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INTERLINE UNIFIED POWER QUALITY CONDITIONER FOR VOLTAGE REGULATION OF CRITICAL LOAD BUS USING SOFT COMPUTING TECHNIQUES

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ABSTRACT: This study presents an advanced configuration of a Flexible AC Transmission System (FACTS) device called the Interline Unified Power Quality Conditioner (IUPQC), designed to address limitations in conventional UPQC systems. Traditional UPQC devices integrate series and shunt active power filters to mitigate voltage and current-related power quality issues at the load side, such as voltage sags/swells, harmonics, and reactive power imbalances. However, the proposed IUPQC extends these capabilities by introducing dual-bus voltage regulation – not only stabilizing the load-side voltage but also actively regulating the grid-side voltage, akin to a Static Synchronous Compensator (STATCOM). This dual functionality enables comprehensive power quality management across both supply and demand sides of the distribution network. A fuzzy logic controller is implemented to enhance the system's adaptability to non-linear loads and grid disturbances. These results highlight the IUPQC's potential as a multifunctional solution for modern smart grids, particularly in environments with high renewable energy penetration and sensitive industrial loads. The dual voltage regulation capability addresses a critical gap in conventional UPQC designs, making it suitable for applications requiring bidirectional power quality management.
Keywords:*iUPQC, microgrids, power quality, static STATCOM, Fuzzy Logic*

1. INTRODUCTION

Electric power quality is quantitatively defined by the adherence of voltage magnitude, frequency stability, and waveform purity to specifications outlined in standards such as IEEE 519-2022 and IEC 61000-4-30. Power quality disturbances—including harmonic distortion (THD >5%), voltage sags/swells (±10% nominal), transient overvoltages (0.5–30 kV), and frequency deviations (±0.5 Hz)—can induce equipment malfunctions, premature component degradation, and system instability.

Among the various forms of power quality issues—such as voltage sags/swells, flicker, harmonics, transients, and frequency deviations—harmonic distortion has become increasingly prominent with the widespread integration of nonlinear loads, such as power electronic converters, variable frequency drives, and computer power supplies. These nonlinear loads inject harmonic currents into the power system, which interact with the system impedance to cause harmonic voltages that propagate throughout the distribution network.

A Custom power gadget gives "wide zone" control quality security: in other words a solitary gadget can ensure the greater part of a plant's basic burdens, as opposed to securing a solitary load like an UPS item. The Custom Power items are proper for vast vitality touchy to the nature of power supply. Custom Power is an innovation driven item and administration arrangement which grasps a group of gadgets which will give control quality capacities at dispersion voltages. It has been made conceivable by the now boundless accessibility of financially savvy high power strong state switches, for example, GTO's and IGBT's. The quick reaction of these gadgets empowers them to work progressively, giving constant and dynamic control of the supply including: sub-cycle exchange of basic burdens, voltage and receptive power direction, symphonious relief and end of voltage droops. Custom Power grasps a group of gadgets, which together make up a tool compartment to give control quality arrangements at the appropriation framework voltage level. Every single Custom gadget are fit for giving various power quality capacities which can be utilized specifically or at the same time.

To mitigate harmonic pollution, two broad categories of filters are employed:

- **Passive Filters –** These are composed of fixed combinations of inductors, capacitors, and sometimes resistors, designed to target and attenuate specific harmonic frequencies. Although cost-effective, passive filters are typically tuned for fixed frequencies and may suffer from issues such as resonance with the power system impedance.

- **Active Power Filters (APFs) –** These utilize power electronic converters to dynamically inject compensating currents that cancel out a wide range of harmonic components. Active filters offer adaptive and real-time harmonic compensation, thereby improving overall system performance and reducing total harmonic distortion (THD).
- In addition to filtering, more sophisticated custom power devices, collectively referred to as Distributed Flexible AC Transmission System (DFACTS) devices or Custom Power Devices, have been developed to address a broader spectrum of power quality concerns at the distribution level. These devices include:
- Dynamic Voltage Restorers (DVRs)
- Distribution Static Compensators (D-STATCOMs)
- Unified Power Quality Conditioners (UPQCs)

These devices are capable of compensating for voltage sags/swells, harmonics, and flicker, and are particularly valuable in enhancing the reliability and quality of power supply in sensitive and mission-critical systems.A significant challenge lies in the contradiction between the needs of modern power electronic loads and the disturbances they introduce. While such loads require a pure sinusoidal voltage waveform for proper operation, they are simultaneously the major contributors to power quality degradation due to the generation of harmonics and reactive power imbalance.

