



## Power Quality Improvement in a Grid Connected Solar-PV System with Adaptive Neuro-Fuzzy Controller Based UPQC

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**Abstract:** Power quality (PQ) problems are frequently encountered in power grids, and these problems become more severe as the number of devices increases. Therefore, one of the primary responsibilities of utility systems remains to supply people with electricity by standard sinusoidal voltage and current configurations at appropriate amplitudes and frequencies adjoining the point of common connection (PCC). This research examines a solar-photovoltaic (PV) coordinated unified power quality controller (UPQC) to enhance the PQ in the distribution grid network. This paper proposes a UPQC control method relied on the Adaptive Leakage Least Mean Square (AL\_LMS) algorithm. This approach uses both the Adaptive Neural Fuzzy Inference System (ANFIS) controller and Proportional-Integral (PI) controller to compare between the serial and shunted active converter switching of UPQC. The technique switches the UPQC's shunt and series voltage source converters (VSCs) to obtain a reference signal through iterative weight update. Through iterative weight update, the method obtains a reference signal by switching the shunted and serial VSCs of the UPQC. Therefore, the PQ disturbances such as load voltage drop and ripple and harmonic distortion of the grid's current are abridged after the control technology is applied to the solar PV-UPQC. Conferring to the simulation results, the proposed ANFIS control AL\_LMS algorithm stands the utmost operative in improving the PQ after applied to the solar-PV sourced UPQC, while complying with the IEEE-519 standards. The work was done in using MATLAB/Simulation software.

**Keywords:** Renewable Energy Source, Power Quality, UPQC, Voltage Source Converter, ANFIS Control

### 1. Introduction

As traditional energy sources are increasingly depleted and have a undesirable impact on the environment, the usage of renewable energy sources (RES) for instance solar-photovoltaic (PV) systems and also wind power systems for electricity generation is becoming increasingly popular. Researchers in academia and industry are now strongly focusing on the network interactions of these RES to improve system performance. RES are more popular than traditional energy sources due to their cost-effectiveness, environmental friendliness, and ease of use [1]. On the other hand, a large number of control equipment, statistics processing equipment, RES, and subtle power electronic equipment (PEE) have been added to the electricity distribution network in recent decades, resulting in a sharp increase in electricity demand, which is accompanying with a substantial increase in PQ problems in the distribution network [2]. PQ is crucial for ensuring the proper operational of connected devices and the overall resilience of decentralized systems. Therefore, power and voltage quality are critical. The authors in [3] described how PQ complications such as

voltage sag & swells, harmonics and flickering can cause disturbances, damage delicate equipment and reduce the effectiveness of power systems. Therefore, the use of PQ enhancement methods (PQE) has become increasingly popular as a way to reduce over voltages and power outages. Various tools and procedures have been proposed and employed to progress the stability and performance of power systems and to solve PQ problems [4]. Innovative technological options for improving voltage regulation, as well as stability and instantaneous apparent control of dynamic power and reactive power by the nominal frequency, such as FACTS (Flexible AC Transmission System) devices, are presented in [5]. Other technologies use unique power devices that offer a range of options including parallel and also series recompense of active power and reactive power towards refining PQ, controlling voltage and performing at substantial and harmonic frequencies in both steady-state and active situations [6]. One possible solution to the voltage and current PQ problems of distribution systems is the UPQC, a dedicated power device that can be applied to the PCC distribution network. Through voltage regulation and mitigation of frequent PQ complications such as voltage sags, swell,

harmonics, etc., its main intention is to guarantee continuous improvement of PQ. It has a common DC bus and consists of two parts: Series (-SeAPF) and Shunt (-ShAPF) active power filters. The SeAPF compensates for voltage correlated anomalies, including sags and swells, whereas the ShAPF controls the DC bus voltage and dispels current interrelated problems, for e.g., reactive power (Q) demand and harmonics [7].

According to [8], RES, exclusively solar-photovoltaic (PV) systems, are increasingly integrated into the grid, bringing many benefits to sustainable development and low carbon emissions. Quite a lot of rewards could be achieved by combining solar-PV systems to a UPQC. Initially, solar-PV systems can function by way of clean RES, lowering the demand for conventional fossil fuel power generation and encouraging a more sustainable supply of electricity. Secondly, according to the authors [9, 10], photovoltaic systems can dynamically support active power, allowing the UPQC to stabilize the grid and regulate the voltage underneath diverse load conditions. In order to switch the shunt compensator or series compensator, an appropriate UPQC control structure must be conditioned to engender the source current signal and the load reference voltage signal. Some studies have used traditional time-domain methods, such as the symmetrical current component theory (ISCT), the synchronous reference frame method (SRF or d-q-0), the reactive power theory (IRPT or p-q) and the sliding mode control [11-14]. Due to the low efficiency of the low-pass filter, these usual algorithms developed based on these theories do not work well when the load is unbalanced. Several frequency-domain techniques have been implemented using fast Fourier transform and wavelet transform [15], although as shown in [16], these techniques require higher computational efficiency, use more memory and have slower elastic response. As mentioned in [17], control strategies based on computational software techniques (like Neural Networks) remain also castoff to classify and distinguish PQ problems. Built on the Leaky LMS adaptive filter algorithm, research [18] proposed a method to reduce the THD of solar photovoltaic systems. By using the proposed filter, the harmonic content of the input signal is significantly reduced and sent to the load. Therefore, the combination of modern power electronic equipment and control methods provides long-term help in solving PQ problems [19].

Here, the focal aim is to solve the PQ problem caused by 3- $\Phi$  nonlinear loads in the integration of the proposed solar-PV power supply UPQC hooked on the grid system. To approximate the references of voltage and current when the series and shunt compensators work together, a control method created on the AL\_LMS algorithm and by distinctive PI and AFIS controllers is provided toward deriving the reference signals used to jointly drive the UPQC parallel and series VSCs. The adaptive leakage constraint features of the AL\_LMS

technique provides better concert in both steady-state in addition dynamic scenarios, and the weighted parameter shift does not go out of bounds, which makes the proposed AFIS controller a better choice than the traditional PI controller. In this way, the reference signal for switching the VSC is estimated quickly and accurately to alleviate the PQ problem, in so doing enlightening the concert of the UPQC provided by the solar PV.

## 2. Model System Description

Figure 1 schematically shows the grid connection method of the proposed system paradigm, which combines UPQC with solar photovoltaic system. A 3-phase series injection transformer (Tse) and a coupling inductor (Lse) are used to connect the UPQC series converter elements in sequence through the supply grid network. The shunt-VSC element is connected in competition with the load point through the interfaced inductor (Lsh), and the two compensators are connected through a capacitor (Cdc). The solar photovoltaic module is connected to the DC capacitor through a reversing diode. The high frequency voltage components instigated by VSC switching can be removed by adding ripple filters (Rr and Cr). A diode bridge rectifier (3- $\Phi$  nonlinear load) near the system is connected for PQ problem analysis.

## 3. Methodologies for UPQC

In this case, the VSC of the UPQC is shunted, maintaining the DC bus voltage at a significant level while reducing the harmonics of the mains source current. It also helps the PCC in providing the required reactive power. Connecting the VSC in series reduces the harmonics, dips and ripples of the load voltage. As explained in the next section, an appropriate UPQC control structure essential be conditioned to provide the load reference voltage signal besides the source current signal towards switching the serial and shunted compensators, correspondingly.

