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Application of ANFIS Controlled Unified Power Quality Conditioner in Distribution Network for Power Quality Improvement

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Abstract- — The study examines power quality improvement in Rumuomoi distribution network addressing issues such as harmonic distortion and voltage sags which degrade system efficiency and affect sensitive loads by implementing an Adaptive Neuro-fuzzy Inference System (ANFIS)-controlled Unified Power Quality Conditioner (UPQC). The challenge (harmonic distortion and voltage sag) arise due to the increasing penetration of nonlinear loads, such as variable frequency drives, rectifiers, and industrial machinery, which introduce significant current and voltage harmonics into the distribution network, leading to excessive Total Harmonic Distortion (THD), voltage instability, and inefficient power distribution. Conventional PID controllers often exhibit limitations in dynamic compensation, adaptability, and optimal performance under varying load conditions, necessitating an intelligent control approach that can effectively mitigate power quality disturbances in real-time. Fast Fourier Transformation analysis in MATLAB/Simulink software was used to evaluate performance of the network before and after UPQC(series APF and shunt APF) installation comparing total harmonic distortion and voltage sag. The result obtained from base case simulation shows that the nonlinear load injected harmonic distortion at PCC (point common coupling) that violates the statutory limit of 5% IHD (individual harmonic distortion) and 8% VTHD (voltage total harmonic distortion) according to IEEE 519-2022 standard for low and medium voltage system. The highest harmonic current distortion consists of 5th order resulting to a total harmonic distortion of 12.59%. However, the performance of the ANFIS-controlled UPQC demonstrates significant improvements, with a reduction of total harmonic distortion from 12.59% to 0.15% which is below 5% ensuring compliance with IEEE 519 harmonic standards. Furthermore, the ANFIS-controlled UPQC effectively mitigates voltage sag conditions, restoring voltage deviations within ±5% of nominal values, which is critical for ensuring the stability and reliability of sensitive electrical loads. The practical implications of this study highlight the feasibility of deploying ANFIS-controlled UPQC in distribution networks to achieve IEEE 519 power quality standards, ensuring efficient, reliable, and high-quality power delivery for industrial, commercial, and residential applications.

Keywords: Artificial Neural Inference System; Active Power Filter; Distribution Network; Rumuomoi Substation .

I. INTRODUCTION

Electricity is an integral aspect of daily living in most industrialised nations. In every home, business, and factory, among many other places, it is utilised for living, working, and travelling. The majority of the tremendous growth in the number of electrical devices linked to the power system over the past century has occurred in the last twenty to twenty-five years (Gbadamosi et al., 2022). Despite the proliferation of connected devices, the overall demand for power has grown at a slower rate. New devices and those that have been replaced are using more power-efficient equipment, which is the reason behind this. Although the electricity infrastructure has been expanded to accommodate the higher usage, it was constructed at the outset of the growth in many locations. Naturally, there is a great deal of diversity across nations, and there are also variations for various voltage levels. Also dating back to this time are the large electrical hydro generating plants. Afterwards, nuclear power stations were built. Renewable energy sources, such as solar power and wind turbines, are becoming increasingly commonplace these days.

The new topic of "Power Quality" has been presented with the excellent intention of introducing new approaches to achieve higher performance, control and transmit more power over the power system, and reduce load power consumption. To regulate the load current, these modern methods make use of non-linear components. As a result, the current is no longer a perfect sinusoidal waveform but rather exhibits distortion in the form of harmonic and inter-harmonic currents. Compared to traditional linear loads, several of these modern technologies place a higher premium on voltage quality (Hugo & Aurelio, 2014). Power quality is the reliability, ideality, and nonvariability of the energy that consumers receive from the power grid. There are multiple types of power quality issues. Initially, all that was required was access to a reliable electrical source with a controlled voltage and frequency. In addition to harmonic distortion, short-term transients, imbalances, interruptions, and flickers, consumers are becoming more conscious of the issue as electrical devices become more sensitive. When power systems were more conservatively designed, harmonic distortion was far lower. However, harmonic distortion has also grown in recent years due to the industry's reliance on intricate designs.

Recently, the term "Power Quality" has been bandied around a lot; it encompasses anything that goes wrong with the system when it's not running as it should. While power quality is important, differentiating between voltage and current quality is more accurate. Research on efficient methods for detecting, classifying, and identifying power quality disturbances is a top priority for those working to create effective Power Quality (PQ) monitoring systems. Estimating harmonic parameters for fundamental harmonics, inter-harmonics, and sub-harmonic components of voltage and current signals is another important and difficult issue that researchers have lately highlighted as being relevant to power quality. An essential challenge for monitoring and study of power quality concerns is the accurate and effective calculation of harmonics from distorted voltage signals (Lee et al., 2015).

Due to their efficacy, power electronics-based products have recently become the preferred choice of sectors. While these devices based on power electronics provide many benefits for the electrical and electronics industries, they also cause harmonics to be generated and injected into the power business. The main cause of the harms linked with power quality are electrical disturbances, which include these harmonics. Additional power losses in electrical equipment, malfunctioning safety devices, inaccurate meter readings, and disruptions to communication connections are the primary issues caused by harmonics. In light of this, it is critical to reduce harmonics and enhance power quality.

The singular value decomposition (SVD), Fast Fourier transform (FFT), and least square methodology were all investigated by Goh et al. (2016) as methods for estimating power system harmonics. Disruptions caused by harmonics in the power system lower reliability, increase energy losses, and degrade the quality of the energy supplied to the load. Finding the best approximation of a distorted and noisy waveform required them to examine the methods. Simulations were conducted in MATLAB using the same signal to examine the efficacy of the aforementioned strategies. Mathematical models for estimating power signal harmonics were examined. Although each method has its advantages, the results demonstrate that the singular value decomposition technique outperforms the others by a significant margin when it comes to estimating harmonics in power signals. The development of high performance filters to mitigate harmonics and minimise system transients is crucial due to the stringent constraints on harmonic current distortion and disruption of aircraft electric power supply (Singh et al., 2016). The aircraft's electrical power system in both steady-state and transient modes of operation, taking into account passive AC and DC loads that are equal were examined. The study posit that a single harmonic filter is necessary for a standard aircraft electrical system, while two filters, one each at the generator and AC load buses, are necessary for a modern aircraft electrical system.

In non-sinusoidal power systems, Almutairi and Hadjiloucas (2019) proposed a new technique for distortion suppression that involves determining the value of the shunt single-tuned passive filter (STPF) compensator using the non-linearity current index (NLCI). The goal is to keep the power factor within the desired limits. At the point of common coupling (PCC), the stated goal of the proposed solution is to reduce the nonlinear current of customer loads in the power system. In addition to meeting the requirements set out by IEEE 18-2012 for capacitor loading, the suggested design also accounts for additional realistic limitations on total voltage and individual harmonic distortion, guaranteeing conformity with (Institute of Electrical and Electronics Engineers) IEEE 519-2014 standards while keeping distortions to a reasonable level.