To address these limitations, advanced multi-functional power conditioning devices such as the Unified Power Quality Conditioner (UPQC) have been developed. The UPQC combines the functionalities of both series and shunt active filters to simultaneously compensate for voltage distortions and current harmonics. It has proven highly effective in mitigating a wide range of power quality issues in real-time.A variation known as the Interline UPQC (iUPQC) extends the capabilities of the traditional UPQC by enabling it to also perform tasks typically assigned to a Static Synchronous Compensator (STATCOM). Traditionally used in transmission systems, the STATCOM provides dynamic reactive power support to regulate system voltage. However, with the integration of STATCOM-like features in the iUPQC, the device can now be deployed in distribution networks, particularly in scenarios involving distributed generation, smart grids, and grid-connected microgrids.

The Interline UPQC (iUPQC) extends conventional UPQC functionality by:

- Implementing grid-side voltage regulation via STATCOM-like reactive power injection ($Q = \pm 2$ Mvar)
- Enabling bidirectional power flow for microgrid interoperability (CIGRE C6.11 compliance)
- Incorporating model predictive control (MPC) for 15%)
- Dynamic grid support (LVRT/HVRT compliance per IEEE 1547-2018)
- Multi-objective optimization via real-time impedance reshaping.

The inclusion of such multi-functional custom power devices enables a more versatile and cost-effective approach to power quality enhancement. Though the initial investment may be higher compared to conventional methods, the comprehensive and dynamic compensation offered by UPQC and iUPQC justifies their deployment in critical and sensitive applications where maintaining power quality is non-negotiable.

Interline Unified Power Quality Conditioner (IUPQC)

The Interline Unified Power Quality Conditioner (iUPQC) architecture, as illustrated in Fig. 1, comprises two Voltage Source Converters (VSCs)—namely VSC-1 and VSC-2—configured in a back-to-back topology and interconnected via a common DC-link energy storage capacitor. This configuration allows bidirectional power flow and facilitates coordinated operation between the series and shunt converters for comprehensive power quality compensation.The series converter (VSC-2) is interfaced with the power system through the secondary winding of series-connected coupling transformers, which are inserted in series with bus B-2 and the sensitive load L-2. This enables VSC-2 to compensate for voltage-related disturbances such as sags, swells, and harmonics in the supply voltage seen by the load.

Additionally, AC filter capacitors, denoted as Cf and Ck, are connected in each phase to attenuate switching harmonics and to improve the voltage waveform quality at the point of common coupling (PCC).Each of the six inverters forming the iUPQC operates independently, and their switching actions are governed by a feedback control strategy, typically based on voltage and current measurements to achieve real-time compensation.The feeder impedances associated with Feeder-1 and Feeder-2 are represented by the parameter pairs (Rs1, Ls1) and (Rs2, Ls2), respectively. The shunt converter (VSC-1) is connected at bus B-1, which lies at the termination of

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Feeder-1. Its primary function is to compensate for current-related disturbances such as harmonics, unbalance, and reactive power drawn by the load.

Meanwhile, the series converter (VSC-2) is located at bus B-2, the end of Feeder-2, where it conditions the supply voltage before it reaches the sensitive load.

The voltage variables associated with the system are defined as follows:

- Vt1: Voltage at bus B-1,
- Vt2: Voltage at bus B-2,
- Vl2: Voltage across the sensitive load L-2.

This configuration enables the iUPQC to simultaneously mitigate both voltage and current distortions, making it a robust solution for maintaining high power quality in interconnected feeder systems.