### 3.1. Adaptive Leaky LMS (AL\_LMS) Method

The AL\_LMS algorithm [20, 21] stands a modified standard LMS approach for adaptive filtering applications. The goal of adaptive filtering is to determine the ideal set of filter constants or weights that minimize the odd differences between the expected and the filter's outputs. At this time, a leakage factor is added toward the AL\_LMS algorithm to control the filter coefficient update rate, thus balancing stability and tracking speed [22]. The following equations (1) and (2) explain the mathematical equations related to AL\_LMS and the aforementioned estimator [23].

$$W(t + 1) = [1 - \mu\lambda(t)]. W(t) + \mu E(t). X(t) \quad (1)$$

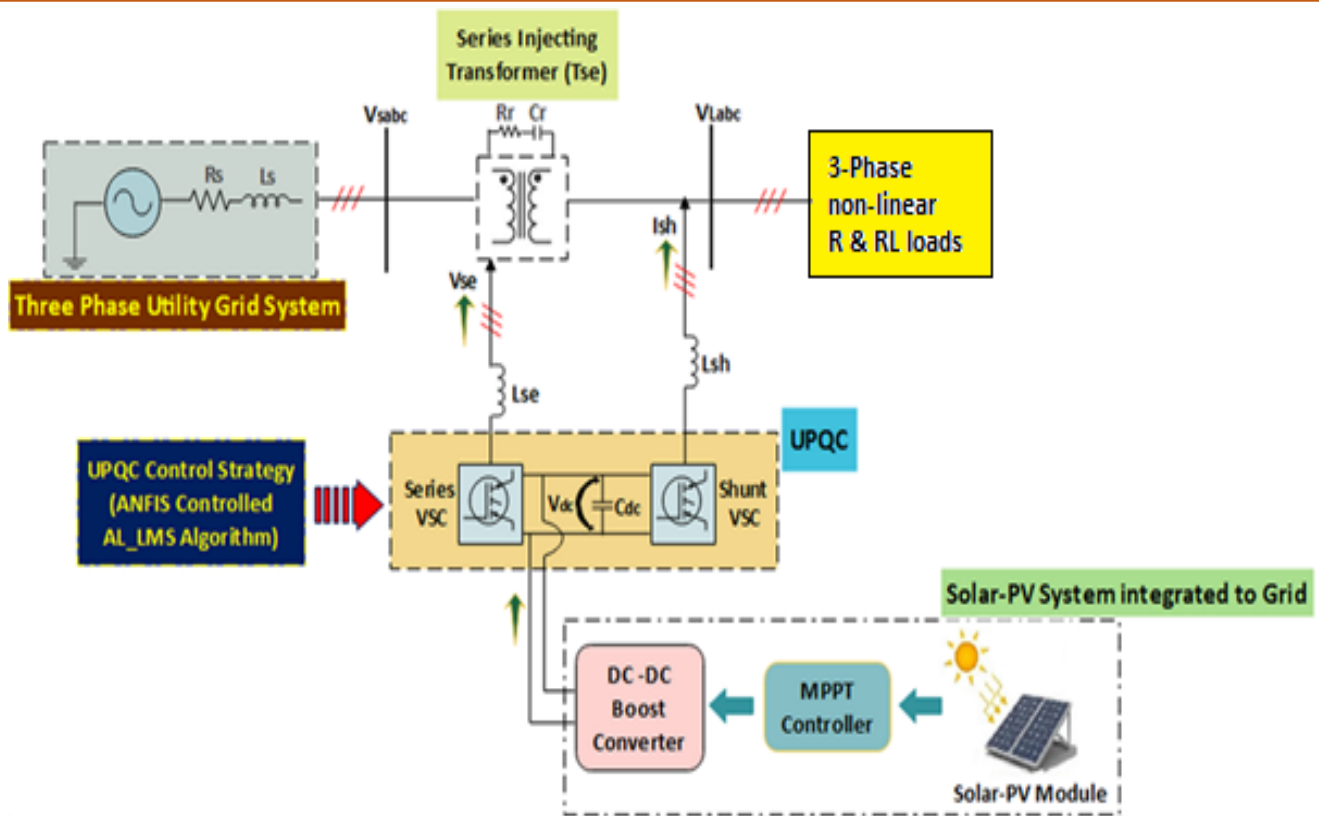


Figure 1. Illustration of a suggested model for a solar-photovoltaic-fed UPQC system

$$Y(t) = W^T(t) \cdot X(t) \quad (2)$$

Where  $X(t)$ : On time step 't', the input vector.

$W(t)$ : Weighted vector of filter quantities by the time pace 't'

$\mu$ : Step-size or erudition rate, governing the adaption rate

$\lambda(t)$ : The leakage factor, which can differ at each time pace 't' depending on system's circumstances

$E(t)$ : The instant erroneous signal at time pace 't', given as anticipated output

'D(t)' minus forecast output 'Y(t)' i.e.

$$E(t) = D(t) - Y(t) \quad (3)$$

The total function  $F_c(t)$  is stated by

$$F_c(t) = E^2(t) + [\lambda(t) \cdot W^T(t) \cdot W(t)] \quad (4)$$

Weights are updated such that they achieve a negligible value. The equations (5) - (8) are used to get the weight update expressions

$$W(t + 1) = W(t) [1 - 2\mu(t) * \lambda(t)] + [2\mu(t) * E(t) * X(t)] \quad (5)$$

$$\lambda(t + 1) = \lambda(t) - [2\mu(t) * \rho * E(t) * X^T(t) * W(t - 1)] \quad (6)$$

$$\mu(t + 1) = [\alpha * \mu(t)] + [\lambda(t) * R^2(t)] \quad (7)$$

$$R(t) = [\beta * R(t - 1)] + [(1 - \beta) * E(t) * E(t - 1)] \quad (8)$$

Here,

$R(t)$ :  $E(t)$  &  $E(t-1)$  Autocorrelation

$\beta$ : An exponential weighting parameter that regulates averaged valued time so that  $0 < \beta < 1$

$\alpha$  and  $\rho$ : Convergence governing time constraints so that  $0 < \alpha < 1$  and  $\rho > 0$ .

Using the AL\_LMS algorithm, the solar PV power supply of the UPQC in this study can be adaptively controlled to generate correct reference signals for equipment operation, as shown in Figure 2. Measurements for successfully correcting PK problems. The above method calculates the difference amongst the measured and expected values of these constraints. The reference signal is then adaptively modified to remove the PQ error, which is represented by the difference between these two values. This method uses the erroneous signal and the learning rate ( $\mu$ ) towards computing the adjustment rate to reliably modify the reference signal. This program generates variable reference signals to control the movement of the UPQC [24]. This process is carried out through a feedback loop, where the UPQC incessantly adjusts its control signal in response to changing electrical conditions within the system, which includes producing suitable compensation signals to resolve power quality complications.