According to Djoudi et al. (2020), electrical equipment in a low-voltage electrical network can be damaged by harmonics, reactive power, current and voltage imbalance, and voltage dips. Because of the harmful contamination effects it causes - the pollution of distribution networks with current harmonics- the proliferation of nonlinear loads or devices in power systems is a big worry for power system engineers (Samal et al., 2016). By implementing a parallel active power filter (APF) technique in two-wire distribution systems, artificial intelligence (AI) helps to resolve power quality issues. In order to identify current harmonics, the active power filtering procedure suggests using an artificial neural network (ANN). A suitable alpha value (learning rate value) and a modified mathematical algorithm (a modified delta rule weight-updating W-H) define the optimal operation of the filters. The novelty control design is an artificial neural network (ANN) that uses this approach. The created modified ANN is quite good at detecting harmonic components. For mitigation, Lai and Key (2014) simulate an electrical system in a typical building and include two single-phase and three three-phase active and passive harmonic filters. We calculate the voltage and current distortions, and we compare the projected losses in a power system without harmonic current compensation to the estimated cost of these filters. The results demonstrate that the effectiveness of harmonic compensating filters varies with the type of filter and its placement in the building's wiring system.

In 2022, Rodríguez-Pajarón and colleague suggested a realistic way to measure voltage harmonic levels at all locations of residential users' connections in real-time. Because of the scarcity of data, the suggested approach treats low voltage residential networks as though their parameters and topology are unknown. Data collected from a smaller number of power quality monitors and more traditional smart meters that are already in place in the network to measure basic voltage and power are the building blocks of the proposed harmonic estimating approach. Power quality meters with a penetration below 10% have shown to accurately estimate network-wide voltage harmonic levels.

Thakur and Yadav (2020) investigate the modelling of a shunt active power filter (SAPF) that is based on simulation for a distribution system to reduce the amount of harmonic current sent to a nonlinear load. Shunt active power filters are portrayed in the paper as crucial for addressing harmonics issues. Moradi et al. (2021) state that in order to determine harmonic losses and power quality indices, it is crucial to forecast current harmonics in distribution networks. The impact of grid impedance and voltage distortions on grid-connected power converters must be taken into account in order to forecast the current harmonics. System analysis becomes more complicated due to the potential nonlinear effects of these parameters on current harmonics. The effects of grid impedance, background voltage harmonics, and multi-parallel grid-connected converters on current harmonics at a common coupling point are examined in this study.

To lessen harmonics produced by PV panels and other nonlinear loads, Parhamfer et al. (2023) investigated the efficacy of an active filter. We take a look at how harmonics develop in the network and how PV units impact it. To remove harmonics from the network, the PV unit's active filter is used. This method controls the electronic power converter in accordance with the non-linear behaviour of PV units in order to reduce harmonics in the network caused by the non-linear demand. It is on the upgraded IEEE 33-bus system that the suggested method operates.

Shunt active power filters, or SAPFs, are used in utility applications to stabilise systems under transient situations by providing leading or lagging reactive power. The dynamic behaviour of linked power systems is primarily intended to be controlled. Using a neural network controller in conjunction with SAPF improves power quality. Each leg of the voltage source converter of the SAPF is controlled by a neural network, which can handle both linear and nonlinear loads (Narmadha et al., 2023). One potential solution to the power quality problems that arise in distribution systems when dealing with non-linear loads is the Distribution Static Compensator (DSTATCOM) that uses an LCL filter topology. A two-level voltage source inverter (VSI) and an LCL filter were used to provide the necessary voltage support for the VSI in order to complete the task. The DSTATCOM was designed to operate efficiently and economically by applying the principle of instantaneous reactive power. The hysteresis current controller (HCC) is used to generate pulses for the voltage source indicator (VSI), and the PI controller is used to maintain a steady DC connection voltage (Palla, 2016).

Using an IEEE model for simulations, we analysed losses in a low voltage distribution system caused by harmonic components. Three separate situations were considered in the analyses, each with its own unique set of load curves derived via fuzzy logic. Losses were shown to be greater in the third scenario. Also, while looking at the losses hourly and taking the average of all the cases into account, it was discovered that the losses are much higher during periods of higher consumption, as indicated by the load curves. According to the findings, the losses that matter most to the system are the ones of the third order harmonic, whilst the losses of really high orders in proportion are unimportant.

In addition, it was confirmed that, for this system, harmonic technical losses account for approximately 19.6% of the total technical losses (Soares et al., 2021). In accordance with IEEE standard 519-1992, Kulkani et al. (2019) examined harmonics and power quality indices in a power distribution network. The purpose of the study is to determine which levels of power quality require monitoring in order to identify the remedies that should be put into place. For several types of non-linear consumers, the indices are examined in the Indian distribution network. Managing the grid's voltage and current fluctuations when linked to the low voltage distribution network is the primary concern with power factors. Keeping total harmonic distortion (THD) and harmonics below 10% is possible with a number of network-level active solutions (Bijwar & Zambre, 2018). A three-phase universal power quality conditioner (UPQC) was analysed by Hassan et al. (2019) for its design and performance.

Two consecutive The UPQC model is constructed by connecting a series compensator and a shunt compensator via a shared DC-bus. When the grid voltage dips or spikes, the series compensator steps in to make up the difference. When the voltage is sag or swell, the series compensator either injects the corrected voltage in phase with the point of common coupling (PCC) or injects it out of phase with this point. Using the shunt compensator, the harmonics in the load current are mitigated. Using MATLAB-Simulink, we examine the steady-state and dynamic performance of the developed model subjected to various disturbances, including PCC voltage harmonics, voltage drops or spikes, and load unbalance caused by a nonlinear load. A unified power quality conditioner (UPQC) is described by Bhosale & Bhosale (2018) as a means to eradicate power quality problems. The DC-link of UPQC incorporates a photovoltaic (PV) panel with a boost converter. A boost converter is used to get the most power out of a PV panel. A shunt and a series inverter work together to form the UPQC. The series inverter gets rid of voltage-related power quality issues like flicker, swell, and sag. In UPQC, the shunt inverter is utilised to eradicate issues connected to current, such as current harmonics. This means the UPQC can handle both voltage and current issues simultaneously.

