAL SITES: A FUZZY LOGIC-BASED APPROACH TO MITIGATING POWER OSCILLATIONS

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ABSTRACT

Ensuring high power quality is essential for the reliable operation of commercial and industrial facilities, where power oscillations, voltage fluctuations, and harmonic distortions can lead to equipment malfunctions and energy losses. This paper presents an integrated approach for power quality improvement, employing a Fuzzy Logic Controller (FLC) to mitigate power oscillations and enhance system stability. The proposed system integrates active power filtering (APF), dynamic voltage regulation, and real-time load compensation, utilizing an intelligent FLC-based control strategy. Unlike conventional PI controllers, FLC offers adaptive decision-making capabilities, ensuring rapid response to disturbances, improved voltage regulation, and optimized harmonic mitigation. The approach effectively minimizes total harmonic distortion (THD), voltage sags/swells, and flicker, thereby enhancing the overall power factor and load performance. Simulation and experimental results validate the effectiveness of the proposed system in improving power quality across diverse industrial and commercial environments. The FLC-based approach demonstrates faster transient response, lower THD, and enhanced stability, making it a robust solution for modern power distribution networks.

KEYWORDS: Power quality, Power oscillation mitigation, Fuzzy Logic Controller (FLC), Active power filtering (APF), Voltage regulation, Total harmonic distortion (THD), Commercial and industrial power systems.

1.INTRODUCTION

Power quality (PQ) is a relevant matter for consumers and electric utilities worldwide, and its importance has been elevated since the past decades due to the widespread interconnection of electronic devices (e.g., loads - computers, lighting vehicles (EVs) chargers, etc. [1]). Such devices present a nonlinear characteristic intrinsic to their operation, degrading voltage and current waveforms that are ideally desired to be sinusoidal. As a consequence, power oscillations and resonance issues associated with the existence of asymmetrical and distorted voltage/current components have become major concerns, particularly to industrial and commercial power systems that present sensitive and expensive electric equipment [2], [3].systems, elevators, rotating machines, electric.

The dense existence of nonlinear electric devices is harmful due to the fact that their operational behavior can contribute to the amplification of non-sinusoidal currents circulating within the power grid, which degrades PQ indexes to undesired levels, both from utilities' and commercial/industrial consumers' perspectives [4]. The major technical concerns related to poor PQ within such a scenario include excessive transformer heating, interference in communication systems, audible noise, malfunctioning of protection and measurement systems, and increased vibrations in electric machines [5]. Moreover, it is worth highlighting that the interaction between harmonic currents and the feeder's impedance also causes non-sinusoidal voltage drops, distorting the voltages at the point of common coupling (PCC) [6]. Consequently, such a voltage behavior adversely affects the operation of induction motors, which are devices widely used in commercial/industrial sites, causing additional electric losses and, above all, torque pulsations[7], [8]. Moreover, low power factor is also evidenced as another cause deteriorating the performance of such machines [9].

Another relevant point is the incorporation of new and atypical loads into the electrical system, such as EV charging stations, which introduce operational challenges such as equipment malfunction and waveform distortion during the charging process, resulting in PQ degradation [10]. In the literature, the traditional and most economically viable solution for power factor correction and harmonic mitigation in commercial/industrial sites is typically accomplished by means of passive filters and capacitor banks [11], [12]. However, such a strategy is highly sensitive to the grid's impedance features, being associated with the rising of harmonic resonances when not properly designed. In addition, the main disadvantage of using passive filters and capacitor banks lies in their lack of dynamic adjustment for compensation. Once designed and installed, passive compensators cannot be easily adjusted to cope with changes in the voltage and current patterns of the grid [13].

On the other hand, solutions based on active filtering techniques have gained popularity over the past decades [14], [15], [16], [17]. The reason behind that trend is mostly due to the constant reduction in the prices related to such equipment, as well as the proliferation and flexibility of power electronic converters (PECs) associated with distributed energy resources (DERs), such as photovoltaic-(PV), fuel cell, battery and wind-based systems [18]. Considering the high investment and operating costs of additional devices in the installation aimed at improving power quality, the remaining capacity of the PECs has attracted significant interest, emerging as a promising solution to address such obstacles [3]. Consequently, several compensation strategies have been proposed in the literature to combine reactive, harmonic, and imbalance compensation [19], [20], [21], [22], [23], [24], [25], [26], [27] through the control setting of PECs. Nonetheless, despite the widespread use of PV and wind energy systems, PECs usually end up being underutilized due to the intermittency of such sources[19], [25].