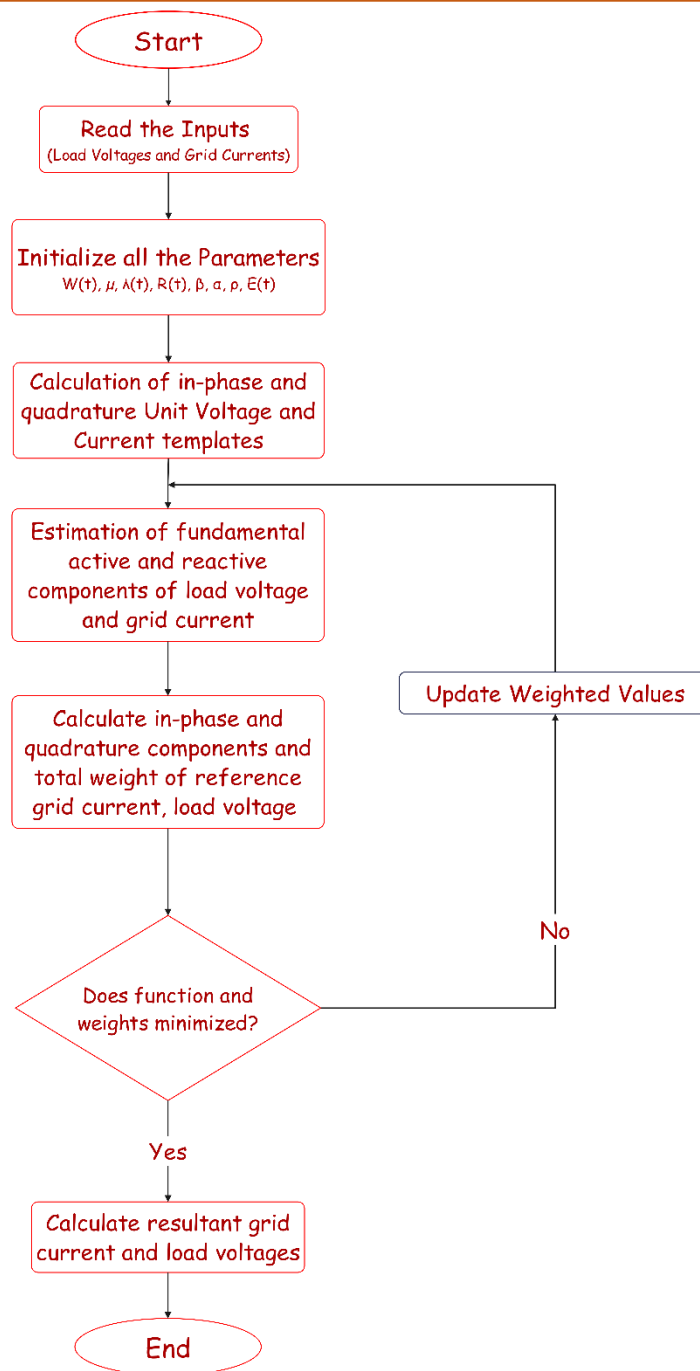


Figure 2. Proposed AL\_LMS Flow Chart

### 3.2 Proposed Schematic for Shunt-VSC

The proposed controller diagram for parallel VSCs is shown in Figure 3 below. In this way, a stable sinusoidal grid/source current can be generated while controlling the DC link's voltage. First, measure the instantaneous phase voltages ( $v_{sa}$ ,  $v_{sb}$ , and  $v_{sc}$ ) of each phase at the PCC. The PCC voltage's ( $V_{sp}$ ) phase amplitude being then premeditated as shown in equation (9).

$$V_{sp} = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \quad (9)$$

The source voltages in-phase unit templates are described by the equation (10)

$$v_{pa} = \frac{v_{sa}}{V_{sp}}; v_{pb} = \frac{v_{sb}}{V_{sp}}; v_{pc} = \frac{v_{sc}}{V_{sp}} \quad (10)$$

The combination of quadrature and in-phase unit templates of voltage are defined by below equation (11).

$$v_{qa} = \frac{-v_{pb} + v_{pc}}{\sqrt{3}}; v_{qb} = \frac{\sqrt{3}}{2}v_{pa} + \frac{1}{2\sqrt{3}}(v_{pb} - v_{pc}); v_{qc} = -\frac{\sqrt{3}}{2}v_{pa} + \frac{1}{2\sqrt{3}}(v_{pb} - v_{pc}) \quad (11)$$

The PV arrangement and power grid affords the required active power toward the load through the control mechanism. In addition, the grid maintains a stable DC link's voltage, thereby eliminating the inherent losses of UPQC.

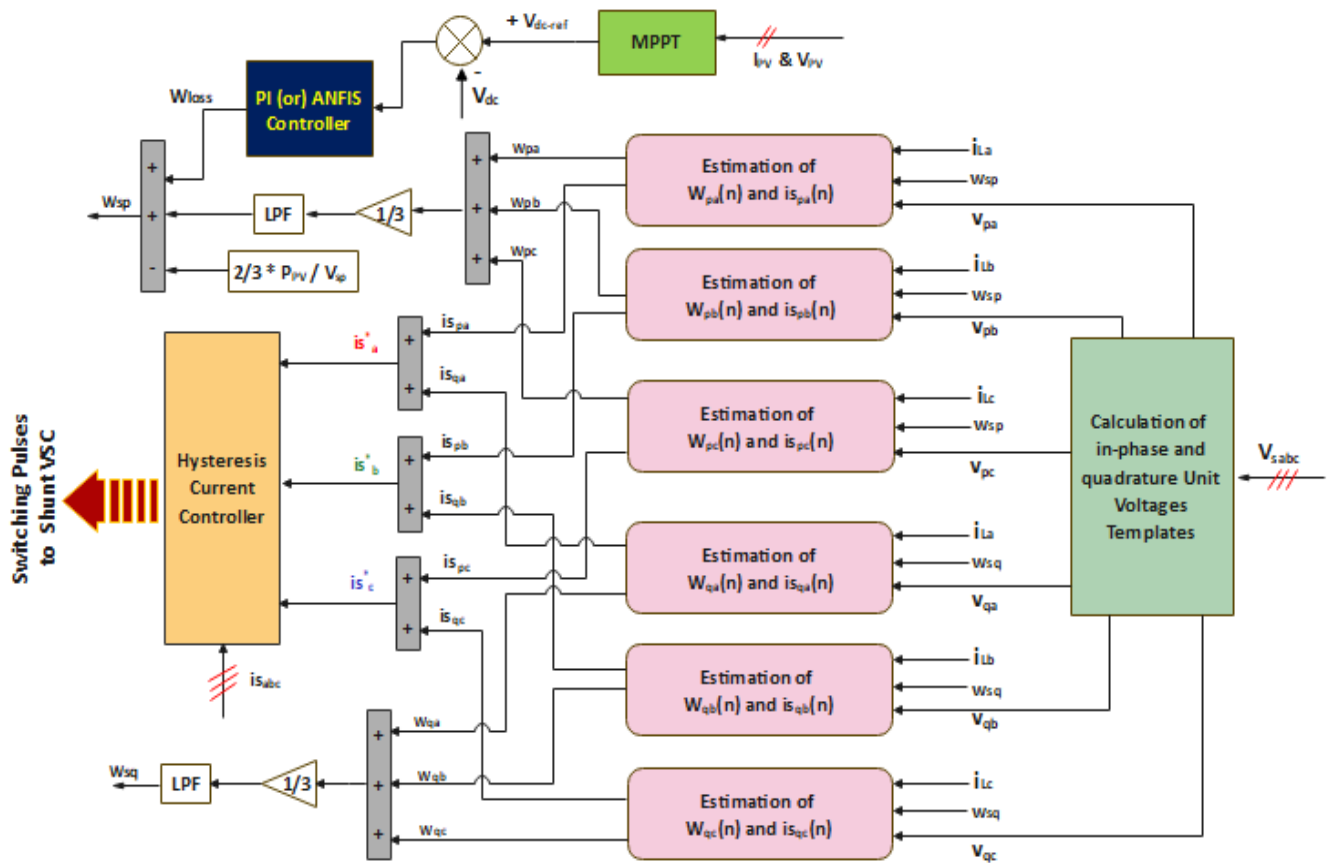


Figure 3. Control Schematic Diagram of proposed Shunt-VSC

Through the determination of minimizing the error, the observed capacitor voltage at DC link ( $V_{dc}$ ) is correlated by the expected DC link's voltage ( $V_{dcref}$ ) obtained from the MPPT solar PV output to generate an error signal ( $E_{dc}$ ), which is then sent to the PI /ANFIS controller. Therefore, the required loss component ( $W_{loss}$ ) is given by equations (12) and (13) and written as

$$E_{dc}(t) = V_{dcref}(t) + V_{dc}(t) \tag{12}$$

$$W_{loss}(t + 1) = W_{loss}(t) + K_p * [E_{dc}(t + 1) - E_{dc}(t)] + K_i * E_{dc}(t + 1) \tag{13}$$