One major issue that requires fixing is the high harmonic content of PV systems, despite the fact that they are one of the most popular forms of clean energy (Alhafadhi et al., 2020). A novel approach to reducing THD via adaptive predictive filtering is suggested by them. The suggested method uses a single one-step THD reduction approach rather than utilising several THD reduction strategies at different phases of the PV system from input to output. By applying the LMS, NLMS, and LLMS algorithms to a single-phase standalone PV model, we can assess the method's efficacy. In all algorithms tested, the simulation results showed that the suggested strategy successfully reduced PV system THD by over 70%. The sensitivity analysis also shows that the filter length and step size are the two most important parameters for THD reduction efficacy. To reduce harmonic voltage, Park et al. (2021) integrated motor drives for a roughing mill (RM) and a finishing mill (FM) into a single power system. Flickering, voltage distortion, and other power quality issues can occur when dealing with non-linear, large-capacity changing loads, such as AC/DC converter type RM drives. To some extent, the voltage drop can be mitigated by employing a power capacitor bank with the appropriate capacity. Also, according to IEEE Std., the voltage distortion can be adjusted. 519 with the help of the motor drive load's distinctive harmonics-matching passive harmonic filter. As long as the reactive power supply is suitable, the passive harmonic filter can reduce harmonic distortion and offer a cost-effective solution. The use of a solar fed shunt power quality conditioner to enhance power quality was investigated by Mishra and Ray (2015). The device's primary function is to reduce reactive and harmonic power. Solar panels not only offset some of the active power consumption of a load when the sun isn't shining, but they also reduce voltage stress on the traditional power grid. The capability of the developed PVSAF in fulfilling the recommended harmonic standard limitations set by IEEE-519 has been confirmed, together with its viability and efficacy.

The capacity of the electrical network or grid to provide a consistent and clean supply of electricity is known as power quality. Many power quality difficulties arise from the proliferation of electronic equipment, which in turn causes an increase in electric power consumption and nonlinear loads on the power system. A rise in loss and heat, as well as an overload of the power system, are consequences of poor power quality (Sulaiman et al., 2019). A novel idea for making the most of a unified power quality conditioner (UPQC) was put out by Rakate and Shendge (2019). By coordinating with the shunt inverter, the UPQC series inverter may compensate for voltage drops or spikes and share reactive power from the load all at once. The two inverters' reactive power is coordinated using the active power control method, which is utilised to adjust for voltage sags or swells and is integrated with the theory of power angle control (PAC) of UPQC. This idea is called UPQC because the series inverter supplies reactive and active powers at the same time. In a transmission or distribution system, UPQC simultaneously correct for voltage and current power quality concerns while maintaining acceptable power quality indices (Jadhav et al., 2019). The two APFs in a UPQC configuration - a series and a shunt - are connected in series and operate independently; nevertheless, they share a DC link voltage. Eliminating issues with current, improving power factor, and regulating DC link voltage are the primary benefits of the shunt active filter. However, by functioning as a controlled voltage source, the series APF aids in the rectification of voltage-related issues. The input voltage plus the voltage injected by the series inverter create a sinusoidal load voltage, which is the outcome of a control law that the series Active Power filter is programmed to follow (Habib et al., 2020).

The increasing need for clean energy on a worldwide scale, along with the relative ease of access to RES, is driving its attractiveness. A model for planning the expansion of generation and transmission that incorporates large-scale RES and takes harmonic emissions restrictions into account was provided by Gbadamosi et al. (2022). This method minimises total costs, active power loss, and harmonic power loss by combining the multi-objective optimisation issues using a weighted sum approach. The harmonic emissions from the RES components were estimated and quantified using an analytical technique. Algebraic modelling language was used to tackle the proposed AC mixed-integer non-linear optimisation issue. The 48-bus power system in Nigeria and the non-distorted Garver's test bus system are used to show the suggested paradigm. Finding the optimal strategy to reduce harmonic emissions from grid-integrated RES is possible with the help of the sensitivity analysis results.

Lee et al. (2015) introduced a hybrid active filter to suppress harmonic resonance and reduce harmonic distortion in industrial power systems. This is because tuned passive filters and line inductances can cause unintended series and/or parallel resonances, which can lead to severe harmonic distortion. In order to minimise harmonic distortion to an acceptable level in reaction to changes in the load or variations in the power system's parameters, the suggested hybrid filter is operated as a variable harmonic conductance based on the voltage total harmonic distortion. To manage power network voltage harmonic distortion, Sabuncu and Yildiz (2019) put up a solution. A correct solution to real-world problems, bearing in mind the specific harmonic distortion pattern and design of the relevant power system, formed the basis for the creation of the proposed solution concept. An examination of feasibility and sensitivity is used to ascertain the position of the SHAPLCs (single-harmonic active power line conditioners) for each harmonic h that is of interest. The FFT-ADALINE technique, developed by Goh et al. (2016), is a hybrid fast Fourier transform adaptive linear element algorithm that can quickly and accurately estimate harmonics. The fast Fourier transform (FFT) transforms the time domain to the frequency domain, but because it uses a buffer, it is unable to react instantly to changes in the observed harmonics. The ADALINE's learning capability gives it better immediate response capabilities, but it takes about two measurement signal cycles for it to settle. The suggested approach combines the two algorithms for harmonic estimating in such a way that it reacts instantly to changes in the observed harmonics and reduces the settling time to half the measurement signal's cycle.

One way to reduce harmonics, according to Soomro and Almelian (2015), is to use a passive filter. This eliminates the need for a capacitor to supply additional kVAr. The design and implementation of passive filters have been extensively studied because of these two appealing properties. In order to reduce power frequency harmonics, this study aims to optimise the design of a single tuned passive filter. The Lagrange interpolation approach was used to determine the best values for the filter's parameters. This filter works as expected, according to the findings produced by MATLAB's simulation.

The Unified Power Flow Conditioner (UPFC) was used by Rajasekhar and Babu (2016) to reduce harmonics. DPFC makes use of the distributed idea, which involves dividing a three-phase series converter into multiple single-phase series dispersed converters along a line and doing away with the common dc-link between the shunt and series converters. Harmonics, voltage sag, and swell are the most significant power quality issues, according to the increasing demand for electricity and the amount of non-linear loads in power grids. The voltage variation and power quality can be improved with the use of DPFC. In the MATLAB/Simulink environment, the simulations are executed. The simulation findings that were provided here prove that the DPFC may really enhance power quality.

