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Comparative Analysis of Power Quality Enhancement of Distribution System using Unified Power Quality Conditioner

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Abstract - *The increased use of nonlinear electronic loads is the primary driver behind the focus on the quality of electric power. The utilities are finding it difficult to deal with the different power quality challenges such as voltage swell, sag, interruptions, harmonic current, and voltage harmonics. Many issues are brought on by current harmonics, including an increase in power system losses, conductor overheating, a burden of reactive power, relay malfunctions, and low power factor. The burden of ensuring power quality is therefore constantly enormous. Electric companies and end users are now concentrating on the quality of electricity. The economic benefit is the main driver behind concentrating on electrical power quality. The use of custom power devices is taken into account to protect such delicate loads. The quality and dependability of the power given to clients are improved through custom power. Low harmonic distortion, a reduction in supply voltage flicker, and a decrease in voltage sag and swell are all effects of improved power quality. Thus, in this paper, Unified Power Quality Conditioner, widely known as UPQC is modeled and analyzed through various control strategies to mitigate the power quality issues of a 16-bus distribution System and the results have been compared accordingly.*

Key Words: **Power Quality, Voltage Sag, Harmonics, UPQC, PI Controller, Neural Network, ANFIS**

1. INTRODUCTION

The power system is constantly evolving and poses various challenges for electrical engineers, particularly in terms of power quality. With the increasing use of sensitive equipment and non-linear loads, voltage sag and harmonics have emerged as the most significant power quality issues, which are influenced by loads and switching circuits. In response to these challenges, active power filters have been developed and widely adopted as means to compensate for current- and voltage-based distortions. The Unified Power Quality Conditioner (UPQC) is a particularly advanced solution that combines both shunt and series APFs to mitigate power quality issues. By addressing both current and voltage distortions, UPQC offers a comprehensive solution for end-users seeking to improve power quality and ensures the stable operation of their electrical systems.

The main objective of this paper is to analyze the Unified Power Quality Conditioner (UPQC) for improving power quality in the 16-bus distribution system proposed by S. Civanlar, using different types of controllers such as PI, Neural Network, and ANFIS. The modeling of the UPQC has been carried out and the outputs obtained from the various controllers have been compared. [1]

2. UNIFIED POWER QUALITY CONDITIONER (UPQC)

The power system has been improved by integrating the Unified Power Quality Conditioner (UPQC), which provides fast and efficient compensation of both active and reactive power. As a hybrid Active Power Filter (APF), UPQC is a versatile device capable of mitigating multiple power quality issues related to both voltage and current simultaneously

UPQC = Series APF + Shunt APF

The Unified Power Quality Conditioner (UPQC) is a combination of shunt and series Active Power Filters (APFs) that can simultaneously mitigate voltage distortions on the supply side and current harmonics on the load side. As a result, it can provide pure sinusoidal voltage and current at both the supply and load ends

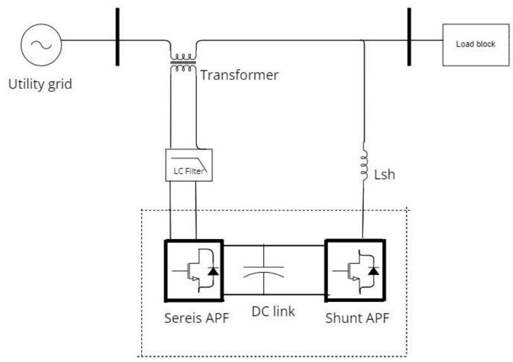

Fig.1: Block Diagram of UPQC

Apart from the series APF and shunt APF, the other components of UPQC are: -

- DC link: The charge-storing capacitor can be used as a common DC link that supplies the DC voltage.
- LC filter: The high switching ripples generated by the series active filter are minimized by the low-

pass LC filter. The LC filter acts as the low-pass filter.

- Lsh Filter: The ripples generated during switching mode are minimized by the high-pass Lsh filter.
- Injection transformer: The series injection transformer is used for voltage injection to the power system.