The equation (14) specifies how much of active current provided by a solar-photovoltaic ( $W_{pv}$ ) array.

$$W_{pv} = \frac{2}{3} * \frac{P_{pv}}{V_{sp}} \tag{14}$$

Now, using the weight updates basic formula found in equivalences (5) - (8) above, the key elements of the active load current meant to phase "a" can be inscribed as;

$$W_{pa}(t + 1) = W_{pa}(t) [1 - 2\mu_{pa}(t) * \lambda_{pa}(t)] + [2\mu_{pa}(t) * E_{pa}(t) * v_{pa}(t)] \tag{15}$$

$$\lambda_{pa}(t + 1) = \lambda_{pa}(t) - [2\mu_{pa}(t) * \rho * E_{pa}(t) * v_{pa}(t) * W_{pa}(t - 1)] \tag{16}$$

$$\mu_{pa}(t + 1) = [\alpha * \mu_{pa}(t)] + [\lambda_{pa}(t) * R_{pa}^2(t)] \tag{17}$$

$$R_{pa}(t) = [\beta * R_{pa}(t - 1)] + [(1 - \beta) * E_{pa}(t) * E_{pa}(t - 1)] \tag{18}$$

The Error estimate can endure as;  
 $E_{pa}(t) = i_{La}(t) - v_{pa}(t) * W_{pa}(t)$  (19)

The load current of phase "a" is stated as  $i_{La}$ . Phases "b" and "c" of the parallel VSC, as well as the active component weights ( $V_{pb}$  and  $V_{pc}$ ), leakage coefficients ( $\lambda_{pb}$  and  $\lambda_{pc}$ ), step sizes ( $\mu_{pb}$  and  $\mu_{pc}$ ), error autocorrelation ( $R_{pb}$ ,  $R_{pc}$ ), and prediction errors ( $E_{pb}$ ,  $E_{pc}$ ) can be modified at any time, just like phase "a". Equation (20) therefore gives the weighted average of the fundamental active components ( $W_{pave}$ ).

$$W_{pave} = \frac{W_{pa}(t) + W_{pb}(t) + W_{pc}(t)}{3} \tag{20}$$

The formula for calculating the active components of the reference network's currents ( $i_{spa}$ ,  $i_{spb}$ ,  $i_{spc}$ ) and the total active component weight ( $W_{sp}$ ) is:

$$W_{sp} = W_{pave} + W_{loss} - W_{pv} \tag{21}$$

$$i_{spa} = W_{sp} * v_{pa}; i_{spb} = W_{sp} * v_{pb}; i_{spc} = W_{sp} * v_{pc} \tag{22}$$

Similarly, equation (23) includes updated weightiness intended to the reactive current's components and is also used to calculate the reactive constituent of the load current utilizing the vector voltage patterns of the quadrature elements.

$$i_{sqa} = W_{sq} * v_{qa}; i_{sqb} = W_{sq} * v_{qb}; i_{sqc} = W_{sq} * v_{qc} \quad (23)$$

Herein case, the weighted average of the fundamental reactive components is alike to the weighted total reactive components (Wsq). Therefore, adding the components to the above equations (22) and (23) will give the current drawn from the final reference source as shown:

$$i^*_{sa} = i_{spa} + i_{sqa}; i^*_{sb} = i_{spb} + i_{sqb}; i^*_{sc} = i_{spc} + i_{sqc} \quad (24)$$

Henceforth, to alleviate the current harmonic problems, the Hysteretic Current Controller (HCC) now works by integrating the obtained reference currents ( $i^*_{sa}$ ,  $i^*_{sb}$  and  $i^*_{sc}$ ) by means of the measurement system source currents ( $i_{sa}$ ,  $i_{sb}$  and  $i_{sc}$ ) and the resulting errors.

### 3.3. Proposed Schematic for Series Converter

Figure 4 shows the control scheme of the VSC series. The objective of the controlling is to ensure that the load voltage has the appropriate amplitude and sinusoidal waveform. As shown below, the load reference voltage is assessed using the proposed AL\_LMS technique. 3- $\Phi$  load's currents ( $i_{La}$ ,  $i_{Lb}$  and  $i_{Lc}$ ) be detected in order to calculate their amplitude ( $I_{Lp}$ ), whose unit samples are given by equations (25) and (26).

$$I_{Lp} = \sqrt{\frac{2}{3}(i_{La}^2 + i_{Lb}^2 + i_{Lc}^2)} \quad (25)$$

$$u_{pa} = \frac{i_{La}}{I_{Lp}}; u_{pb} = \frac{i_{Lb}}{I_{Lp}}; u_{pc} = \frac{i_{Lc}}{I_{Lp}} \quad (26)$$

Additionally, these in-phase unit templates were utilized to calculate the quadrature current unit templates, which can be shown as

$$u_{qa} = \frac{-u_{pb} + u_{pc}}{\sqrt{3}}; u_{qb} = \frac{\sqrt{3} * u_{pa}}{2} + \frac{1}{2\sqrt{3}}(u_{pb} - u_{pc}); u_{qc} = -\frac{\sqrt{3} * u_{pa}}{2} + \frac{1}{2\sqrt{3}}(u_{pb} - u_{pc}) \quad (27)$$

The weighted load's voltage in-phase component ( $W_{vpa}$ ) of the phase 'a' be now determined by means of the basic weighted update expressions, given by the below equations (28) - (31).

$$W_{vpa}(t + 1) = W_{vpa}(t)[1 - 2\mu_{vpa}(t) * \lambda_{vpa}(t)] + [2\mu_{vpa}(t) * E_{vpa}(t) * u_{pa}(t)] \quad (28)$$

$$\lambda_{vpa}(t + 1) = \lambda_{vpa}(t) - [2\mu_{vpa}(t) * \rho * E_{vpa}(t)] * [u_{pa}(t) * W_{vpa}(t - 1)] \quad (29)$$

$$\mu_{vpa}(t + 1) = [\alpha * \mu_{vpa}(t)] + [\lambda_{vpa}(t) * R_{vpa}^2(t)] \quad (30)$$

$$R_{vpa}(t) = [\beta * R_{vpa}(t - 1)] + [(1 - \beta) * E_{vpa}(t) * E_{vpa}(t - 1)] \quad (31)$$

Error Estimate could be computed as

$$E_{vpa}(t) = V_{sa}(t) - [u_{pa}(t) * W_{vqa}(t)] \quad (32)$$

Where,  $V_{sa}$  : source's voltage of phase 'a'. At each point of the VSC series, the same method can be used to adjust the phases "b" and "c", the phase weight components ( $W_{vpb}$  and  $W_{vpc}$ ), the leakage factors ( $\lambda_{vpb}$  and  $\lambda_{vpc}$ ), the step sizes ( $\mu_{vpb}$ ) and  $\mu_{vpc}$ ), the error autocorrelations ( $R_{vpb}$  and  $R_{vpc}$ ) and the prediction errors ( $E_{vpb}$  and  $E_{vpc}$ ). Equation (33) below is used to find the phase components weighted average ( $W_{vpave}$ ).