A model for lowering harmonic in power systems by means of shunt active power filters was devised by Mukherjee et al. (2014). A dc link capacitor, a PI controller, and a filter hysteresis current control loop make up the suggested model. Hysteresis current controller approaches generate the filter's switching signals. All of these components work together to lower THD in shunt active power filters. A balanced non-linear load is employed by the suggested shunt active filter model. This method effectively compensates for current harmonics and reduces the THD to levels within IEEE standards. The model, which was created in MATLAB/SIMULINK, effectively decreases the source current's harmonic. Active power filters were investigated by Prasad and Sudhakar (2015) in relation to their effects on single-phase systems and their function in reducing harmonic distortion. In contrast to passive filters, which require n units to moderate n order harmonics, active power filters isolate the harmonic from the fundamental component, thereby mitigating the entire order of harmonics. According to their theory, engineers may encounter challenges when trying to implement active power filter operations because of the complexity of the control strategies and compensating current generation techniques involved. When it comes to series active power filters (APFs), Nayak and Shaw (2017) suggested using the hysteresis control technique to enhance power quality. In this work, a series active power filter model and its control technique using a hysteresis pulse width modulation (PWM) controller have been implemented in MATLAB SIMULINK. The analysis of voltage sag and total harmonic distortion (THD) has also been implemented using the fast fourier transform (FFT) techniques. The predicted performance of the suggested configuration for series APF is confirmed by the simulation results.

In order to lessen the voltage harmonics present at the output of a fifteen-level cascaded multilevel inverter (CMLI) fed by solar photovoltaic (SPV) cells, Alexander and Thathan (2014) suggested an OHSW technique. Finding the best switching angles requires solving the harmonic elimination equations using stepped waveform analysis, which this method accomplishes. The OHSW technique reduces the size of six harmonic orders by viewing the output voltage waveform as four equal symmetries in each half cycle. To demonstrate the efficacy of the suggested method, a 3 kWp solar plant is fabricated in hardware and simulations are conducted in MATLAB/SIMULINK. When compared to the traditional PWM method, the OHSW based method is clearly the superior option for applying selective harmonic elimination to solar PV systems. One benefit of this approach is that it doesn't need complicated computing algorithms, filters, lookup tables, or output transformers.

The rate mismatch or discrepancy of reactive power has been generated by power electronics devices and the unexpected switching on or off of massive induction motors. Even though fixed capacitors and inductors have been employed to alleviate the reactive power issue, they are bulky and not easy to control when it comes to power flow (Biraja & Animesh, 2017). Power system problems such as voltage sag, voltage swell, harmonics, and interruptions have also increased. The power system's harmonic level has been decreased through the usage of synchronous condensers. It uses a variable inductor and capacitor, but, being a rotating device, it requires cooling and maintenance, which are limitations (Vijayakumar & Vijayan, 2015). Research into the Static VAR (SVC) Compensation method for enhancing power quality and reducing harmonics has been conducted. The thyristor-controlled inductor and manually-operated switch capacitor allow for precise regulation of current. One drawback is that it can't compensate for low voltages (Lankanan & Kumar, 2014).

There are two vital components for limiting voltage distortion levels on the overall utility system viz:

Limiting the harmful currents released into the system by individual users is essential. Reducing the quantity of injected harmonic currents can minimise voltage distortion since these currents, via the system impedance, propagate towards the supply source and cause voltage distortion. Based on the recommendations of IEEE standard 519-1992, this is the fundamental method for regulating level of distortion.

Even when the harmonic current injections are kept within limitations, the overall voltage distortion levels can still be too high. When a harmonic current frequency is close to a system resonance frequency, this typically occurs. Some parts of the system may experience voltage variations that are not necessary as a result of this. When a capacitor bank is involved in the resonance, the voltage distortion is at its worst. This spot doesn't have to be close to where the injection was made.
The objectives of this research are to model the distribution network using MATLAB/Simulink software 2021, model an ANFIS Controlled Unified Power Quality Conditioner via Matlab/Simulink, simulate the network without ANFIS controlled UPQC, simulate the distribution network with ANFIS controlled UPQC; and to compare the results of without and with UPQC with respect to harmonics and sag reduction

II. MATERIALS AND METHODS

2.1 Materials

The materials used for this study include the following;

- The single line diagram of the existing Rumuoimoi 11kV Distribution Network
- Load Data
- Line Data
- Unified Power Quality Conditioner (UPQC)
- MATLAB/SIMULINK Software

2.1.1 Description of Existing Network

Rumuomoi is a community located in Port Harcourt at 4° 48’43” N latitude and 7°2’14” E longitude. The community plays host to many multi-nationals, cooperate businesses, and commercials thereby providing housing for many expatriates and employees working in many multinational oil and gas company at the area. Power supply to Rumuomoi is via 11kV line duly linked to Rumuola Injection Substation.

Figure 1 shows the Simulink model of Rumuomoi 11kV distribution network, Table 1 and 2 show the load and line Data respectively. The network consist of 11kV Power Source representing the grid supply, twelve (12) distribution transformers for stepping down voltage for local distribution and load connected at various buses with real/reactive power demand. The MATLAB Simulink is a graphical simulation tool for modeling and analyzing dynamic systems. It is widely used in power systems, control systems, and embedded systems due to its block-based interface and seamless integration with MATLAB scripting. Its key features includes graphical user interface (GUI) for drag-and-drop block modeling, multi-domain simulation for supports electrical, mechanical, and control systems, specialized tools for power systems, load flow, and fault analysis and real-time simulation for hardware-in-the-loop (HIL) and embedded system integration.

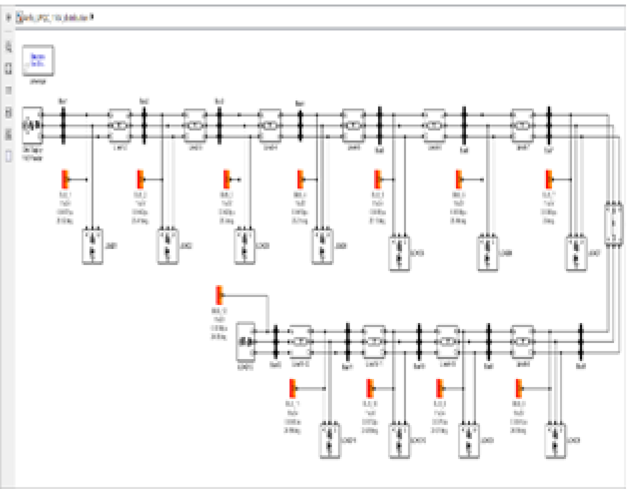

Figure 1: Simulink Model of Rumuomoi 11kV Distribution Network.