2.1 Series Control Strategy

In a transmission line, series APF is generally connected in series. The series Active Power Filter is a voltage source inverter connected in series with the transmission line through a transformer named as an injection transformer. The series control strategy is a method used to address and mitigate problems caused by voltage distortions and imbalances. It involves injecting a compensating voltage to regulate and balance the load voltage. The series control strategy involves comparing the source voltage (VS) and load voltage (VL) to determine the necessary feedback voltage. A PLL is used to maintain the system frequency consistency. The feedback voltage's magnitude and phase are then determined, and a reference voltage (Va, Vb, Vc) is calculated. The compensating voltage is then injected back into the system using an insertion transformer. By the use of PWM (Pulse Width Modulation) technology, series inverters are controlled. It functions as a generator of regulated voltage. It is capable of compensating for voltage imbalances, regulating the voltage at the utility consumer point of common coupling (PCC).

2.2 Shunt Control Strategy

In transmission lines, shunt Active Power Filters (APFs) are typically connected in parallel to compensate for distortions and harmonics caused by the flow of current. These harmonics are often produced by non-linear loads, and shunt APFs are used to keep the source current completely sinusoidal and free from distortion. The shunt control strategy utilizes both the source voltage (VS) and load current (IL) to calculate active power (P) and reactive power (Q). To convert the 3-phase source voltage (VS) into 2-phase values (Vα and Vβ), Clark's transformation technique is applied.

$$\begin{bmatrix} V0 \\ V\alpha \\ V\beta \end{bmatrix} = \left(\frac{\sqrt{2}}{\sqrt{3}}\right) \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \text{.......... (1)}$$

Using PQ theory, the reference current (Iα, Iβ) can be calculated in αβ coordinates.

$$\begin{bmatrix} I0 \\ I\alpha \\ I\beta \end{bmatrix} = \left(\frac{\sqrt{2}}{\sqrt{3}}\right) \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \text{.......... (2)}$$

The load side instantaneous real and imaginary power components can be calculated using load currents and phase-neutral voltages as follows:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix} \begin{bmatrix} I\alpha \\ I\beta \end{bmatrix} \text{.......... (3)}$$

The load side instantaneous real and imaginary powers comprise both AC and DC components. The DC components of power (p) and reactive power (q) are made up of the positive sequence components ($\overline{p}$and$\overline{q}$) of the load current. The AC components of active power ($\tilde{p}$) and reactive power ($\tilde{q}$) comprise harmonic and negative sequence components of the load currents.

$$p0 = V0 * I0 \text{ .... (4)}$$

A PI controller compares the reference voltage with the voltage flowing across the capacitor and outputs the power lost proportionally to the error produced by comparing the two.

$$\begin{bmatrix} Is\alpha * \\ Is\beta * \end{bmatrix} = \frac{1}{V\alpha^2 + V\beta^2} \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + ploss + p0 \\ -q \end{bmatrix} \text{..(5)}$$

Where the reference currents are in αβ coordinates. The reference current is then transformed back into abc coordinates using inverse Clark's transformation.

$$\begin{bmatrix} Ia * \\ Ib * \\ Ic * \end{bmatrix} = \left(\frac{\sqrt{2}}{\sqrt{3}}\right) \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Is\alpha * \\ Is\beta * \end{bmatrix} \text{.......... (6)}$$

The reference current (Ia*, Ib*, Ic*) is compared with the current flowing through the shunt controller, and the output is passed through a hysteresis controller to generate gate pulse signals for the IGBTs within the shunt inverter. This produces a harmonic-free current.

3. CONTROLLERS USED

3.1 PI Controller

The PI controller is a commonly used feedback mechanism in various industrial control systems and other applications. It employs two parameters: the Proportional (P) and the Integral (I) parameters. The P parameter governs the controller's response to the current error, whereas the I parameter determines the response based on the accumulation of past errors. This dual approach allows the controller to provide a stable and accurate response to dynamic changes in the system. Mathematically, the PI controller can be expressed as an equation in the following form:

$$Y(t) = Kp.e(t) + Ki.\int_0^t e(t)$$

The output of the PI controller represented as Y (t), can be calculated using an equation that takes into account the proportional gain Kp, integral gain Ki, and the input voltage error value e (t).