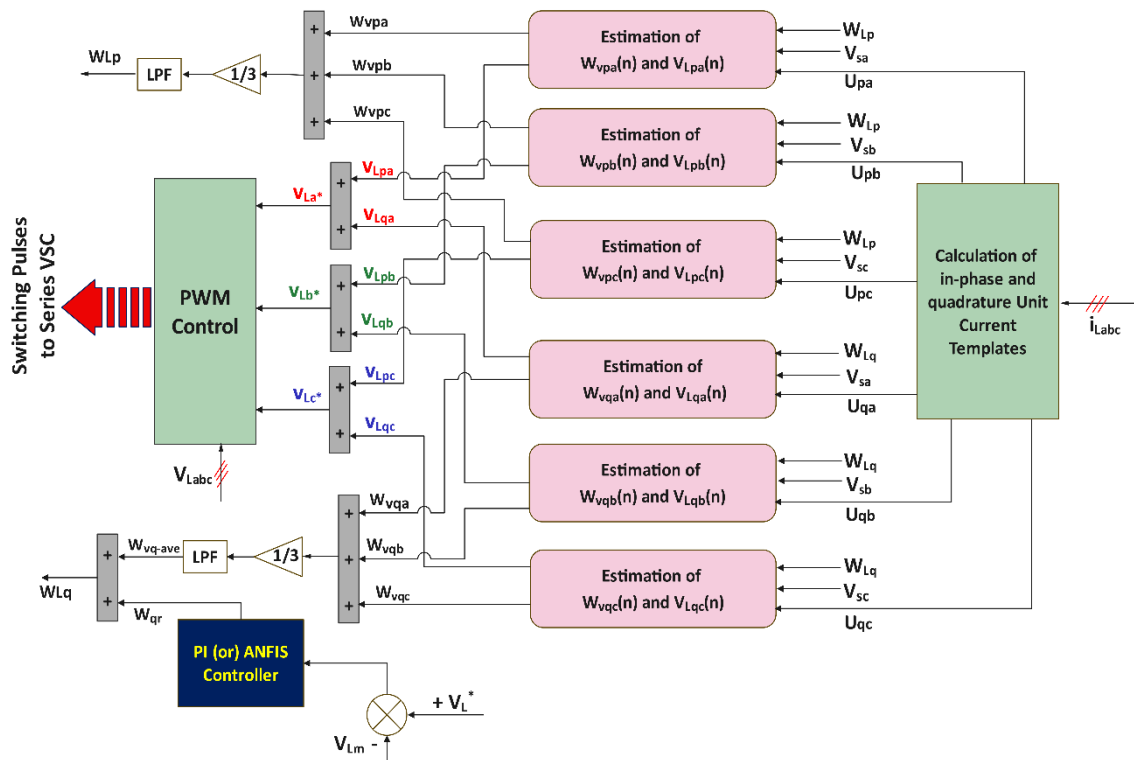


Figure 4. Control Scheme for Proposed Series-VSC

$$W_{vpave} = \frac{W_{vpa}(t) + W_{vpb}(t) + W_{vpc}(t)}{3} = W_{Lp} \quad (33)$$

The elements of the measured in-phase reference load's voltage are as follows:

$$V_{Lpa} = W_{Lp} * u_{pa}; V_{Lpb} = W_{Lp} * u_{pb}; V_{Lpc} = W_{Lp} * u_{pc} \quad (34)$$

Alike to this, the AL\_LMS system is also proposed to estimate the weights of the quadrature components of load's voltage ( $W_{vqa}$ ,  $W_{vqb}$  and  $W_{vqc}$ ). The following equation (35) represents the weighted average reactance component.

$$W_{vqave} = \frac{W_{vqa}(t) + W_{vqb}(t) + W_{vqc}(t)}{3} \quad (35)$$

Now consider the loss component ( $W_{qr}$ ) in this case which is written as equation (36) to regularize the load voltage.

$$W_{qr}(t + 1) = W_{qr}(t) + K_{pq} * [E_{ac}(t + 1) - E_{ac}(t)] + K_{iq} * E_{dc}(t + 1) \quad (36)$$

By comparing the measured load voltages ( $V_{La}$ ,  $V_{Lb}$  and  $V_{Lc}$ ) with the nominal load's voltage ( $V_L^*$ ), an signaling error is engendered and sent to the PI/ANFIS controller. The following equation shows the ability of the regulator to ultimately maintain the desired amplitude of the load voltage.

$$V_{Lm} = \sqrt{\frac{2}{3}(V_{La}^2 + V_{Lb}^2 + V_{Lc}^2)} \quad (37)$$

$$E_{ac}(n) = V_L^*(n) - V_{Lm}(n) \quad (38)$$

The equation (39) for the total quadrature weighted voltage component ( $W_{Lq}$ ) associated with the load is represented by

$$W_{Lq} = W_{vqave} + W_{qr} \quad (39)$$

The entire quadrature component of the load's reference voltage is described by the following equation (40).

$$V_{Lqa} = W_{Lq} * u_{qa}; V_{Lqb} = W_{Lq} * u_{qb}; V_{Lqc} = W_{Lq} * u_{qc} \quad (40)$$

Subsequently, the substantial load's voltages references for each in the 3-phase as given:

$$V_{La}^* = V_{Lpa} + V_{Lqa}; V_{Lb}^* = V_{Lpb} + V_{Lqb}; V_{Lc}^* = V_{Lpc} + V_{Lqc} \quad (41)$$

Finally, by means of relating the reference voltage with the calculated load's voltage, this variable is transferred towards the PWM generator in providing switching pulsations intended for the series VSC. In the future, multiple UPQC components will be implemented to improve the PQ allegations.

### 3.4 Adaptive Neuro-Fuzzy Inference System (ANFIS) Control

Another neural network-based system is the Adaptive Neuro-Fuzzy Inference System (ANFIS) [25], combines advantages of the Fuzzy Logic (FL) and Neural Networks (NN). Control systems that incorporate redundant mechanisms and neural networks are often used to increase their effectiveness and efficiency. The weight of the neural network ranges from -1 to 1 and is accustomed for modifying the constraints of the Fuzzy Inference System (FIS), as shown in Figure 4. A standard fuzzy rubrics set was produced by means of the FIS using real voltage and current constraints like input variables and compensatory voltage and current signals like output variables, as shown in Table 1. The interpretation of these factors by the system is crucial since incorrect tuning may result in either overfit or underfit data.

ANFIS model parameters can be varied using a hybrid approach combining Least Squares (LS) with Mean Square Error (MSE) methods. Reducing training error is the goal of the training process [26]. During the training process, the NN and FIS parameters are adjusted to minimize the difference amongst the actual compensation voltage and current and the predicted compensation voltage and current. A set of validation rules is used to assess the precision of the trained ANFIS algorithm in approximating compensation voltage and current requirements under different operating conditions. After training and verification, the ANFIS system is incorporated into the control system to establish the necessary relationships between ANFIS outputs (such as control signals) and ANFIS inputs (such as errors and error changes) to integrate PI controller and replace with ANFIS controller as shown in Figures 5 and 6.