Table 1 : Load Data

Distribution Substation				**I_R**	**I_Y**	**I_B**	**I_N**
Bus No	**Bus Name**	**KVA**	**kV**	**(A)**	**(A)**	**(A)**	**(A)**
1	Ohiamini Road	500	11/0.415	270	240	200	80
2	Location Road	500	11/0.415	200	190	210	90
3	Ideogu Estate	500	11/0.415	265	356	314	128
4	Omunakwa Road	300	11/0.415	419	380	400	102
5	Okabie Road	300	11/0.415	420	386	412	150
6	Amadi Road 1	300	11/0.415	460	420	440	60
7	Amadi Road 2	500	11/0.415	332	330	330	80
8	Bakery Road	500	11/0.415	300	380	375	85
9	Silicon Valley Ltd	500	11/0.415	295	385	365	75
10	PHWC	500	11/0.415	310	374	370	82
11	Super Geometrics	300	11/0.415	326	380	375	70
12	Ichiegbo Road	500	11/0.415	358	385	365	96

Source: Port Harcourt Electricity Distribution Company (PHEDC)

Table 2: Line Data

Line ID	**From Bus**	**To Bus**	**Impedance (Z)**
1-2	Ohiamini Road	Location Road	0.015+j0.057
2-3	Location Road	Ideogu Estate	0.037+j0.049
3-4	Ideogu Estate	Omunakwa Road	0.026+j0.028
4-5	Omunakwa Road	Okabie Road	0.049+j0.041
5-6	Okabie Road	Amadi Road 1	0.083+j0.025
6-7	Amadi Road 1	Amadi Road 2	0.040+j0.011
7-8	Amadi Road 2	Bakery Road	0.058+j0.030
8-9	Bakery Road	Silicon Valley Ltd	0.027+j0.059
9-10	Silicon Valley Ltd	PHWC	0.042+j0.013
10-11	PHWC	Super Geometrics	0.055+j0.047
11-12	Super Geometrics	Ichiegbo Road	0.088+j0.060

Source: Port Harcourt Electricity Distribution Company (PHEDC)

2.2 Method Used

The Rumuomoi 11kV distribution network was modeled MATLAB/Simulink. ANFIS controlled unified power quality conditioner (UPQC) was used for improving power quality in Rumuomoi 11kV distribution network. UPQC was used because it performs both series and shunt compensation thereby suitable for mitigating fault, voltage sag and swell compensation, current harmonic compensation, reactive power compensation, and active power flow control. Fast Fourier Transformation Analysis was applied to evaluate the performance of the network before and after UPQC installation, comparing total harmonic distortion and voltage sag.

2.2.1 Load Determination

The calculated static load data is shown in Table 3. The load parameters of the network can be determined through the following ways:

2.2.2 Total Load Current (IL)

The average load current 〖(I〗 _L) of the distribution transformer is giving by

$$I_L = \frac{I_R + I_Y + I_B + I_N}{3} \qquad (3.1)$$

Where
I_R is current in the red phase
I_Y is current in yellow phase
I_B is current in the blue phase
I_N is current in neutral

2.2.3 Apparent Power (KVA)

The load apparent is giving by

$$KVA_{Load} = \sqrt{3} * I_L * V_s \qquad (3.2)$$

Where
IL is average load current
Vs is the secondary voltage of the transformer

2.2.4 Real Power (kW)

The load real power is giving by

$$kW_{Load} = PF * KVA_{Load} \qquad (3.3)$$

Where
PF is the power factor: 0.85
〖KVA〗 _Load is the load apparent power

2.2.5 Reactive Power (KVAr)

The load reactive power is giving by

$$Kvar_{Load} = \sqrt{(KVA_{Load})^2 - (kW_{Load})^2} \quad (3.4)$$

Where
〖KW〗 _Load is the load real power

〖KVA〗 _Load is the load apparent power

Table 3: Calculated Static Load Data

Distribution Substation		**I_L**	**S**	**P**	**Q**
Bus No	**Bus Name**	**(A)**	**(KVA)**	**kW**	**kVar**
1	Ohiamini Road	263.33	189.28	160.89	99.71
2	Location Road	230.00	165.32	140.53	87.09
3	Ideogu Estate	354.33	254.70	216.49	134.17
4	Omunakwa Road	433.67	311.72	264.96	164.21
5	Okabie Road	456.00	327.77	278.61	172.67
6	Amadi Road 1	460.00	330.65	281.05	174.18
7	Amadi Road 2	357.33	256.85	218.32	135.30
8	Bakery Road	380.00	273.14	232.17	143.89
9	Silicon Valley Ltd	373.33	268.35	228.10	141.36
10	PHWC	378.67	272.19	231.36	143.38
11	Super Geometrics	383.67	275.78	234.41	145.28
12	Ichiegbo Road	401.33	288.48	245.21	151.97

2.3 Determination of Network Operating Condition

Newton-Raphson power flow technique was used in determining the network operating condition. This to identify stress buses in the network. The technique was considered due to its powerful convergence characteristics compared to other techniques.

The real and reactive power injected in the network is given by

$$S_i = V_i I_i^* = P_i + jQ_i \qquad (3.5)$$

$$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*} \qquad (3.6)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{n} Y_{ik} V_k \qquad (3.7)$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k\right) \qquad (3.8)$$

Let $V_i^* = V_i \angle - \delta_i$, $V_k = V_k \angle \delta_k$ and $Y_{ik} = Y_{ik} \angle \theta_{ik}$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k \angle \delta_k + \theta_{ik} - \delta_i \right) \quad (3.9)$$

$$P_i - jQ_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \left[\cos(\delta_k + \theta_{ik} - \delta_i) + j \sin(\delta_k + \theta_{ik} - \delta_i) \right] \quad (3.10)$$

Separating (3.10) into real and imaginary parts we have,

$$P_i = \sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \cos(\delta_k + \theta_{ik} - \delta_i) \quad (3.11)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_i||V_k| \sin(\delta_k + \theta_{ik} - \delta_i) \quad (3.12)$$

Where
Y_ik = the admittance matrix
P_i = the injected real power
Q_i= the injected reactive power
δ_i= phase angle

2.3.1 UPQC Voltage and Current Compensation

The voltage and current of the unified power quality conditioner (UPQC) which are crucial parameters can be determined in the following ways:

2.3.1.1 Voltage Compensation

The series active filter injects voltage in series with the supply voltage to ensure the load voltage is at the desired reference value. The injected voltage is given by

$$V_{inj} = V_{ref} - V_s \quad (3.25)$$

By applying Kirchhoff's voltage Law

$$V_L = V_s + V_{inj} \quad (3.26)$$

2.3.1.2 Current Compensation

The shunt active filter injects current to compensate for the reactive and harmonic components of the load current. The source current should ideally be free of harmonic and reactive components.

$$I_{inj} = L_L - I_s \quad (3.27)$$

By applying Kirchhoff's voltage Law

$$I_s = I_L + I_{inj} \quad (3.28)$$

2.3.1.3 Algorithm for Control Strategy of the Proposed UPQC

Step 1: Transform the three phase voltage and current into stationary α-β reference frame using instantaneous reactive power theory (p-q theory)

$$\begin{pmatrix} v_\alpha \\ v_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \quad (3.29)$$

$$\begin{pmatrix} i_\alpha \\ i_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \quad (3.30)$$

