

Power Quality Improvement Through Harmonic Compensation Using Shunt– Series Active Power Filter

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ABSTRACT

Harmonic and reactive power compensation in ac power networks with non linear loads, active filtering is proven to be efficient technique. This paper presents shunt and series active power filter – improved Unified Power Quality Conditioner (iUPQC) with two different control strategies, that is PI and Fuzzy Logic Control (FLC) for suppressing harmonics and to compensate reactive power. Because of dual topology of iUPQC extending its applicability in power- quality compensation, as well as in micro grid applications. By using this controller, beyond the conventional UPQC power quality features, including voltage sag/swell compensation, the iUPQC will also provide reactive power support to regulate not only the load-bus voltage but also the voltage at the grid-side bus. Simulation is carried out by using Simulink/Matlab-R 2014a to design iUPQC with PI and Fuzzy Logic Controller to calculate Total Harmonic Distortion (THD) value. Its value is to be well within the specified limit of IEEE standard(<5%). Simulation for without filter, with PI and FLC finally FLC gives better performance over PI is to be proven results are compared.

Keywords:– PI and Fuzzy Logic Controller, improved Unified Power Quality Conditioner, Total Harmonic Distortion, Power Quality Improvement.

1. INTRODUCTION

Power quality has become a critical issue in modern electrical power systems due to the increasing use of non-linear loads such as rectifier units, adjustable speed drives, domestic electronic appliances, and arc furnaces. These loads draw non-sinusoidal currents from the supply, leading to distortion in system voltage and current. Power quality problems are generally defined as any undesirable deviation in voltage or current that negatively affects the normal performance of electrical and electronic equipment. In other words, power quality refers to the extent to which voltage and current waveforms deviate from their ideal sinusoidal shape.

Various power quality disturbances commonly observed in distribution systems include voltage sag and swell, momentary and prolonged interruptions, voltage spikes, harmonic distortion, voltage fluctuations, and electrical noise. These disturbances differ in their characteristics, causes, and impacts, but all of them can result in malfunction, reduced efficiency, or damage to sensitive equipment [1–3].

Among these issues, harmonic distortion has emerged as a major concern for power system engineers because of its adverse effects on both sensitive consumer loads and overall power distribution networks. The rapid growth in the use of power electronic devices has significantly increased harmonic pollution in electrical systems. As a result, effective compensation of harmonic currents and reactive power has become essential to maintain acceptable power quality levels.

Traditionally, harmonic mitigation has been achieved using power conditioning techniques such as passive and active filtering methods. Passive LC filters have been widely used to suppress current harmonics and improve the power factor. However, passive filters suffer from several limitations, including fixed tuning, susceptibility to parameter variations, inability to adapt to changing load conditions, and the risk of resonance with the supply system. Due to these drawbacks, harmonic problems cannot be completely eliminated using passive filters alone.

To overcome these limitations, active power filters have gained significant attention as an effective solution. Active power filters are connected either in series or in parallel with non-linear loads and employ power electronic converters to generate compensating currents or voltages. These compensating signals are designed to cancel the harmonic components produced by non-linear loads, thereby improving overall power quality and system performance [4].

2. ACTIVE POWER FILTER

Active Power Filters (APFs) are advanced power conditioning devices specifically designed for the elimination of harmonic distortions in electrical power systems. These filters are capable of compensating harmonic components whose frequencies are well below the switching frequency of the converter. Unlike conventional filtering methods, active power filters can effectively suppress both lower-order and higher-order harmonics present in the system. The fundamental distinction between active and passive power filters lies in their mode of operation. Active power filters mitigate harmonics by generating and injecting compensating currents or voltages having the same magnitude and frequency as the undesired harmonics but in opposite phase, thereby achieving cancellation. In contrast, passive power filters are constructed using fixed combinations of resistors (R), inductors (L), and capacitors (C) and operate without the need for external power sources or semiconductor switching devices. Due to their adaptive and dynamic nature, active power filters are capable of compensating a broader range of harmonic disturbances compared to passive filters [5].