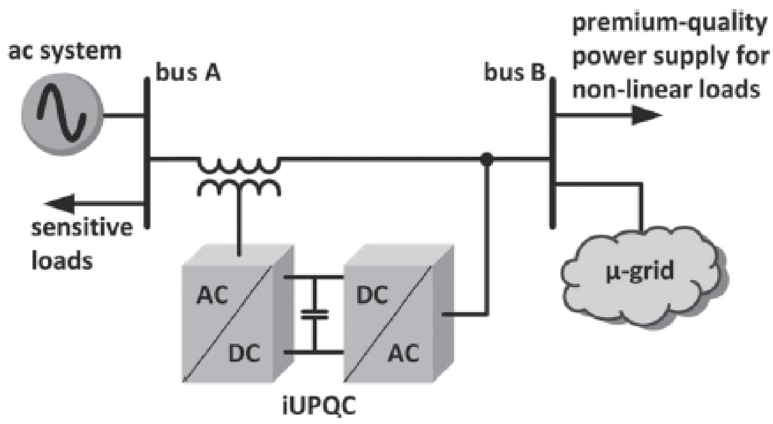

Fig. 1 Electrical System with two buses.

Modified IUPQC

The enhanced IUPQC topology operates as a bidirectional power interchange interface between Bus A and Bus B. Furthermore, the microgrid integrated with Bus B comprises a sophisticated architecture incorporating distributed generation (DG) units, an energy management system (EMS), and supplementary control subsystems for grid stabilization.

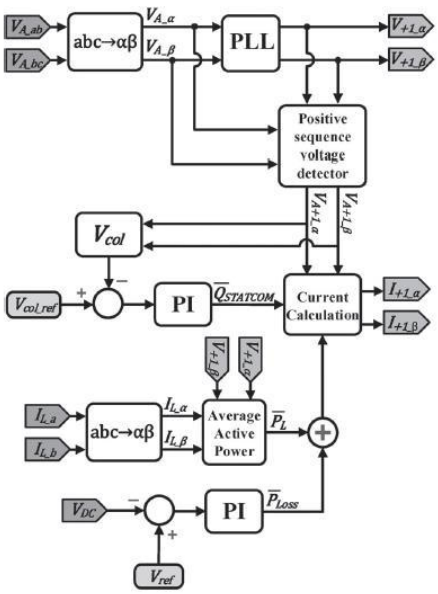

Figure 2 Improved iUPQC controller.

The iUPQC system incorporates both its own hardware and measured parameters from a three-phase, three-wire electrical network within its control architecture. As depicted in Figure 3, the controller processes inputs such as the load current at bus B (iL) and the DC-link voltage (VDC). The controller generates reference signals for both the shunt voltage and the series current, which are fed to the Pulse Width Modulation (PWM) controllers.

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Basic or advanced PWM controllers may be employed depending on the desired performance level, particularly in addressing voltage and current imbalances or harmonic distortion. The shunt converter governs the voltage at bus B, which necessitates the generation of sinusoidal waveforms with nominal amplitude and frequency. To achieve this, the reference signals for the PWM controllers are typically derived from Phase-Locked Loop (PLL) outputs, which maintain a unit amplitude (1 p.u.) to ensure synchronization.

In the proposed iUPQC control strategy, the voltage reference for the shunt converter can be selected either from the PLL outputs or from the fundamental positive-sequence component (VA^{+}_{1}) of the system voltage. Using VA^{+}_{1} is advantageous as it minimizes circulating power between the series and shunt converters during normal operation, while ensuring that the grid voltage remains within acceptable limits. However, this principle is modified in the enhanced iUPQC control scheme. Here, the grid voltage is actively regulated by the modified iUPQC itself. As a result, both bus voltages are independently controlled, enabling the system to track distinct reference values for each bus, thus offering greater flexibility and enhanced power quality performance.

2. FUZZY LOGIC CONTROLLER

The Fuzzy Logic Controller (FLC) operates based on a set of linguistic rules, eliminating the need for precise mathematical modeling. This is achieved by converting numerical variables into linguistic (semantic) variables, facilitating control through approximate reasoning. The fuzzification process maps crisp inputs into degrees of membership within a continuous universe of discourse. The inference mechanism employs Mamdani's "min" operator for rule evaluation, while the defuzzification process utilizes the "height" method to convert fuzzy outputs back into crisp control actions. The functional structure of the FLC is illustrated in Figure 3.