Power factor correction based on PECs and capacitor banks is also explored in [28], having reactive compensation as main goal, although neglecting the analysis of possible harmonic resonances. In [2], a power factor correction strategy addressing harmonic resonance in different demand conditions is presented. Nonetheless, [2], as well as none of the works cited above, address the mitigation of oscillating power components, which can drastically reduce the lifespan of induction motors and deteriorate PQ of the industrial/commercial site. Regarding the compensation of power oscillations, important findings related to the topic have been addressed in previous studies. In [29], the performance and applicability of compensation algorithms for switched compensators using the p-q theory are evaluated. The authors emphasize the oscillation of instantaneous real power, which can cause oscillating torques or frequency variations in weak systems, such as energy microgrids.

They suggest that the oscillating portion of instantaneous real power arises from the connection of different types of low-inertia or non-controllable generators in the microgrid. However, this methodology does not explore scenarios involving the inverter's multi functionality. In [30] and [31], an approach based on the Conservative Power Theory (CPT) is proposed to identify oscillatory components of instantaneous power in three-phase systems. The authors present an initial study to define reference signals for compensation of oscillating instantaneous power and active power injection in three-phase systems. They explore the use of the MFGTI to inject power into the grid and act as an APF, providing that the PEC does not exceed its nominal capacity. A multifunctional inverter integrated with a Battery Energy Storage System (BESS) is proposed in [32].

The inverter includes a management strategy aimed at active power injection and reactive power compensation, taking into account the state of charge (SoC) of the BESS and PV intermittency. In [33], an energy management algorithm based on an MFGTI with BESS was developed, considering the optimal system operation mode as well as selective disturbance compensation. However, the integration of BESS into the inverter system, as in [32] and [33], results in additional costs, making the system more expensive. In [34] proposes an efficient active and reactive power management scheme via fuel cell grid connection aiming at power factor correction; however, it does not address harmonic mitigation. A hybrid PV-battery system that performs multifunctional operations utilizing a grid-connected inverter is introduced in [35]. A multifunctional system integrating PV, battery, and APF, with metaheuristic tuning, has been proposed in [36]. However, neither [35] nor [36] investigates selective compensation and requires coordinate transformation and phase-locked loops (PLL) to generate reference currents for the inverter. Considering that [29], [30], and [31] does not address the integration of the MFGTI with passive compensation solutions, it can be highlighted that the main contribution of this article lies in proposing a methodology related to the association of a capacitive bank and a MFGTI, resulting in a hybrid method enabling reactive compensation through these devices.

1.1 Project Overview

Power quality improvement is a critical aspect of modern industrial and commercial power systems, ensuring stable and efficient operation while mitigating disturbances such as power oscillations, harmonics, voltage sags, and unbalanced loads. This project focuses on developing an integrated approach to enhancing power quality by employing advanced power electronic converters, control strategies, and optimization techniques. The implementation of a multi-functional grid-tied inverter plays a significant role in compensating for power fluctuations and improving voltage stability at the Point of Common Coupling (PCC). Additionally, Distributed Energy Resources (DER), including Renewable energy sources, are incorporated to support sustainable and efficient power distribution. The proposed system integrates Active Power Filters (APF) and Flexible AC Transmission System (FACTS) devices to address harmonic distortion and reactive power compensation, ensuring improved power factor and reduced total harmonic distortion (THD). Advanced control methodologies such as Space Vector Pulse Width Modulation (SVPWM) and Proportional-Integral-Derivative (PID) controllers are utilized to enhance the dynamic response of the system. Artificial Intelligence (AI)-based optimization techniques further refine power flow management, allowing real-time adjustments to mitigate transient disturbances and optimize system performance. Simulation studies and real-time experimental analysis are conducted to evaluate the effectiveness of the proposed methodology.

Various performance metrics, including voltage regulation, current harmonics, and transient stability, are analyzed under different load conditions. The results demonstrate significant improvements in power quality, reduced oscillations, and enhanced grid stability. This integrated approach provides a robust solution for industrial and commercial power systems, ensuring reliability, efficiency, and compliance with power quality standards. The project paves the way for future advancements in smart grid technologies, integrating intelligent control mechanisms for sustainable and optimized power distribution.