Table 1. Fuzzy Rules Table Set

e \ ce	NB	NS	Z	PS	PB
NB	NB	NB	Z	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

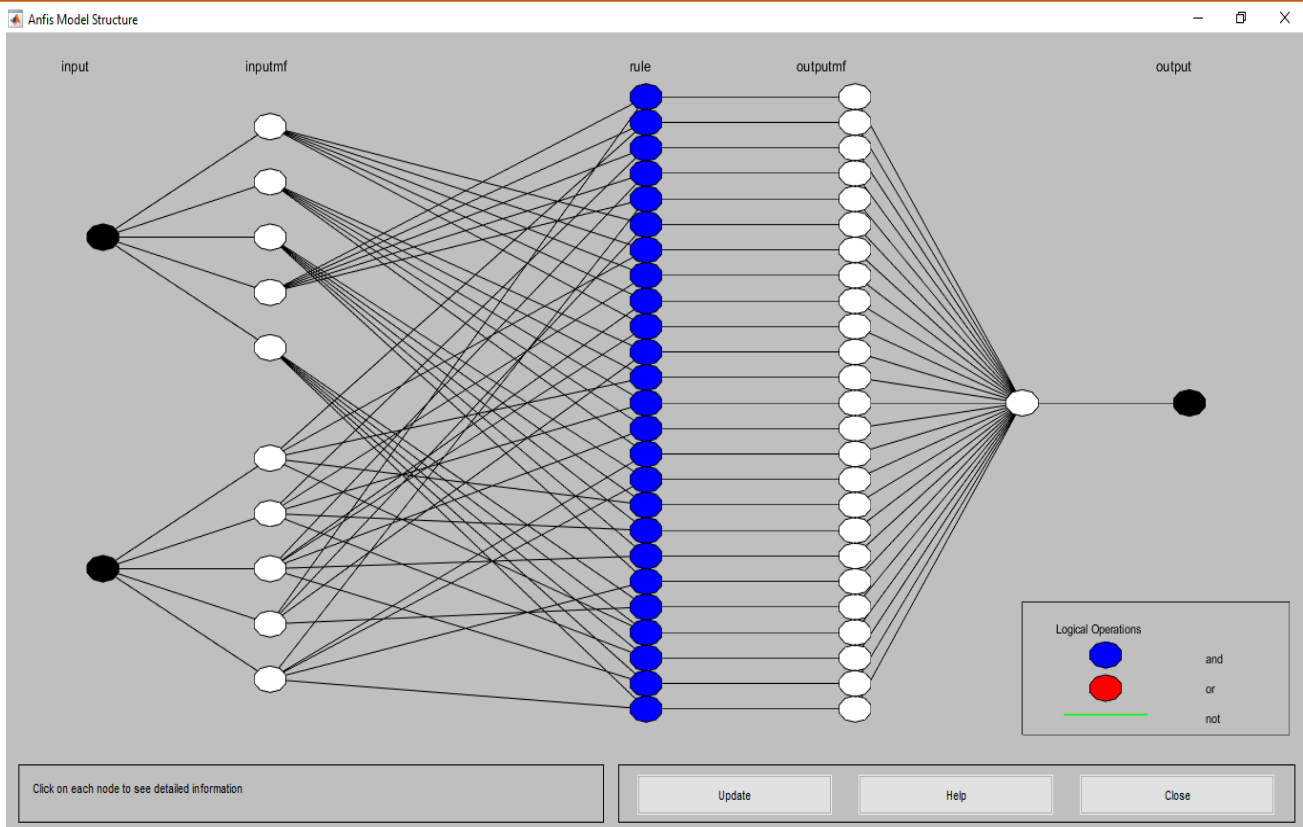


Figure 5. ANFIS Model Structure

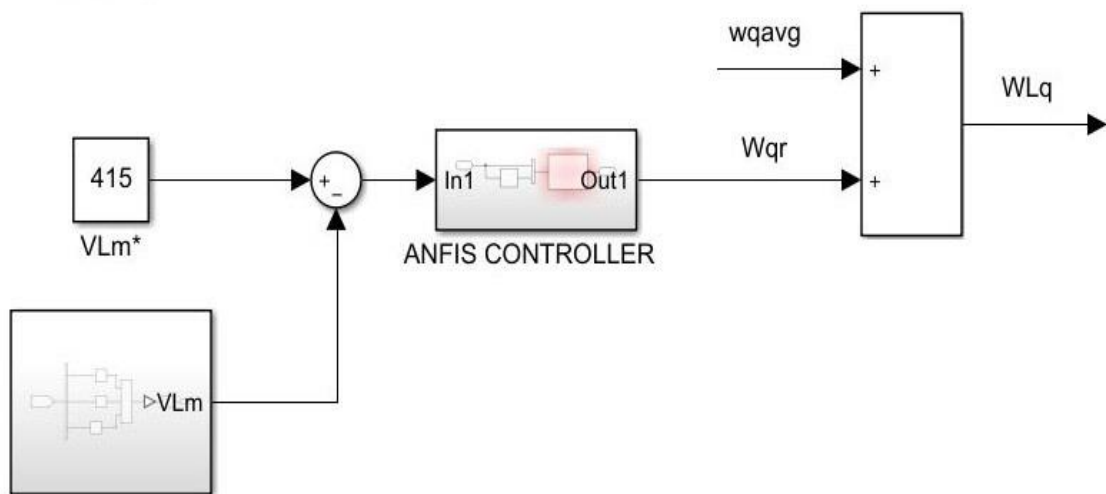


Figure 5. Series-VSC ANFIS Control Strategy

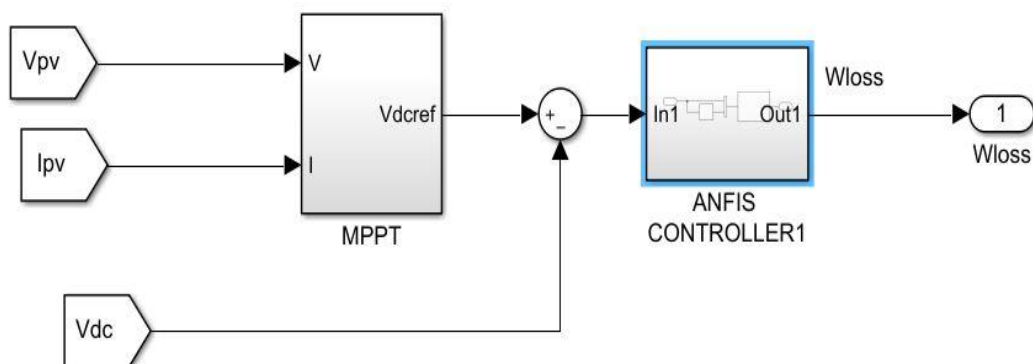


Figure 6. Strategy in Shunt-VSC by ANFIS Control

### 4. Results and Discussion

As shown in Figure 7, the solar photovoltaic compatible UPQC arrangement is modelled in MATLAB/Simulink software, and at that time the proposed AL\_LMS algorithm is used in combination with traditional PI and AFIS controller algorithms.

The following table 2 lists the parameters that were used to simulate the system that is being discussed.

### 4.1 Series VSC's Performance Analysis for Voltage Sag and Swell conditions

#### 4.1.1 with Custom PI Controller

Using the AL\_LMS algorithm based on a traditional PI controller, the figure below shows the performance of the UPQC series VSC under voltage drop and ripple voltage. By connecting VSC UPQC in series, the voltage drop of each unit at  $t=0.1$  seconds is smoothed by 0.5, and the voltage jump of each unit at  $t=0.3$  seconds is smoothed by 1.2 to obtain the rated load voltage.