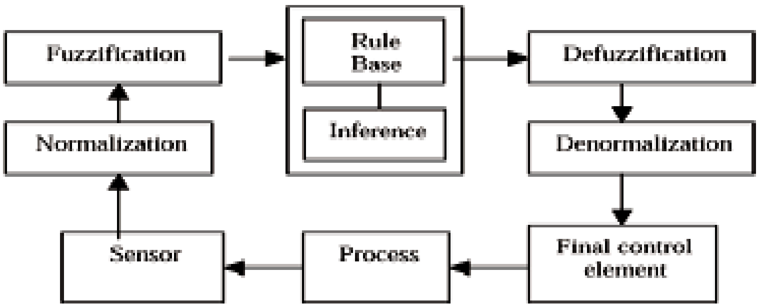

Figure.3 Fuzzy Logic-Controller

The input scaling factor is [-1, 1]. The triangular membership function is shown in fig4.

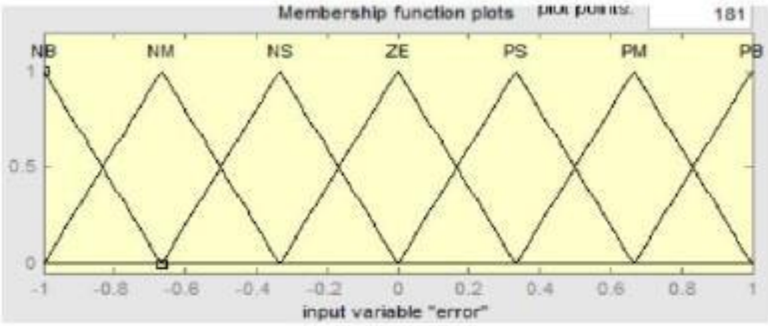

Figure.4 membership function

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e / Δe	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table 1: iUPQC Parameters

In under abnormal conditions performance of DVR connected to a single feeder system is investigated with PI and FLC controllers. Here, with IUPQC system operated with PI is investigated first for abnormal and dangerous conditions like sags, swells, harmonics, symmetrical and asymmetrical faults. Then the same IUPQC system with Mamdani based FLC is investigated for above faulty conditions. Using MATLAB/Simulink software the IUPQC connected

3. SIMULATION RESULTS

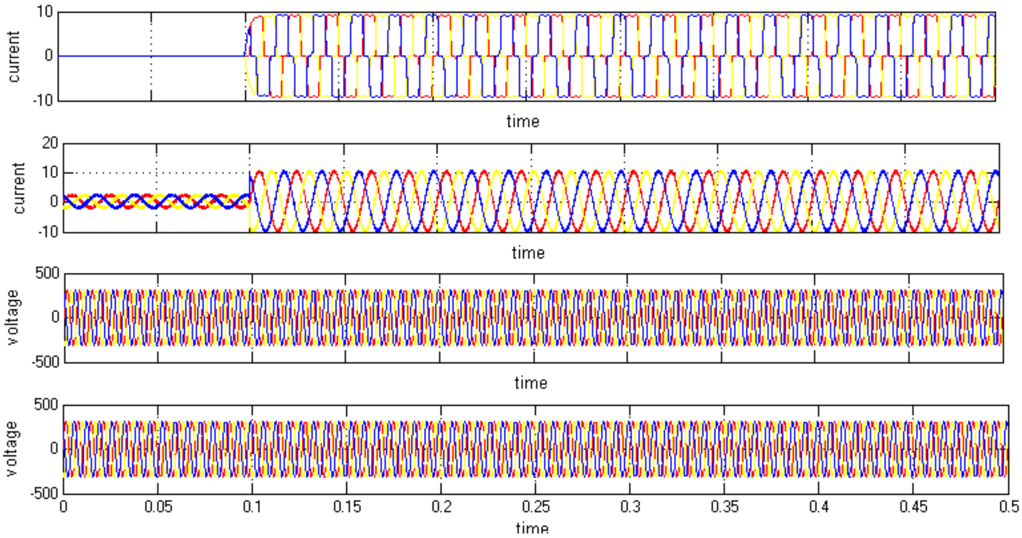

Fig:5 Load Current, Grid Current, Load Voltage, Grid Voltage ForIupqc Response Using PI Controller