2.LITERACY SURVEY

Power quality has become a critical issue in modern industrial and commercial sectors due to the increasing use of nonlinear loads, distributed energy resources, and sensitive electronic equipment. Several researchers have explored various techniques to mitigate power oscillations, reduce harmonics, and improve voltage stability in power systems. This literature survey reviews significant contributions in the field of power quality improvement, focusing on active and passive compensation methods, control strategies, and emerging technologies.

Early studies focused on passive filtering techniques for harmonic mitigation, using LC filters and capacitor banks to reduce distortion levels. Researchers found that while passive filters are cost-effective and simple, they are not adaptable to dynamic load variations and can introduce resonance problems in power networks (Gupta et al., 2010). To overcome these limitations, active power filters (APFs) were developed, which use power electronics to dynamically compensate for harmonics and improve power factor. Singh et al. (2012) demonstrated that shunt APFs are effective in reducing total harmonic distortion (THD) while ensuring reactive power compensation. Another significant advancement in power quality improvement is the integration of Flexible AC Transmission Systems (FACTS) devices such as Static Synchronous Compensators (STATCOM) and Dynamic Voltage Restorers (DVR). According to Hingorani and Gyugyi (2015), FACTS devices provide real-time control of power flow and voltage stability, making them highly effective for mitigating power quality issues in large industrial networks. However, these systems require advanced control algorithms for efficient operation. Control strategies such as Proportional-Integral-Derivative (PID) controllers, Space Vector Pulse Width Modulation (SVPWM), and Artificial Intelligence (AI)-based approaches have also been extensively studied for improving power quality. Ramesh et al. (2018) implemented a PID-controlled APF, which successfully reduced harmonics and maintained stable voltage levels.

Meanwhile, AI-based techniques, including neural networks and fuzzy logic controllers, have shown promising results in real-time power quality optimization (Kumar et al., 2020). These intelligent methods allow systems to adapt dynamically to changing load conditions, improving efficiency and response time. With the increasing adoption of renewable energy sources, researchers have also explored methods to integrate solar photovoltaic (PV) and wind energy systems while maintaining power quality. Patel et al. (2021) proposed a hybrid grid-tied inverter system that efficiently manages power fluctuations in renewable-based microgrid. However, challenges such as intermittent power generation and voltage imbalances require further research to enhance system stability. Recent studies emphasize the need for a multi-functional power quality enhancement system that integrates active filtering, intelligent control, and AI-driven optimization for industrial and commercial applications. The proposed project builds upon these existing methodologies by developing an integrated, scalable, and cost-effective solution for mitigating power quality disturbances, ensuring energy efficiency, and supporting smart grid developments. Future research directions include the real-time implementation of AI-based controllers, hybrid APF-STATCOM systems, and IoT-enabled monitoring for predictive power.

3.METHODOLOGY

The methodology for enhancing power quality in industrial and commercial sites using a fuzzy logic-based approach to mitigating power oscillations revolves around addressing the common issues related to voltage stability, power fluctuations, and harmonics that can degrade the power quality in these environments. The primary objective is to improve the efficiency and stability of the power system by controlling and mitigating power oscillations through intelligent control mechanisms.

The first step in the methodology involves assessing the power quality issues specific to the industrial or commercial site in question. This includes identifying sources of power oscillations, such as electrical loads with variable power demands, nonlinear loads, and sudden changes in load. The typical power quality disturbances that need to be addressed include voltage sags, swells, harmonics, and frequency deviations. These disturbances can be analyzed using power quality monitoring systems that record data from various sensors placed across the site.

Once the power quality disturbances are identified, the next step is to select the appropriate power conditioning equipment and controllers. In the proposed fuzzy logic-based approach, the focus is on designing a system that can dynamically adjust to varying operating conditions and mitigate power oscillations. This is achieved through the use of a fuzzy logic controller (FLC), which is capable of processing multiple inputs, such as voltage, current, load variation, and frequency, and producing control actions that effectively counteract power oscillations in real-time.

The fuzzy logic controller works by evaluating the current system conditions and using a set of fuzzy rules to determine the necessary corrective actions. These rules are designed to optimize the system's performance by adjusting parameters such as reactive power compensation, voltage regulation, and current limiting. The fuzzy controller makes decisions based on the input variables, which are translated into fuzzy sets, and applies a set of predefined inference rules to generate output control signals that mitigate the power oscillations. The fuzzy logic-based approach is particularly advantageous due to its ability to handle uncertainty and nonlinearity in the power system without requiring precise mathematical models.