The main objective of the PI controller is to maintain the DC-link voltage at a specified reference value. To achieve this, the DC-link capacitor must be supplied with a certain amount of real power, which is proportional to the difference between the actual voltage and the reference voltage. By controlling this power flow, the PI controller helps to regulate the DC-link voltage and ensure the stable operation of the system.

The power that is needed by the DC-link capacitor can be mathematically expressed as follows:

$$Ploss = Kp(Vref - Vactual) + Ki\int_0^t (Vref - Vactual)\,dt$$

When the proportional gain (Kp) and integral gain (Ki) values are set to be large, the regulation of the DC-bus voltage becomes dominant and the steady-state DC-bus voltage error is low. Conversely, when Kp and Ki are small, the effect of real power unbalance on transient performance is negligible. Therefore, selecting appropriate Kp and Ki values is crucial in achieving satisfactory control performance and ensuring that the required power is supplied to the capacitor.

In the initial approach to setting Kp and Ki values, a trial and error method is typically used. This involves selecting initial values for Kp and Ki and then observing the system's response. Based on the observed behaviour, the values are adjusted iteratively until the desired performance is achieved.

3.2 ANN Controller

Artificial Neural networks are mathematical models designed to process information and make predictions based on that information. While these are inspired by the structure and function of biological neural networks, they are not exact replicas.

An Artificial Neural Network (ANN) is a group of simple, interconnected processing elements that can learn and adapt. In a neural network, the individual neurons receive inputs from other neurons, or from the outside world, and then process that input before sending an output signal to other neurons in the network. The weights assigned to each input determine the strength of its influence on the neuron's output. The activation function in a neural network is responsible for calculating the neuron's output based on the sum of the weighted inputs and a threshold value. This function plays a critical role in determining the network's performance and can have a significant impact on the accuracy of its predictions.

ANNs are identified by their structure, the way they interact with their surroundings, their training approach, and their information processing capacity. Due to their user-friendliness, dependability, and fault tolerance, ANNs have become a feasible means of control. Neural controllers, which share the goal of upgrading hard controllers with intelligent ones to enhance control quality, are often used as an alternative to fuzzy controllers.

A feed-forward neural network functions as a generator of a compensation signal, with the output of the compensator being determined by the input and its progression over time. The neural network is trained to produce fundamental reference currents, which are then compared to obtain switching signals in a hysteresis band current controller.

3.3 ANFIS Controller

ANFIS stands for Adaptive Neuro-Fuzzy Inference System, which is a type of artificial neural network that integrates the strengths of both neural networks and fuzzy logic. ANFIS was developed by Jang in 1993 as a means of modelling complex systems that are difficult to describe mathematically.

ANFIS networks use a set of rules that combine fuzzy logic with neural network training techniques to generate an output. These rules consist of fuzzy if-then statements that define the relationship between the inputs and outputs of the system. The ANFIS network uses these rules to generate a set of membership functions that describe the input-output relationship.

These membership functions are then used to generate a set of parameters that are optimized using a neural network training algorithm. This algorithm adjusts the membership functions and their parameters to minimize the error between the network output and the desired output.

ANFIS networks have been applied in a variety of applications, including control systems, forecasting, data classification, and image processing. They are especially useful when the underlying system is complex and difficult to model mathematically, but there is enough data available to train the ANFIS network.

4. MODELLING AND SIMULATION

4.1 Modelling of 16 Bus distribution test system

This section illustrates the process of modeling and implementing the 16-bus test system. The IEEE 16-bus distribution system was originally proposed by S. Civnlar [1]. Below is the single-line diagram of the system and the corresponding bus data.