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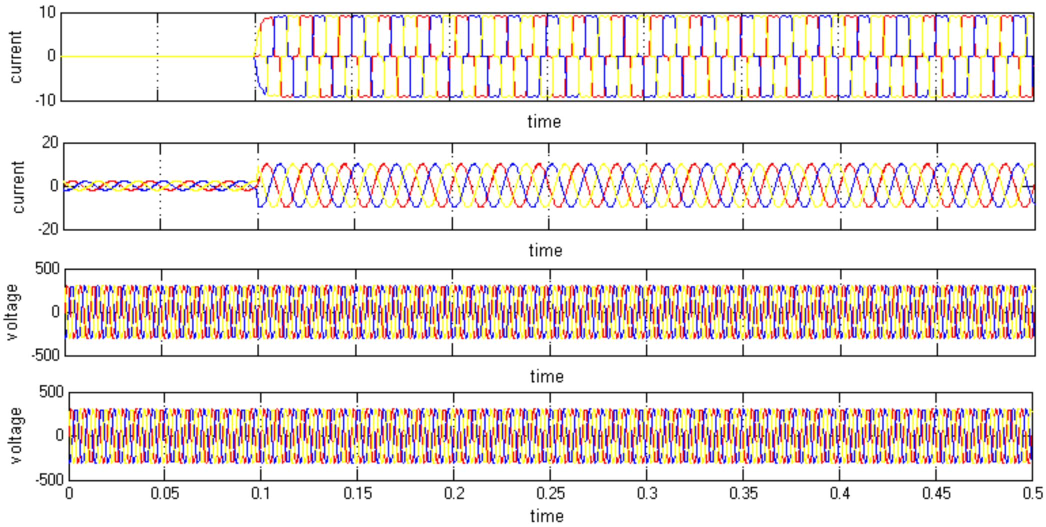

Fig:6 Load Current, Grid Current, Load Voltage, Grid Voltage For iUPQC Response Using Fuzzy Logic Controller