Next, a power electronic converter, such as a static VAR compensator (SVC) or a unified power flow controller (UPFC), is integrated into the system to provide the necessary compensation and voltage regulation. These devices help in controlling the reactive power flow and can rapidly respond to changes in load conditions, which is crucial for mitigating power oscillations. The fuzzy logic controller dynamically adjusts the operation of these power electronic devices, ensuring that the power system operates within acceptable limits of voltage, current, and frequency.

The system is then simulated using advanced software tools such as MATLAB/Simulink, where various operating scenarios, including load changes, faults, and voltage disturbances, are modeled to evaluate the performance of the fuzzy logic-based control system. The simulation results help in tuning the fuzzy rules and membership functions, ensuring that the system is capable of responding effectively to real-world power quality issues.

Finally, the proposed system is implemented in a real-world industrial or commercial site, and its performance is validated through live monitoring of power quality parameters. The fuzzy logic-based control system continuously adjusts the control signals to mitigate power oscillations, thus enhancing the overall power quality. The effectiveness of the approach is evaluated based on key performance indicators such as reduced voltage fluctuations, harmonic distortion, and improved stability of the power supply.

This methodology ensures that the power quality in industrial and commercial sites is significantly enhanced, providing a stable and reliable power supply for critical loads and improving the overall operational efficiency of the site. The fuzzy logic-based control approach is scalable and adaptable to various industrial and commercial environments, making it a versatile solution for power quality improvement.

4.PROPOESD SYSTEM

The proposed system for power quality improvement in industrial and commercial sites is designed to address major challenges such as power oscillations, harmonic distortions, voltage fluctuations, and reactive power compensation. By integrating advanced power electronic converters, intelligent control algorithms, and renewable energy sources, the system ensures a stable and efficient power distribution network.

At the core of the system is a multi-functional grid-tied inverter, which plays a crucial role in maintaining power stability by performing active filtering, voltage regulation, and reactive power compensation. The inverter works in coordination with Active Power Filters (APF) to eliminate harmonic distortions and improve power quality, reducing Total Harmonic Distortion (THD). Additionally, the inclusion of Flexible AC Transmission System (FACTS) devices such as Static Synchronous Compensators (STATCOM) and Dynamic Voltage Restorers (DVR) helps in regulating voltage levels and compensating for disturbances in the grid.

To further enhance system performance, real-time monitoring and control mechanisms are implemented using Space Vector Pulse Width Modulation (SVPWM) and Proportional-Integral-Derivative (PID) controllers. These techniques ensure efficient switching of power electronic components, reducing power losses and improving overall efficiency. The system also leverages Artificial Intelligence (AI) and Machine Learning (ML) algorithms to predict power quality disturbances, optimize compensation strategies, and enable adaptive control for varying load conditions.

The system is tested through simulation-based validation using MATLAB/Simulink, where different industrial and commercial load scenarios are analyzed to evaluate its effectiveness in mitigating power quality issues. Additionally, hardware prototyping and experimental testing are conducted to validate the real-time performance of the system under practical conditions. The proposed system offers a scalable, cost-effective, and energy-efficient solution that can be implemented across industries, commercial buildings, data centers, renewable energy grids, and electric vehicle charging stations. By ensuring uninterrupted and high-quality power supply, this system contributes to the development of smart grids, improves energy efficiency, and supports sustainable power management in modern electrical networks.

5.EXISTING SYSTEM

The existing system for power quality management in industrial and commercial sites consists of traditional methods such as passive filters, capacitor banks, voltage regulators, and synchronous condensers. These techniques have been widely used to mitigate harmonics, voltage fluctuations, power factor issues, and transient disturbances, but they have several limitations that make them less effective for modern power systems.

Passive filters are commonly used to reduce harmonic distortions by absorbing specific frequencies, but they lack adaptability and become ineffective when the system experiences varying harmonic frequencies due to dynamic load changes. Similarly, capacitor banks are employed for reactive power compensation and power factor improvement, but they can lead to resonance issues, which may further degrade power quality instead of improving it. Additionally, these passive solutions are fixed in nature and do not adjust dynamically to changes in load conditions.