Table 2. System Parameters

Parameters	Values
Supply Grid Voltage (Vs)	415V (L-L)
Coupling inductors (Lse and Lsh)	1.5mH
DC-link Capacitor (Cdc)	8000 $\mu$ F
DC-link Voltage (Vdc)	700 V
Gains of Shunt VSC	$K_P = 2$ & $K_I = 0.1$
Gains of Series VSC	$K_P = 4$ & $K_I = 800$
Solar-PV MPPT (voltage and current)	700V, 60A
Non-linear load	15KW, 7.2KVA

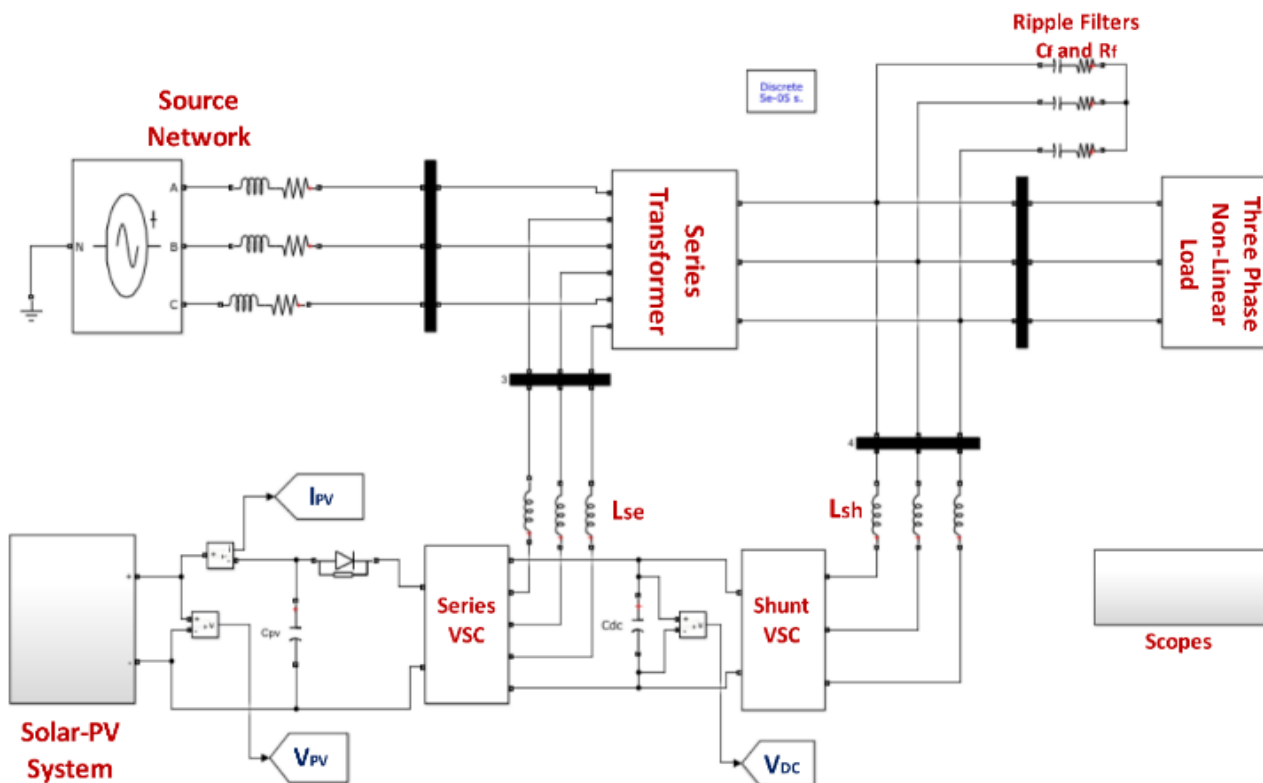


Figure 7. MATLAB/Simulink diagram of a projected Solar-PV integrated UPQC System

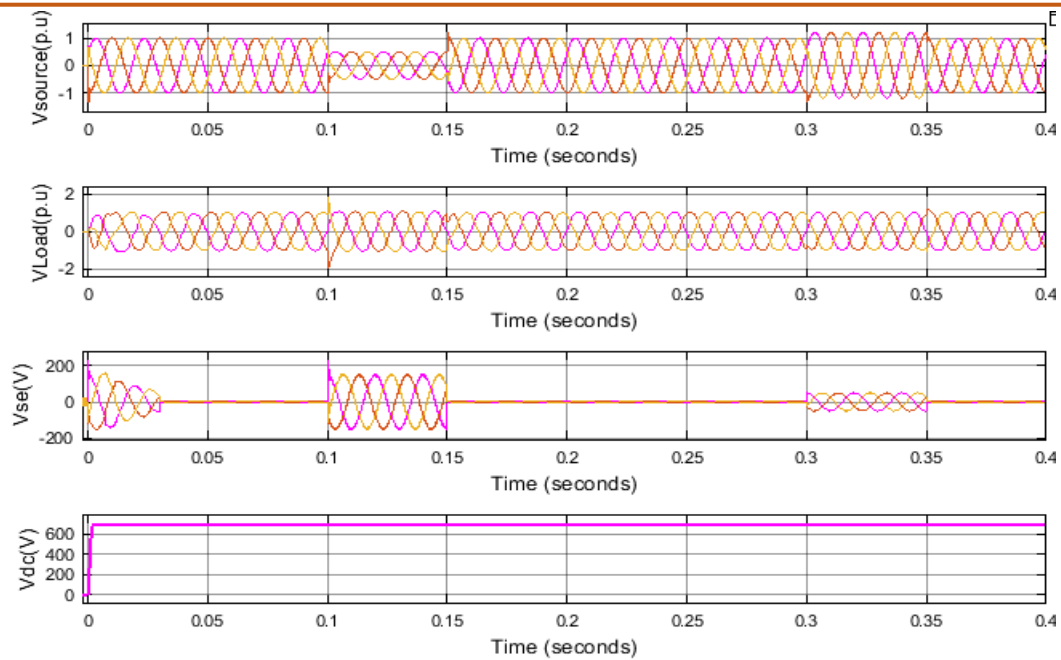


Figure 8. PI Controller based UPQC Compensation to Voltage Sag and Swell Conditioning