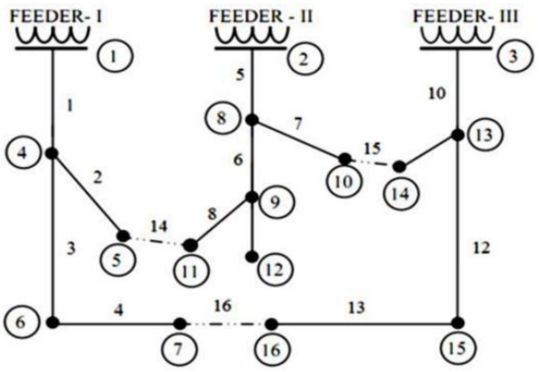

Fig. 2: 16 Bus Distribution System Single Line Diagram

Line No	From Bus i	To Bus j	R(ohms) P.U	X(ohms) P.U	End Bus Load	
					P	Q
1	1	4	0.075	0.10	2.0	1.6
3	4	5	0.08	0.11	3.0	0.4
2	4	6	0.09	0.18	2.0	-0.4
5	6	7	0.04	0.04	1.5	1.2
7	2	8	0.11	0.11	4.0	2.7
8	8	9	0.08	0.11	5.0	1.8
9	8	10	0.11	0.11	1.0	0.9
6	9	11	0.11	0.11	0.6	-0.5
10	9	12	0.08	0.11	4.5	-1.7
15	3	13	0.11	0.11	1.0	0.9
14	13	14	0.09	0.12	1.0	-1.1
16	13	15	0.08	0.11	1.0	0.9
12	15	16	0.04	0.04	2.1	-0.8
4	5	11	0.04	0.04		
13	10	14	0.04	0.04		
11	7	16	0.12	0.12		

Table 1: Bus Data of 16 Bus Distribution System

4.2 Modelling of UPQC

The study assesses a simplified control algorithm for UPQC by analyzing simulation outcomes from SIMULINK. The table below presents the parameters of the simulated UPQC system proposed by the study.

System Parameters		
Supply Voltage	Vabc	23KV
Supply frequency	fs	50Hz
DC Link Voltage	Vdc	700V

Table 2: UPQC Parameters

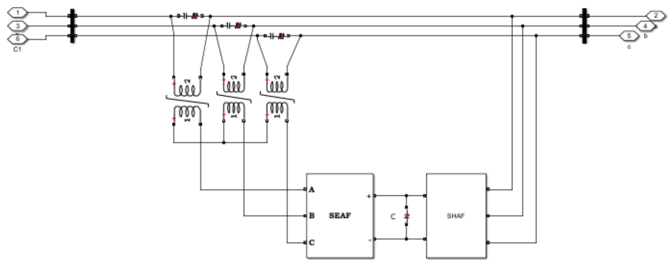

Fig. 3: UPQC Simulation Diagram

4.3 Modelling of Series Active Filter

The series active filter was modelled as described in the series control.

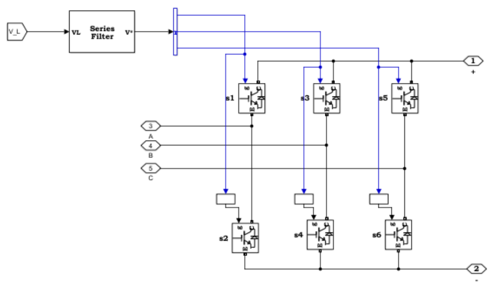

Fig. 4: SEAF Simulation Diagram

4.4 Modelling of Shunt Active Filter

For modeling of shunt active filter, the direct voltage error manipulation approach of the DC link is used. For error calculation between DC link actual value and reference value, the PI controller is used and the Ploss calculated by the controller is fed into compensating current calculation block where compensating current is calculated by means of formulae written according to PQ theory. The reference current generated is fed into the hysteresis band controller to generate gating pulse for 3phase current source inverter and the resulting current is fed using a coupling inductor.