Step 2: Calculate the instantaneous active and reactive power components

$$p = V_\alpha I_\alpha + V_\beta I_\beta \quad (3.31)$$

$$q = V_\alpha I_\beta - V_\beta I_\alpha \quad (3.32)$$

Step 3: Calculate the reference current for shunt active power filter

$$i_\alpha^* = \frac{p*v_\alpha + q*v_\beta}{v_\alpha^2 + v_\beta^2} \quad (3.33)$$

$$i_\beta^* = \frac{p*v_\beta - q*v_\alpha}{v_\alpha^2 + v_\beta^2} \quad (3.34)$$

Step 4: Transform the reference current back to the three phase system

$$\begin{pmatrix} i_a^* \\ i_b^* \\ i_c^* \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_\alpha^* \\ i_\beta^* \end{pmatrix} \quad (3.35)$$

2.4 UPQC Parameter Design

The basic parameters of the unified power quality conditioner are designed in this section

2.4.1 DC Link Voltage

DC voltage is given by

$$V_{dc} = \sqrt{2} * V_{LL} * k \qquad (3.36)$$

$$V_{dc} = \sqrt{6} * V_{LN} * k \qquad (3.37)$$

Where
V_LL: line to line rms voltage
V_LN: line to ground rms voltage
k: safety factor typically ranging from 1.1 to 1.5

2.4.2 DC Link Capacitor

DC link capacitor is given by

$$C_{dc} = \frac{2P}{V_{dc}^2 * \omega * \Delta V_{dc}} \qquad (3.38)$$

Where
P: load active power
Vdc: dc link voltage
〖ΔV〗 _dc: voltage ripple (20V)
ω: angular frequency

2.4.3 Shunt Filter

The shunt active filter inductor value is given by

$$L_{sh} = \frac{\sqrt{2} * V}{2\pi * f_{sw} * \Delta I} \qquad (3.39)$$

Where
V: rms line voltage
f_sw: switching frequency (10kHz)
ΔI : allowable ripple current (5A)

2.4.4 Series Filter

The series active filter inductor value is given by

$$L_{se} = \frac{V_{dc}}{4 * f_{sw} * \Delta I} \qquad (3.40)$$

Where
V: rms line voltage
f_sw: switching frequency (10kHz)
ΔI : allowable ripple current (5A)
The series active filter capacitor value is given by

$$C_{se} = \frac{1}{\omega^2 * L_{se}} \qquad (3.41)$$

Where
ω: angular frequency
L_se: series active filter inductor

2.4.5 UPQC Size Determination

$$S_{UPQC} = \sqrt{S_{series}^2 + S_{shunt}^2} \qquad (3.42)$$

Where
S_series: rating of series active filter in KVA
S_shunt: rating of shunt active filter in KVA

III. RESULTS AND DISCUSSION

3.1 Result of the Network Simulation without UPQC Controlled by ANFIS

Figure 2 shows the FFT view window of harmonic distortion and spectrum plot injected at the point of common coupling (PCC) by nonlinear load when no unified power quality conditioner (UPQC) was installed in the network. The waveform is due to the presence of multiple frequencies in voltage causing the fundamental frequency deviation from its ideal sinusoidal characteristics. The spectrum indicates the order of harmonic frequency present in the power system network. A quick look at Figure 2 shows that the total harmonic voltage distortion injected at the PCC is 12.59% which violated the predefined 8% limit condition for medium voltage power system according to IEEE 519-2022 standard. Figure 3 shows the model of the network showing the nonlinear load's injection.

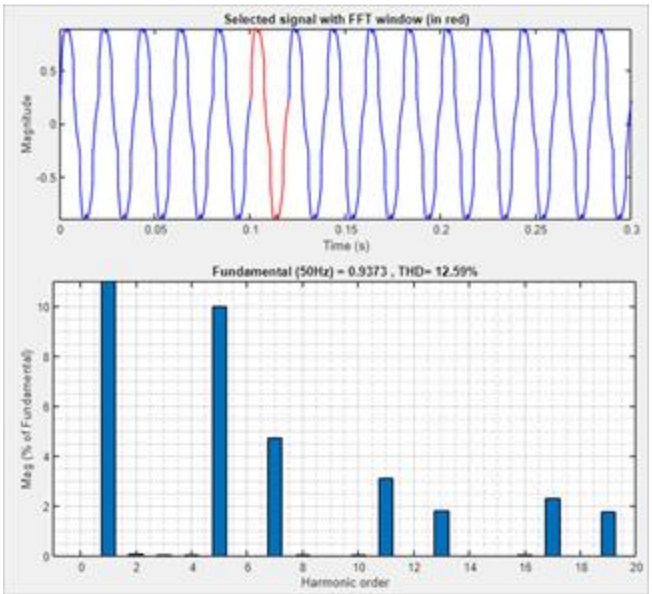

Figure 2: Plot of Total Harmonic Distortion before UPQC

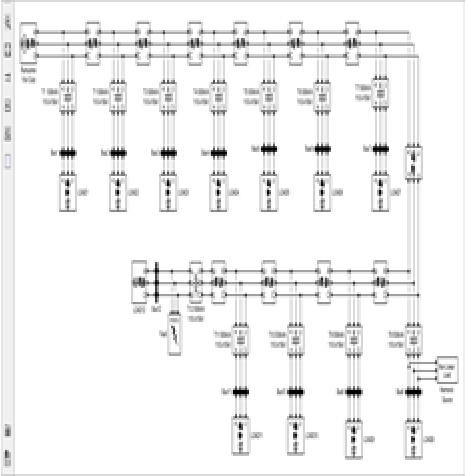

Figure 3: Matlab Simulink Block Representation of Rumuomoi 11kV Network

Figure 4 shows the behavior of the distribution network under three phase fault condition for a duration of 0.1 seconds (between 0.1 – 0.2 secs). A voltage sag of about 50 % of the nominal voltage was observed as shown by the waveform. The system was unable to compensate for voltage sags due to no UPQC device. This results in poor power quality, leading to equipment damage, tripping of sensitive loads, and potential system instability untill after 0.2 seconds when the fault is cleared.