Shunt Active Power Filters are primarily employed for current harmonic compensation by injecting harmonic currents equal in magnitude and opposite in phase to those produced by non-linear loads. Operating as controlled current sources, these filters supply compensating currents that are phase-shifted by 180 degrees relative to the load-generated harmonics. Shunt APFs are typically connected in parallel with the load and are highly effective in addressing current-related power quality issues such as reactive power compensation, power factor improvement, harmonic current suppression, and load unbalance correction [6–7]. Series Active Power Filters are mainly utilized for mitigating voltage-related disturbances and compensating load voltage harmonics. In low-power, single-phase applications, reduced switch-count inverter topologies are often adopted to correct voltage distortions efficiently. To ensure sufficient active power availability during voltage sag conditions, a front-end diode rectifier is commonly employed to supply energy to the compensating system [8]. The Unified Power Quality Conditioner (UPQC) consists of two voltage source converters connected to a common DC-link capacitor that serves as the energy storage element. One converter operates as a shunt compensator connected across the line, while the other functions as a series compensator inserted in series with the supply. A shunt coupling inductor (L_{sh}) is used to interface the shunt inverter with the distribution network and to smooth the injected current waveform. In certain configurations, an isolation transformer is employed to match the voltage rating of the series inverter. The UPQC represents an integrated configuration of shunt and series active power filters sharing a self-supporting DC bus. The shunt inverter is controlled in current control mode to inject a reference current defined by the UPQC control strategy. Additionally, it plays a vital role in regulating the DC-link voltage to its desired reference value, ensuring stable and effective operation of the overall UPQC system [9–12].

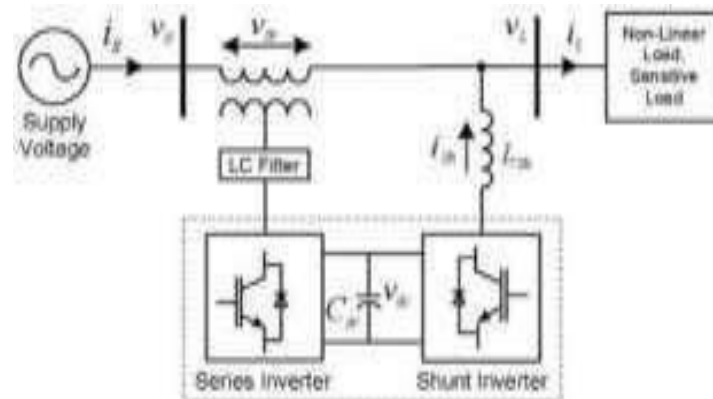


Fig.1: iUPQC in block diagram

3. CONTROL STRATEGY

In the present study, the operational performance of the Unified Power Quality Conditioner (UPQC) is improved through the implementation of an advanced control approach based on Fuzzy Logic Control (FLC). The proposed control strategy offers several advantages over conventional controllers, particularly due to its independence from an accurate mathematical representation of the system. FLC is well suited for handling nonlinear system behavior and parameter variations, making it inherently more flexible and robust than traditional proportional–integral (PI) controllers. As a result, the dynamic response and overall compensation capability of the UPQC are significantly enhanced. Moreover, the fuzzy logic–based controller provides improved stability under varying load and supply conditions, thereby ensuring better power quality performance. In this work, two distinct control schemes are implemented and analyzed to evaluate the

effectiveness of the proposed approach, and their operating principles are discussed in the following sections.

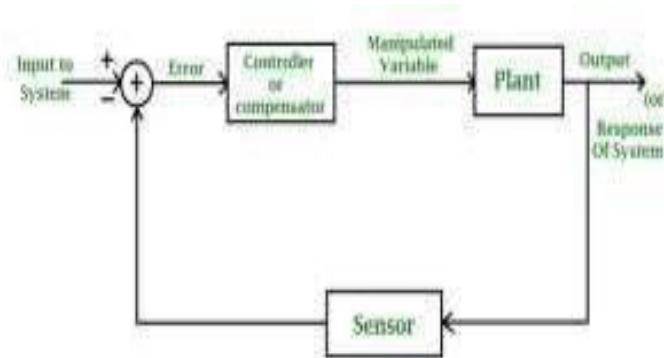


Fig 2: Control Strategy of Fuzzy Logic Controller

PI CONTROLLER

The PI controller-based control scheme comprises a proportional–integral controller, a limiter, and a three-phase sine wave generator for reference current generation and switching pulse formation. The controller output is obtained by combining the proportional component of the error signal with the integral of the error over time. This control action ensures accurate tracking of the reference signal and stable system operation. The mathematical expression governing the PI controller operation is given by:

$$I_{max}(t) = K_i \int_0^t e(t) dt + K_p e(t)$$

Where, K_p - represents the proportional gain that influences the dynamic response of the DC-link voltage control, while K_i denotes the integral gain that primarily affects the steady-state error and settling time of the system.