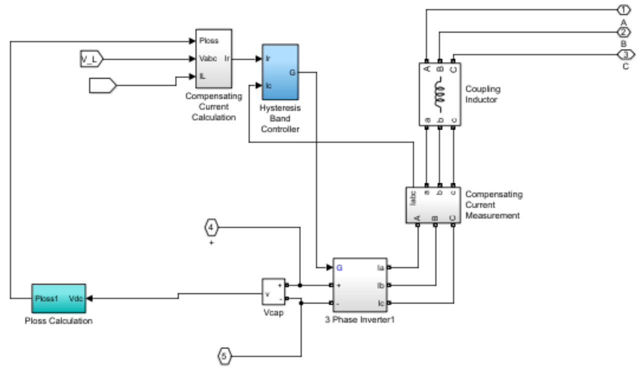

Fig. 5: SHAF Simulation Diagram

4.5 Modelling of PI Controller

Traditionally, a PI controller is used to regulate the DC link voltage in the Unified Power Quality Conditioner (UPQC). However, the effectiveness of this controller depends on system parameters. The controller's output is then directed to the shunt inverter's current control system to ensure that the required amount of active power is drawn from the grid to maintain the DC capacitor voltage. To achieve optimal performance of the UPQC under dynamic power system conditions, such as voltage fluctuations, load changes, and unbalanced loads, the DC link voltage control response needs to be rapid with minimal delay time and lower overshoot. In the simulation, the Kp and Ki values used for the controller are 10 and 0.1, respectively. [7]

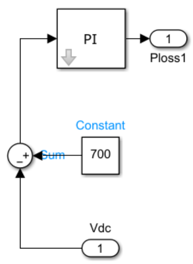

Fig. 6: PI Controller Simulation Diagram

4.6 Modelling of ANN Controller

Neural network training was initiated using the fitting app. Input data and output data were mapped and 10 neurons were selected to train using the Levenberg-Marquardt training algorithm. The function-fitting neural network is generated and deployed in the model.

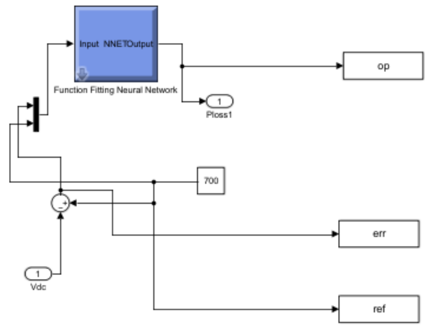

Fig. 7: ANN Controller Simulation Diagram

4.7 Modelling of ANFIS Controller

The input-output data from the PI controller was imported to the neuro-fuzzy designer and the fuzzy file was generated using the grid partition method. The generated fuzzy was optimized using the hybrid method and the number of iterations was selected and the ANFIS model was trained. With each iteration, the error value was optimized. The generated .fiz file is implemented in a fuzzy logic controller and deployed in the model.

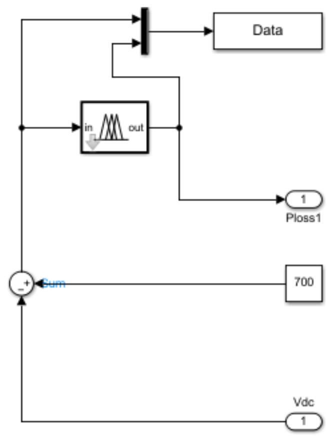

Fig. 8: ANFIS Controller Simulation Diagram

5. RESULTS AND ANALYSIS

The 16-bus distribution system is modeled in MATLAB SIMULINK software and the power quality is conditioned by using UPQC at the 16th Bus, with various controllers like PI controller, ANN controller, and ANFIS controller and the outputs have been compared.