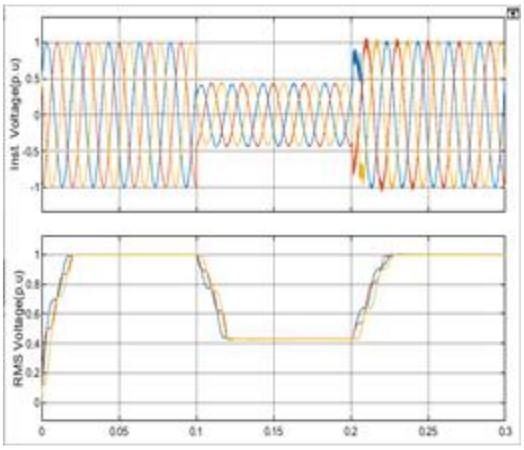

Figure 4 : Plot of Voltage Sag before UPQC

3.2 Result of the Network Simulation with UPQC Controlled by ANFIS

Figure 5 shows the FFT view window of harmonic distortion and spectrum plot when an ANFIS controlled UPQC was installed to mitigate the presence of multiple frequencies in system causing the fundamental frequency is deviated from its ideal sinusoidal characteristics at the point of common coupling (PCC) by nonlinear load. Figure 6 shows the model of the distribution network with UPQC added to it. A quick look at Figure 5 shows that the total harmonic distortion injected at the PCC was reduced to 0.15% after the installation of ANFIS controlled UPQC.

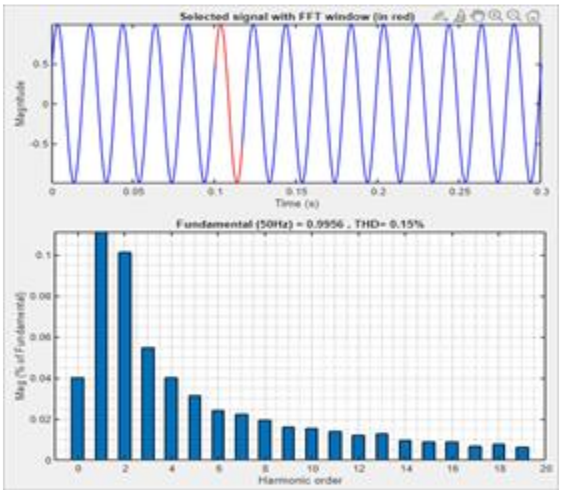

Figure 5 : Plot of Total Harmonic Distortion after UPQC

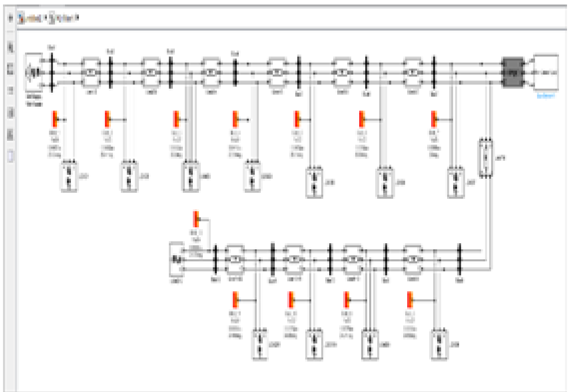

Figure 6 : Model of the Network with UPQC Incorporated

Figure 7 shows the behavior of the distribution network under three phase fault condition for a duration of 0.1 seconds (between 0.1 – 0.2 secs) when an ANFIS controlled UPQC was installed to injects compensating voltage to mitigate sags. The UPQC through the ANFIS controller senses the disturbance and then rapidly responded by injecting a compensating voltage to restore the pre fault load voltage. The injected voltage compensation is in the required magnitude and phase angle for recovery of the system operating voltage.

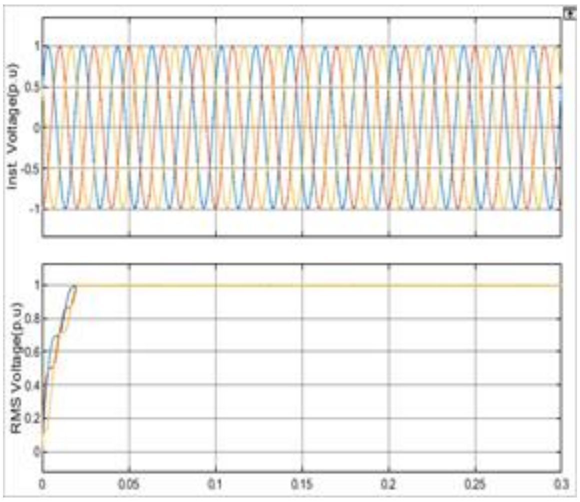

Figure 7 : Plot of Voltage Sag Compensation after UPQC

3.3 ANFIS Controlled Unified Power Quality Conditioner (UPQC)

The ANFIS-based Unified Power Quality Conditioner (UPQC) controller shown in Figure 8 is an adaptive intelligent control system that integrates an Adaptive Neuro-Fuzzy Inference System (ANFIS) into a UPQC for power quality improvement in electrical distribution networks. The Simulink block diagram consists of two key components a series active power filter controller for mitigating voltage sags/swells and regulates voltage and a shunt active power filter for compensating current harmonics and corrects power factor. Other components include : series transformer for injecting compensating voltage into the distribution network to mitigate voltage sags, swells, and distortions.

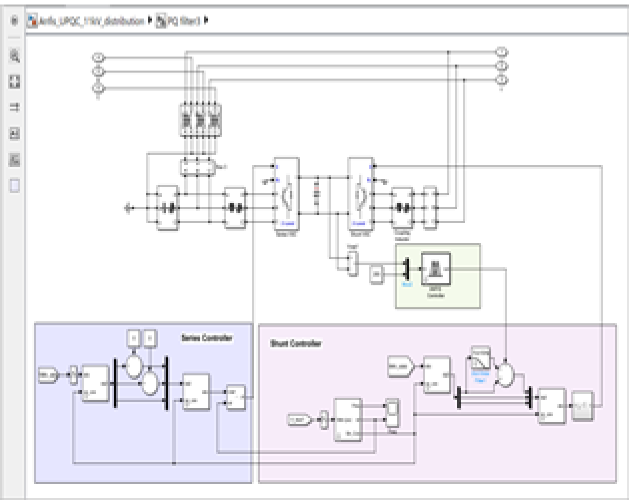

Figure 8 : MATLAB Model of ANFIS Controlled Unified Power Quality Conditioner

The low pass filter consist of a capacitor and an inductor used for removing high frequency harmonic components produced due to switching of voltage source inverter and DC capacitor provides a DC voltage for the working of both inverters. The ANFIS controller Trains the fuzzy system using a hybrid learning algorithm to dynamically adjusts fuzzy membership functions for optimal compensation.

3.4 Comparison of Results of Harmonics and Sag Reduction for Base and Improved Cases

Figure 9 shows the comparison plot of harmonic distortion before and after implementing ANFIS-based control in the unified power quality conditioner (UPQC). A quick look at the first Figure before UPQC, the system experiences high total harmonic distortion (THD) of 12.59% due to the presence of nonlinear loads, which violated the predefined 8% limit condition for medium voltage power system according to IEEE 519-2022 standard resulting in waveform distortions, power quality degradation, and increased losses in electrical components. However, after installing ANFIS controlled UPQC, the dynamically adjusts to load variations and significantly reduces THD, ensuring smoother waveforms, as shown in the second plot indicating improvement in voltage regulation, and better reactive power compensation. The ANFIS-based controller, leveraging adaptive learning and fuzzy logic principles, optimally compensates for harmonics in real time, achieving superior performance with a voltage THD reduction from approximately 20–30% to below 5% and current THD reduction from about 25-35% to nearly 1-5%, thus enhancing power quality, improving efficiency, and ensuring compliance with IEEE 519 harmonic standards.