In the proposed configuration, an interfacing element is used to electrically isolate the inverter from the distribution network. The DC-link is implemented using a capacitor that connects the two inverters and provides a constant self-supporting DC bus voltage. An LC filter acting as a passive low-pass filter (LPF) is employed to suppress high-frequency switching ripples present in the inverter output voltage. Furthermore, a series injection transformer is utilized to connect the series inverter to the power system. An appropriate transformer turns ratio is selected to achieve the desired voltage injection while reducing the current stress on the inverter switches.

FUZZY LOGIC CONTROLLER

The Fuzzy Logic Controller (FLC) overcomes the limitations associated with conventional PI controllers. One of the main challenges with a PI controller is that it operates as a fixed-parameter feedback system and requires an accurate mathematical model of the process. Additionally, PI controllers lack the ability to adapt to system nonlinearities and parameter variations, which can degrade performance under changing operating conditions.

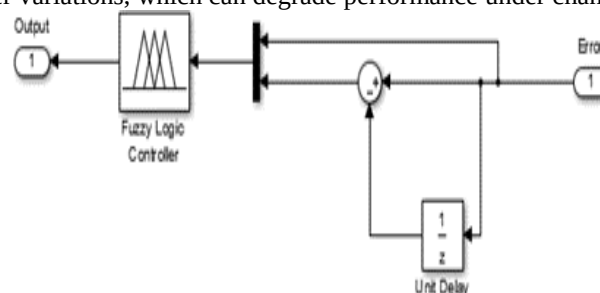


Fig.3: Basic diagram of Fuzzy Logic Controller

Fig. 3 illustrates the basic structure of a Fuzzy Logic Controller. Fuzzy Logic Control is one of the most significant practical applications of fuzzy set theory, as it directly employs linguistic rules to perform control actions. The concept of fuzzy control was first introduced by Ebrahim Mamdani in the late 1970s. The fuzzy control design process typically consists of three main stages: fuzzification, rule evaluation, and defuzzification. The theoretical foundation of fuzzy logic was established in 1965 based on the fuzzy set concept, where system membership is defined in degrees rather than crisp binary values. This approach allows the boundaries of fuzzy sets to be imprecise, making the controller suitable for systems with uncertainty and vague operating conditions.

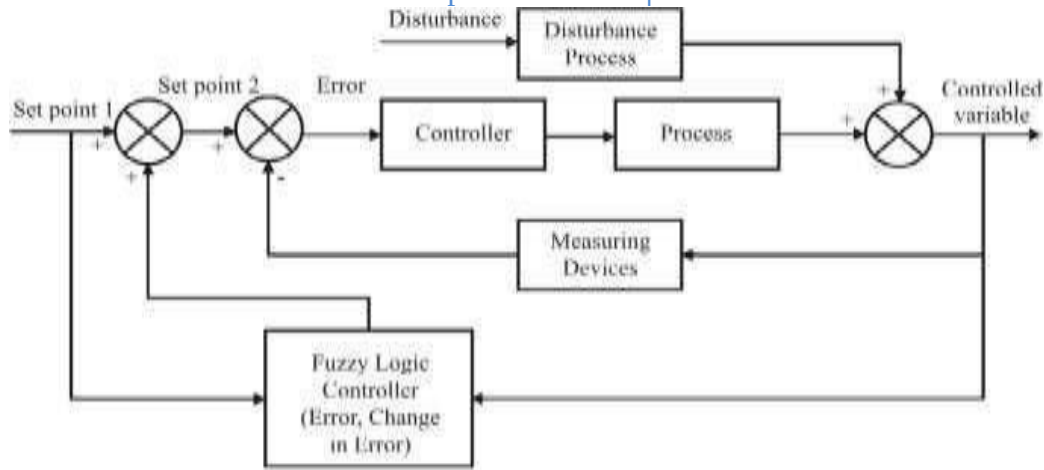


Fig.4: Represents block diagram of FLC

Fuzzy Logic Controllers are particularly effective when precise mathematical modeling of the system is difficult or impractical. **Fig. 4** shows the block diagram representation of the FLC. To implement the control algorithm for the shunt active power filter, the DC-link capacitor voltage V_{DC} is continuously sensed and compared with its desired reference value $V_{DC,ref}$. The resulting error signal, defined as

$$e(n) = V_{DC,ref} - V_{DC}$$

is processed through a Butterworth low-pass filter (LPF) with a cutoff frequency of 50 Hz, allowing only the fundamental component to pass while eliminating high-frequency noise.