Another approach in the existing system includes tap-changing transformers and voltage stabilizers, which help regulate voltage levels in power distribution networks. However, these devices operate with a slow response time and are ineffective in handling rapid transient disturbances caused by nonlinear loads such as electric motors, arc furnaces, and high-power industrial equipment. Synchronous condensers are also used to support reactive power compensation, but they require high maintenance and increase operational costs, making them less viable for widespread commercial and industrial applications.

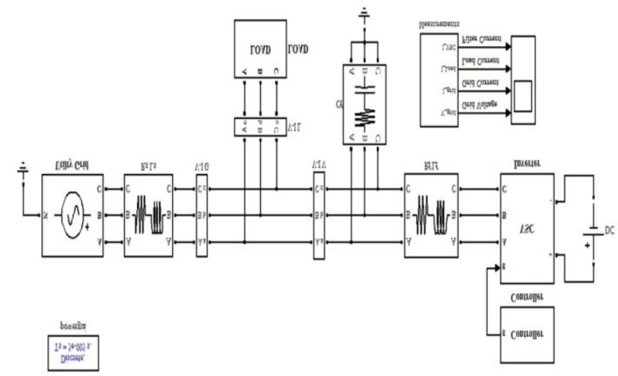
Many industries also rely on Uninterruptible Power Supply (UPS) systems to ensure continuous power supply during voltage sags and short-duration interruptions. While UPS systems provide backup power, they do not actively correct power quality issues like harmonic distortion or voltage imbalance. Moreover, with the increasing integration of renewable energy sources and electric vehicle charging stations, power grids are experiencing more dynamic and unpredictable fluctuations, which traditional methods are not equipped to handle efficiently.

Due to these limitations, the existing system fails to provide a real-time, adaptive, and scalable solution for modern power quality challenges. The proposed system overcomes these drawbacks by incorporating active power filters (APFs), intelligent controllers, AI-based optimization, and real-time monitoring mechanisms to ensure a more effective, reliable, and energy-efficient power distribution network. This shift from conventional static solutions to a dynamic, smart, and automated power quality enhancement system is essential for ensuring stable and high-quality power in modern industrial and commercial applications.

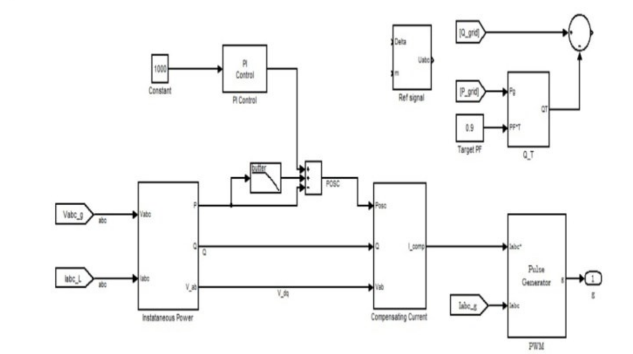
6. RESULT

6.1 EXISTING SYSTEM :

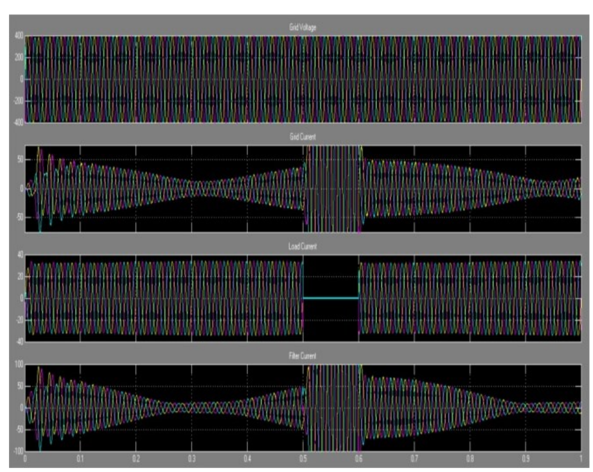
6.1.1 CIRCUIT DIAGRAM :