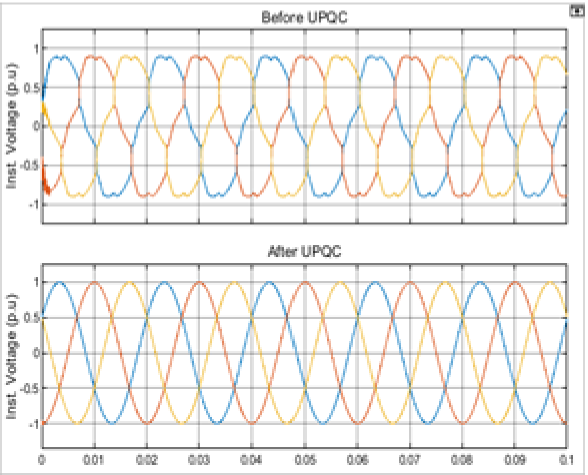

Figure 9 : Comparison Plot of Harmonic Distortion Before and after UPQC Installation

Figure 10 shows the comparison plot of voltage sag before and after implementing ANFIS-based control in the unified power quality conditioner (UPQC). The first plot depicts the network behavior before implementing ANFIS-based controlled UPQC, showing the voltage sag remains a critical issue caused by sudden load variations, or faults leading to a significant drop in voltage magnitude that affects the stability and performance of sensitive loads. However, after integrating ANFIS control UPQC which effectively detects and compensates for voltage sag in real time by dynamically adjusting the series voltage injection, ensuring that the load voltage remains stable and within acceptable limits. The ANFIS-controlled UPQC, leveraging adaptive learning and fuzzy logic, accurately predicts and compensates for voltage disturbances, reducing the sag depth from typical values of 40% below nominal voltage to less than 5%, ensuring continuous and reliable power supply.

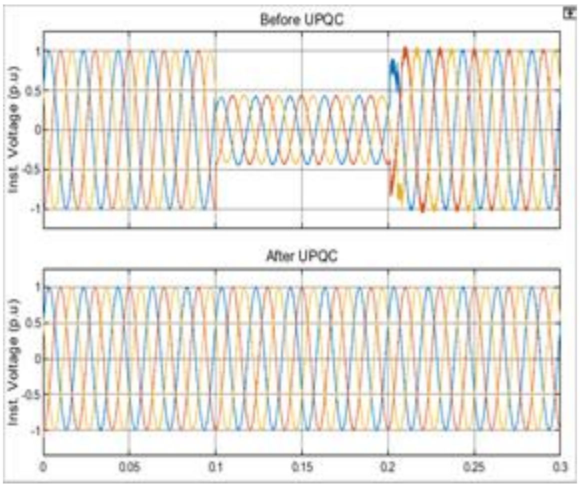

Figure 10 : Comparison Plot of Voltage Sag before and after UPQC Installation

IV. CONCLUSION

This research gives a holistic solution to improving power quality in distribution networks by integrating ANFIS-controlled UPQC. It advances the state of the art in power quality control by providing a more adaptive, efficient and cost effective method for harmonic mitigation, reactive power management and voltage regulation. The ANFIS-based controller integrates the learning capability of artificial neural networks with the decision-making efficiency of fuzzy logic, enabling real-time adjustment of the filtering process to varying system conditions.

The study has met its objectives. The distribution network of Rumuomoi 11kV has been modeled using MATLAB/Simulink 2021 as seen in figure 1 having twelve (12) buses. The ANFIS controlled hybrid power filter was modeled via MATLAB software as found in figure 8. it is an intelligent control mechanism that incorporates the adaptive neuro-fuzzy inference system into the UPQC which improved the power quality of the network. When the network was simulated without the ANFIS controller, the harmonic voltage noticed at the point of common coupling is 12.59% which violated the predefined 8% limit condition for the medium voltage power system according to IEEE 519-2022 standard. A voltage sag of about 50% of the nominal voltage was observed during the three-phase fault initiated at 0.1 second (between 0.2-0.2 second) and the system was unable to compensate for the sags because there was no UPQC device thus, leading to instability in the system. However, with the presence of the ANFIS-controlled UPQC in the network, it senses the disturbance due to the three-phase fault and rapidly responded by injecting a compensating voltage to restore the pre-fault load voltage thereby, reducing the injected harmonic distortion to about 0.15% which is below 5% this, ensuring compliance with IEEE 519 harmonic standards. Furthermore, the ANFIS-controlled UPQC effectively mitigates voltage sag conditions, restoring voltage deviations within ±5% of nominal values, which is critical for ensuring the stability and reliability of sensitive electrical loads. The ability of ANFIS to dynamically optimize control parameters in real time allows for faster transient response, reduced steady-state error, and improved overall power quality compared to conventional controllers. The study has contributed to the body of knowledge in that :

- the ANFIS-controlled UPQC significantly reduces harmonics distortion and effectively restores voltage sag disturbances, providing stable power to sensitive loads in Rumuomoi 11kV distribution system ensuring compliance with IEEE 519 standards.

- it introduces an innovative UPQC design that combines both passive and active filtering techniques. The use of passive filters for certain frequencies and active filters for others offers an optimal solution to the problem of power quality improvement, providing cost-effective and efficient compensation for various disturbances. The integration of an active filter with passive filters allows for better harmonic mitigation and reduces the system's overall reactive power consumption, which can improve overall system stability and reduce losses in the distribution network.

- the key contribution of this research hinges on the application of the Artificial Neural Fuzzy Inference System (ANFIS) for the control of the hybrid power filter. ANFIS, as a combination of neural networks and fuzzy logic, offers an adaptive and robust framework for power quality improvement. Its ability to learn from data and adjust to changes in the network's operating conditions makes it an ideal control strategy for dynamic and complex systems like power filters. This study demonstrates that ANFIS can effectively handle the nonlinear characteristics of the filter and power network, resulting in faster and more accurate filtering performance compared to traditional controllers like PID or PI.

- the integration of real-time power quality monitoring systems with the ANFIS-controlled UPQC. The ability of ANFIS to adapt in real-time to changes in load conditions and power disturbances ensures that the filter maintains optimal performance throughout varying operating conditions. This adaptive feature is crucial in modern distribution networks, where dynamic loads and rapidly changing power quality issues are common.

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