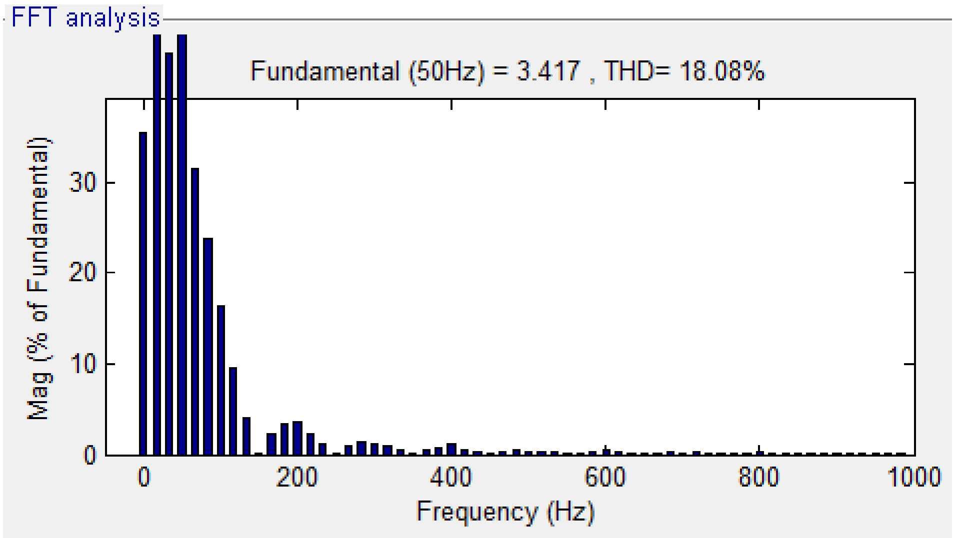

Fig: 7THD without using controller

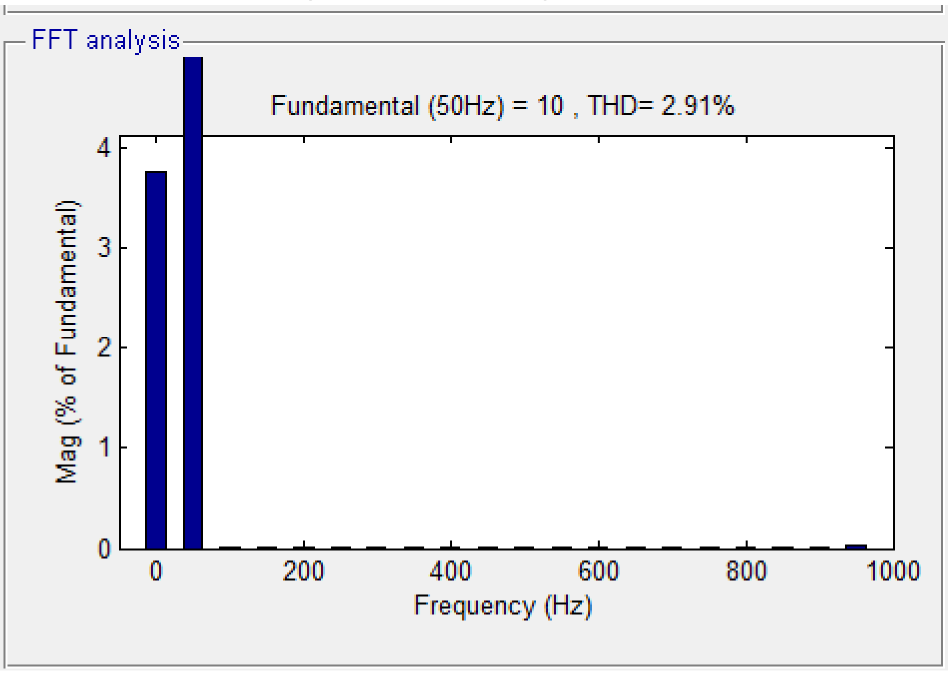

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Fig 8:THD using PI controller

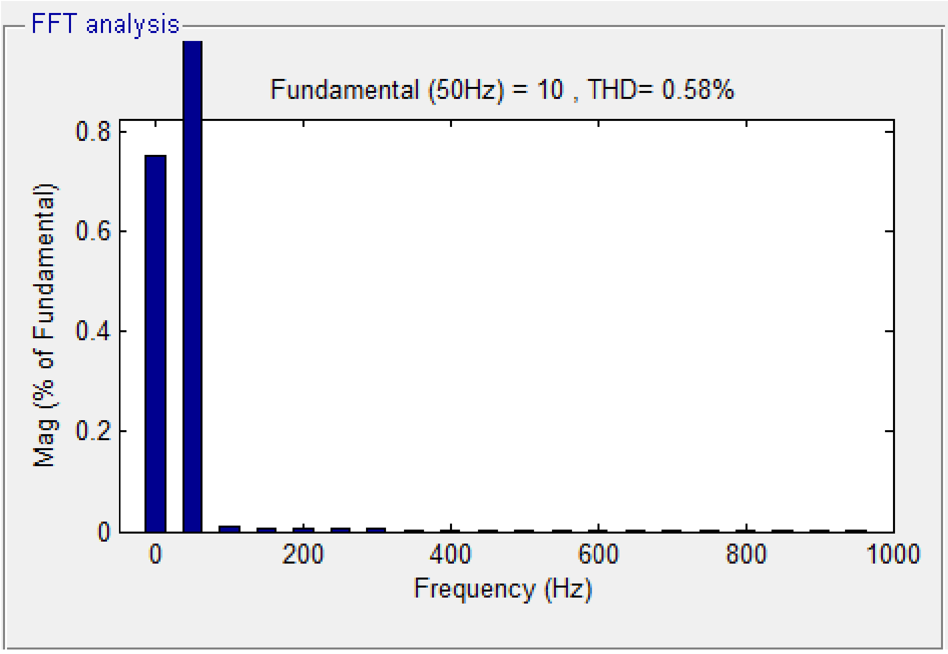

Fig 9:THD using fuzzy logic controller

Comparison Table

Type of the Controller	THD in %
Without controller	18.08
PI controller	2.91
Fuzzy Logic controller	0.58

4. CONCLUSION

The simulation of a non-linear load integrated with an iUPQC system has been effectively carried out using both Proportional-Integral (PI) and Fuzzy Logic Controllers (FLC). Among the two, the fuzzy controller demonstrates superior performance, achieving a Total Harmonic Distortion (THD) of 0.58% in the grid current, significantly lower than the 2.91% THD observed with the PI controller. In contrast, the system without any controller exhibits a much higher THD of 18.08%. For future enhancements, advanced intelligent control techniques such as neuro-fuzzy systems can be explored to further improve power quality and system performance.

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