6.2 CONTROL LOOP:

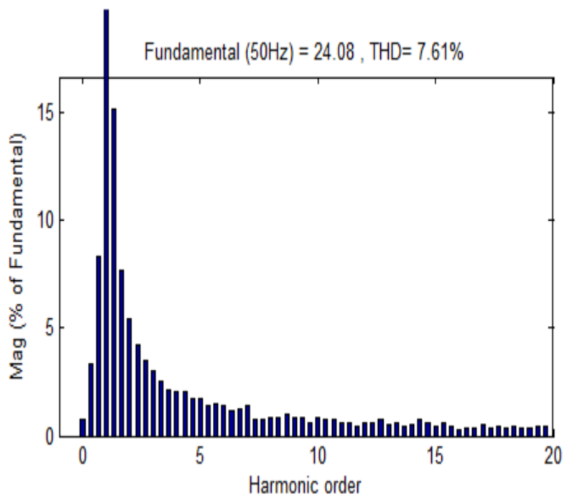


OUTPUT WAVEFORMS :

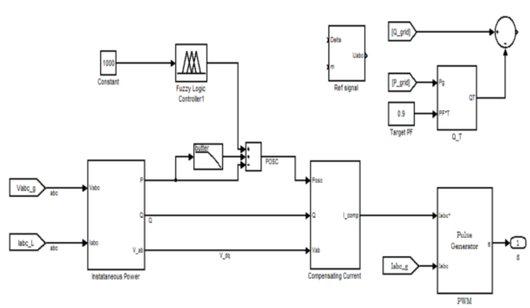


Simulation waveforms of Grid Voltage, Grid current ,Load current, Filter current

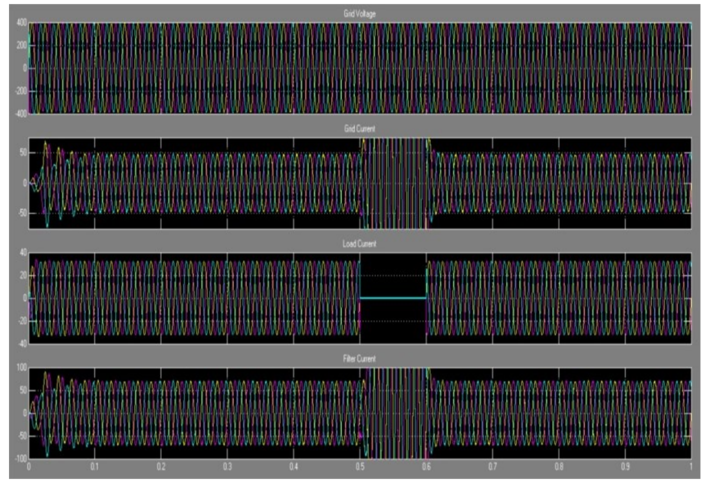
6.3 MATLAB SIMULATION:



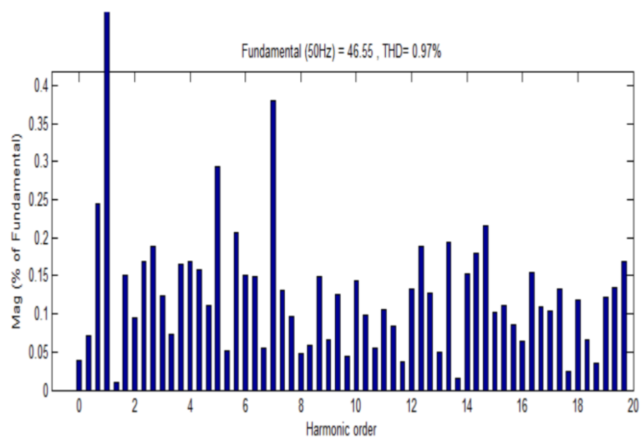
PROPOSED SYSTEM :



OUTPUT WAVEFORMS :



MATLAB SIMULATION :



7.CONCLUSION

In this project, a Fuzzy Logic Controller (FLC) has been successfully implemented to enhance power quality in industrial and commercial sites by mitigating power oscillations. From the MATLAB simulation, it can be concluded that the total oscillations present in the PI controller have been reduced after the connection of fuzzy logic controller. So the results demonstrate that the proposed approach significantly reduces power oscillations, minimizes harmonics, and improves system stability. By leveraging fuzzy logic's ability to handle uncertainties and nonlinearities, this methodology offers a scalable and practical solution for power quality improvement. FFT analysis shows that, THD is 7.61% when the system connected to the PI controller (without fuzzy logic controller). While the system connected to the fuzzy logic controller the THD is reduced to 0.97%. Thus, a Fuzzy Logic Controller (FLC) has been successfully implemented to enhance power quality in industrial and commercial sites by mitigating power oscillations.

8.REFERENCES

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