The design of the Fuzzy Logic Control strategy involves formulating a set of rules that establish a relationship between the input variables and the output control signal. Since FLC does not require an explicit system model, its design primarily relies on heuristic knowledge, intuition, and operational experience of the system. Alternatively, the rule base can also be developed based on the general dynamic behavior of the system and later refined for improved performance. In this work, the input variables to the FLC are the error and the change in error, while the controller output corresponds to the variation in the reference current magnitude (I_{max}).

Table 1 Fuzzy Rules

$e \backslash \Delta e$	NB	NM	NS	ZE	PS	PM	PS
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	PM
PS	NM	NS	ZE	PS	PM	PM	PM
PM	NS	ZE	PS	PM	PM	PM	PM
PB	ZE	PS	PM	PM	PM	PM	PM

Fuzzy Inputs

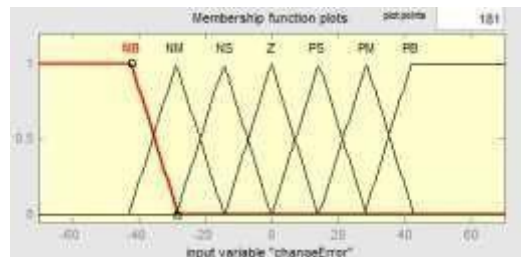


Fig 5(a): Membership function of input variable “error”

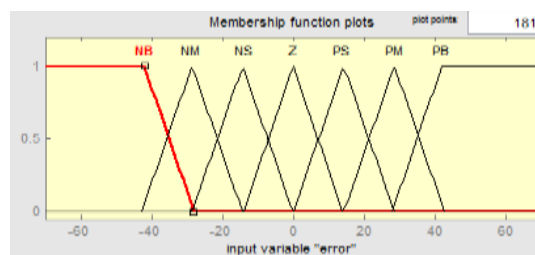


Fig 5(b) : Membership function of input variable“change error”

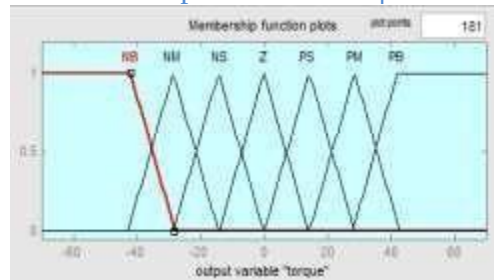


Fig.5(c): Membership function output variable “torque”

Table 1 presents the fuzzy rule base employed in the proposed control scheme. The membership functions for the input variable “error” and “change in error” are shown in Fig. 5(a) and Fig. 5(b), respectively, while Fig. 5(c) illustrates the membership function of the output variable. These membership functions define the fuzzy inference mechanism and play a crucial role in achieving smooth and effective control action.

4. PROPOSED MODEL

The simulation models of the proposed system with and without the Unified Power Quality Conditioner (UPQC) are illustrated in Fig. 8 and Fig. 9, respectively. The performance evaluation of the system is carried out through a comparative analysis of PI and Fuzzy Logic Controller (FLC)–based control strategies. In the modified UPQC configuration, a star-connected transformer integrated with an LC filter is employed to suppress neutral current components, and the LC filter is properly grounded to ensure effective current mitigation. In both the series and shunt active power filter sections, a selective harmonic elimination technique is implemented to compensate for voltage sag and swell conditions in the distribution system. Furthermore, PI-based and fuzzy-based control approaches are utilized to mitigate harmonic distortions present in the system, thereby improving overall power quality.

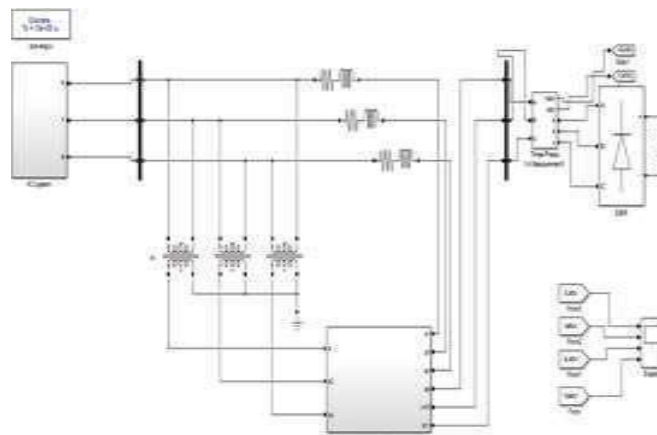


Fig. 6 shows the fuzzy logic–based simulation model with filter implementation.