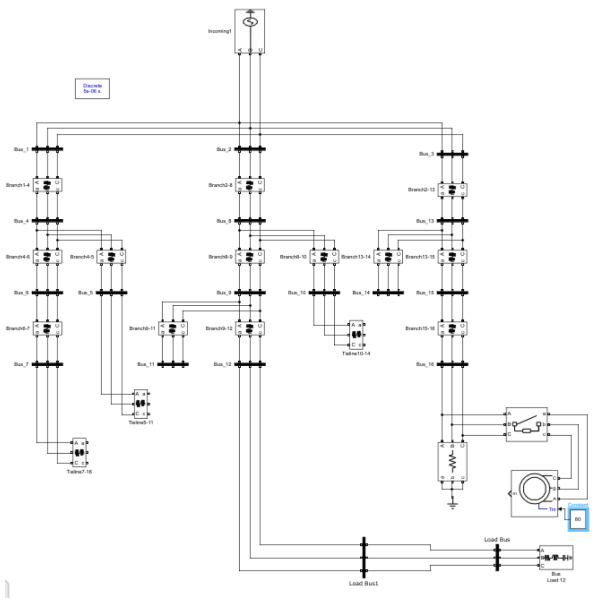

Fig. 9: Simulation for 16 bus distribution system

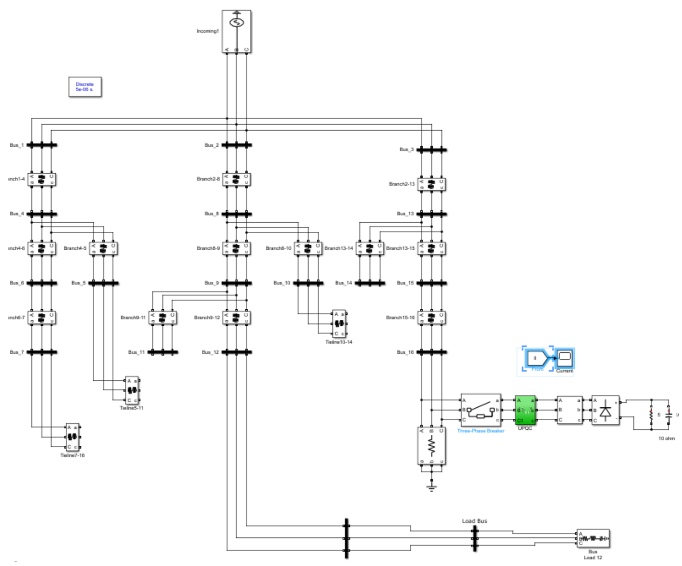

Fig. 12: Simulation for 16 bus distribution system with Non-Linear Load

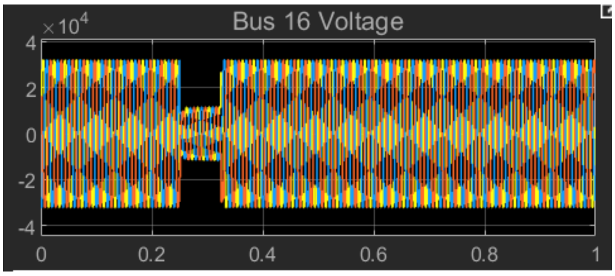

Fig. 10: Bus 16 Voltage waveform without UPQC

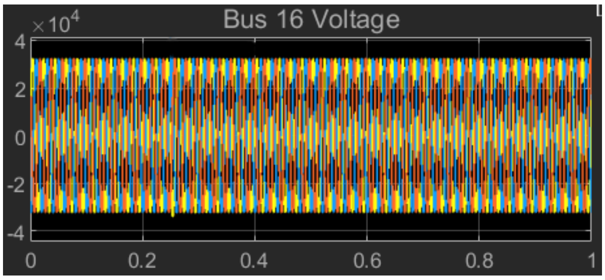

Fig. 11: Bus 16 Voltage waveform with UPQC

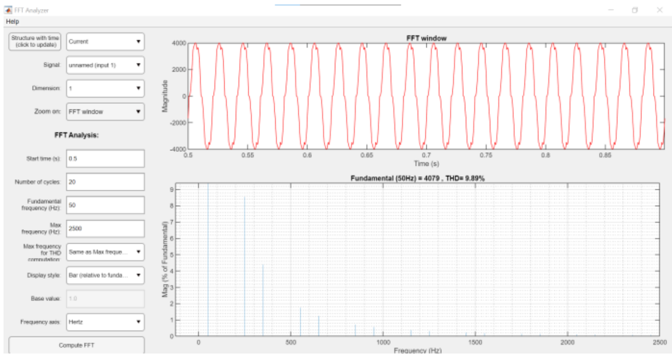

Fig. 13: Load current waveform without UPQC

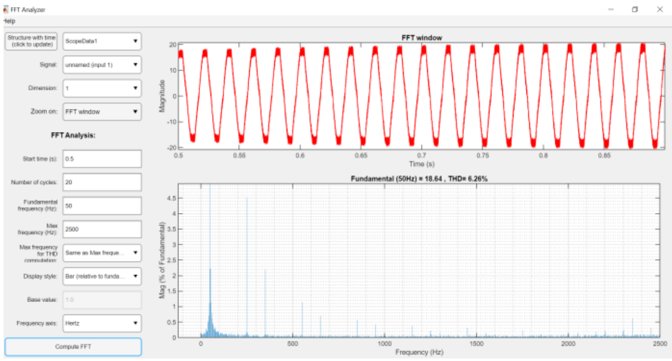

Fig 14: THD of Load current with PI UPQC

To calculate total harmonic distortion (THD), a 16-bus system was modeled with a nonlinear load consisting of a diode rectifier and RC load. The load's resistance (R) was set to 10 ohms, and its capacitance (C) was set to 500 microfarads. The results of the FFT analysis are shown below.

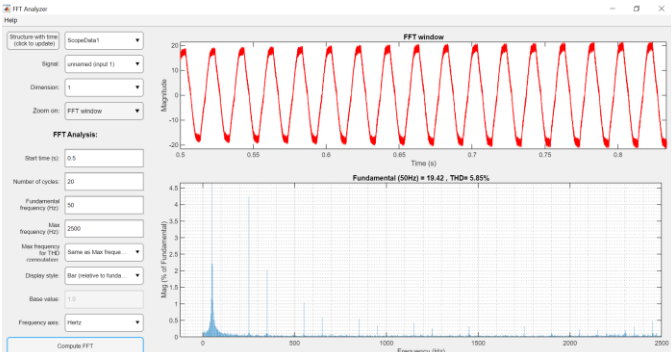

Fig. 15: THD of load current using ANN UPQC

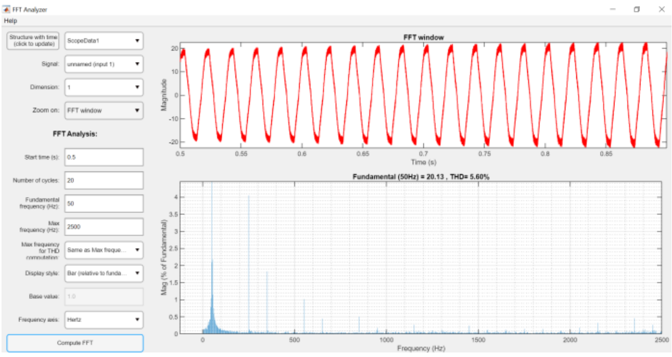

Fig. 16: THD of load current using ANFIS UPQC

THD Comparison of Load Current(fmax=2500Hz)			
Without UPQC	PI Controller	ANN Controller	ANFIS Controller
9.89%	6.26%	5.85%	5.56%

Table 3: Load Current THD

THD Comparison of Load Voltage(fmax=2500Hz)			
Without UPQC	PI Controller	ANN Controller	ANFIS Controller
29.25	1.76%	1.70%	1.69%

Table 4: Load Voltage THD

6. CONCLUSION

The Unified Power Quality Conditioner (UPQC) is a device that can effectively address a variety of power quality issues, including voltage fluctuations and harmonics, reactive power problems, and poor power factors. This study focuses on the necessary system configuration and control topology for the UPQC, as well as a proposed control technique utilizing PI, ANN, and ANFIS controllers individually. Experimental results demonstrate that both ANN and ANFIS controller exhibit similar levels of total harmonic distortion (THD), but the ANFIS-based UPQC displays better dynamic response and fast learning and achieves a THD that is 11% lower than that of the PI controller.

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