5. SIMULATION RESULTS

A three-phase, four-wire UPQC system is connected to a 415 V, 50 Hz three-phase four-wire distribution network having nominal line parameters. The system supplies both linear and non-linear loads. The linear load consists of an RL combination, while the non-linear load is modeled using a three-phase diode bridge rectifier (DBR) feeding an RL load. The entire system configuration is developed in the MATLAB/Simulink environment, and the performance of the UPQC is assessed based on its ability to mitigate voltage and current harmonics under various operating conditions.

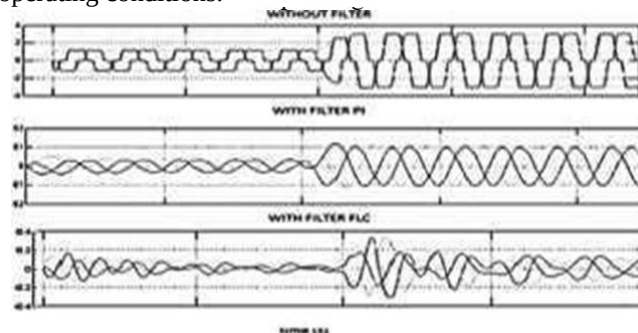


Fig.7:(a) Three Phase Load Current

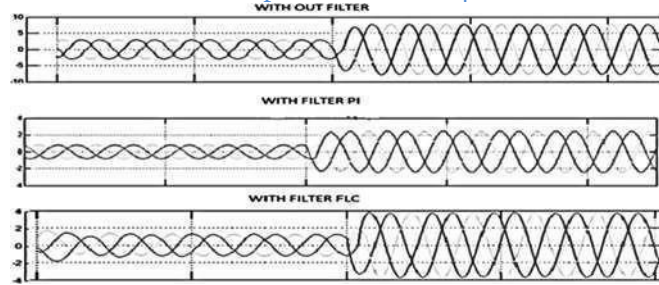


Fig.7:(b) Three Phase Source Current

Fig. 7(a) and Fig. 7(b) present the three-phase load current and three-phase source current waveforms, respectively. These results demonstrate the improvement in current waveform quality after compensation.

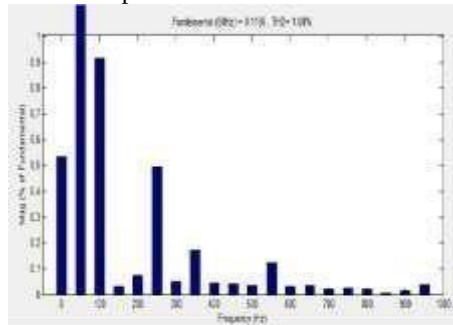


Fig.8(a) THD of load current in with Fuzzy controller based UPQC

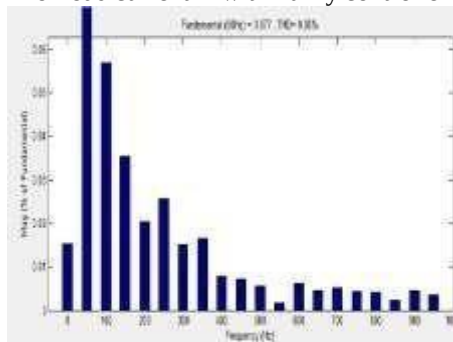


Fig.8(b) THD of source current in with Fuzzy controller based UPQC

Fig. 8(a) illustrates the total harmonic distortion (THD) of the load current when the UPQC operates under fuzzy logic control, while Fig. 8(b) shows the corresponding THD of the source current. The obtained results confirm that the fuzzy controller-based UPQC effectively reduces harmonic distortion and enhances power quality compared to conventional control techniques.

6. CONCLUSIONS

The simulation of non-linear load with iUPQC is successfully accomplished using PI Controller and Fuzzy Logic Controller. The Fuzzy logic controller gives better response with THD of 1.08% in the PI controller compared to THD of 4.88% in the case of PI controller and also the THD of 24.00% without controller in the load current. Work and extend using in the future analysis another controller can be used such as Neuro-Fuzzy for better performance.

7. REFERENCES

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