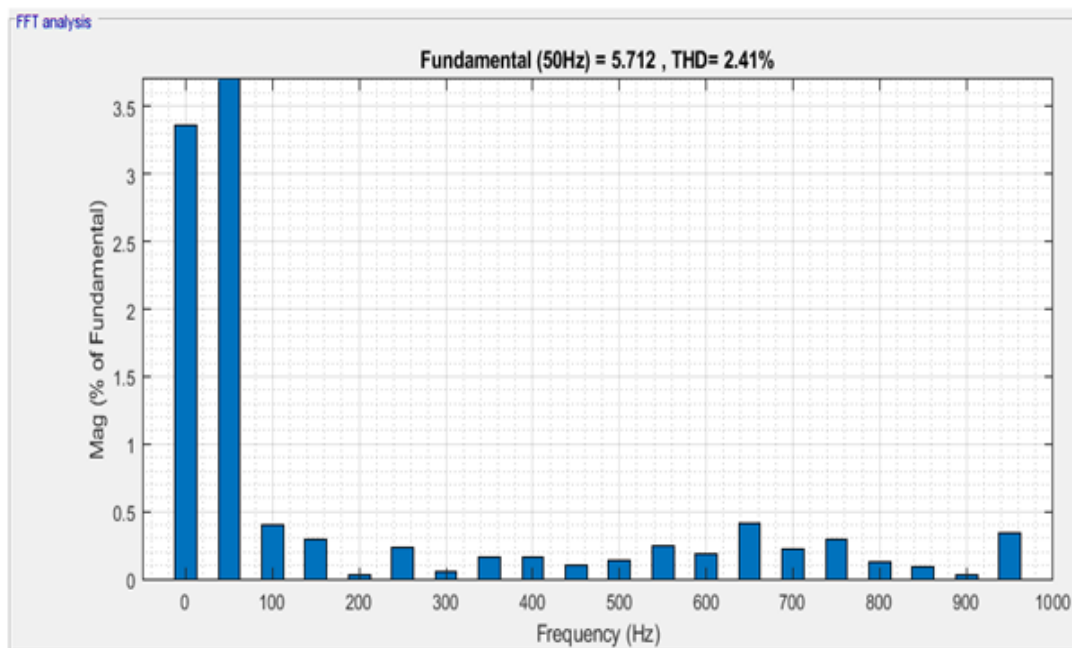


Figure 9. %THD of Load's voltage via custom PI control

Figure 9 shows that using a typical PI controller mounted on UPQC, the load voltage %THD is 2.41%. In addition, as shown below, inspections are performed through the ANFIS controller to improve power quality.

#### 4.1.2 With ANFIS controlled AL\_LMS algorithm

Using the proposed AL\_LMS model for ANFIS control, the performance components of the UPQC series under voltage drop and swell conditions are shown in the figure 10. The UPQC Series VSC improves voltage to rated load voltage, resulting to a 0.5 P.U. voltage drop at t=0.1s and a 1.2 P.U. voltage increase at t=0.3s.

More efficient recompense of voltage sag and swell is achieved with expected ANFIS driven AL\_LMS process by the enhanced %THD performance. Performance analysis of parallel VSCs under nonlinear load conditions shows a measured load voltage %THD of 0.94%, compared to %THD of 2.41% by a custom PI controller.

#### 4.2 Evaluation of Shunt-VSC Performance to Non-linear Load Circumstances

The following description illustrates the effectiveness of parallel VSCs in the existence of non-linear loads.

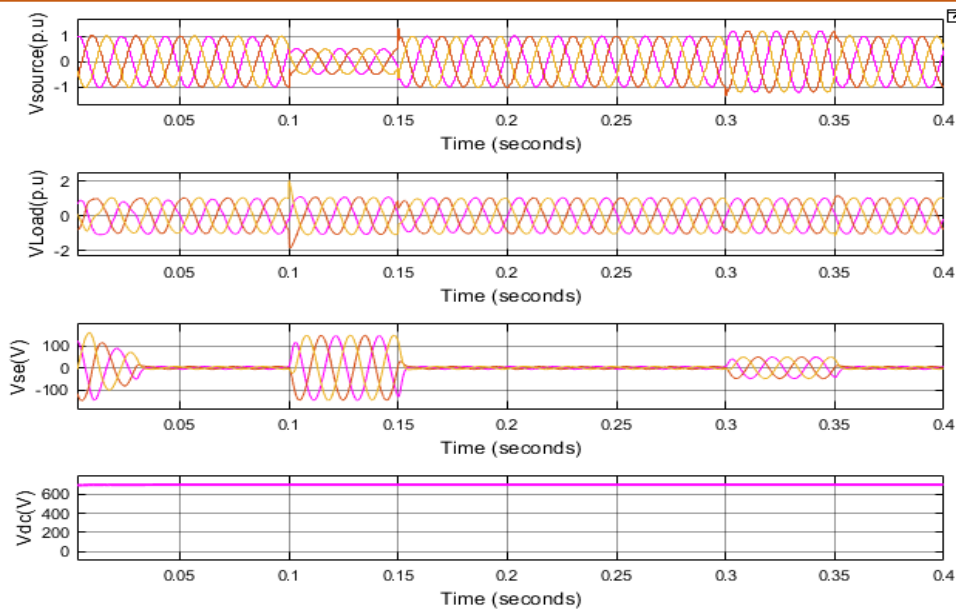


Figure 10. Voltage Sag and Swell conditioning via ANFIS controller

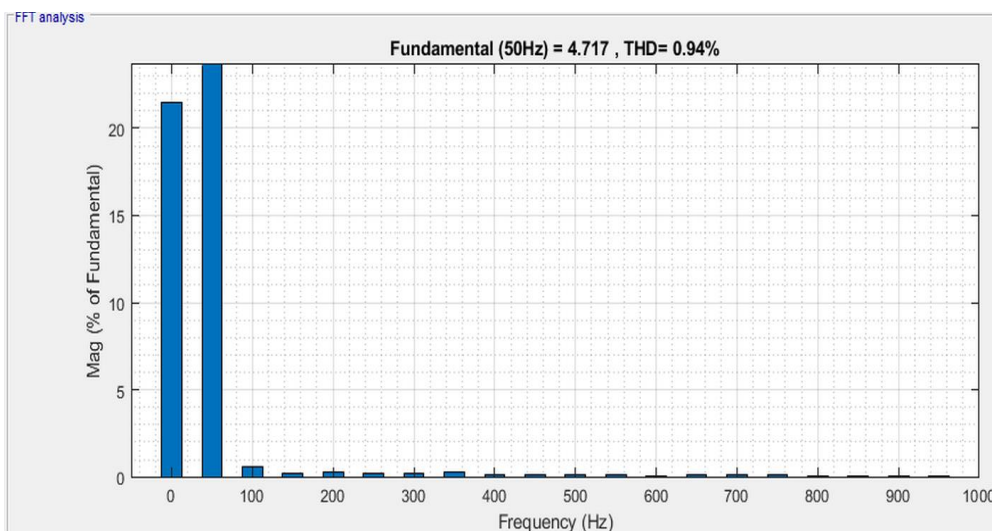


Figure 11. Proposed ANFIS control AL\_LMS model showing THD percentage of load voltage

This control technology involves the grid and solar photovoltaic arrays working together to meet the power demand for load generation and maintain high DC voltages. The results of the ANFIS and PI control techniques are shown in the figure below.

#### 4.2.1 Use of custom PI controlled AL\_LMS algorithm

The line/source current is affected by harmonics generated by the nonlinear load before  $t=0.04$  s, as shown in Figure 12, resulting in a sinusoidal line current. As shown in Figure 13 below, the harmonic equation shows that the resulting current source has a THD of 3.49%.

#### 4.2.2 Use of ANFIS control-based AL\_LMS algorithm

By comparing the proposed ANFIS control with the AL\_LMS algorithm by PI control, the differences in source/grid and load's currents are further minimized. As

given away in Figure 14, the parallel VSC UPQC can also compensate for the nonlinearity caused through the system source current, maintaining a persistent DC bus voltage at  $t=0.04$  s despite the fact generating a sinusoidal grid current.

ANFIS controller achieves 0.98% THD in grid/source current, while typical PI controller achieves 3.49%, as shown in Figure 15. In Table 3, both traditional PI and ANFIS controlled based on AL\_LMS method is presented for %THD of supply/grid current due to nonlinear loads and also infers load's voltage THD due to sag and swell. By comparing AL\_LMS algorithm based on proposed ANFIS controller with PI controller, PQ is improved.

#### 4.3 Assessment of Power flows in the system

The following figures 16 and 17 illustrates the active and reactive power flows in a system meeting the load demand by both the Solar-PV system and Grid supply system.

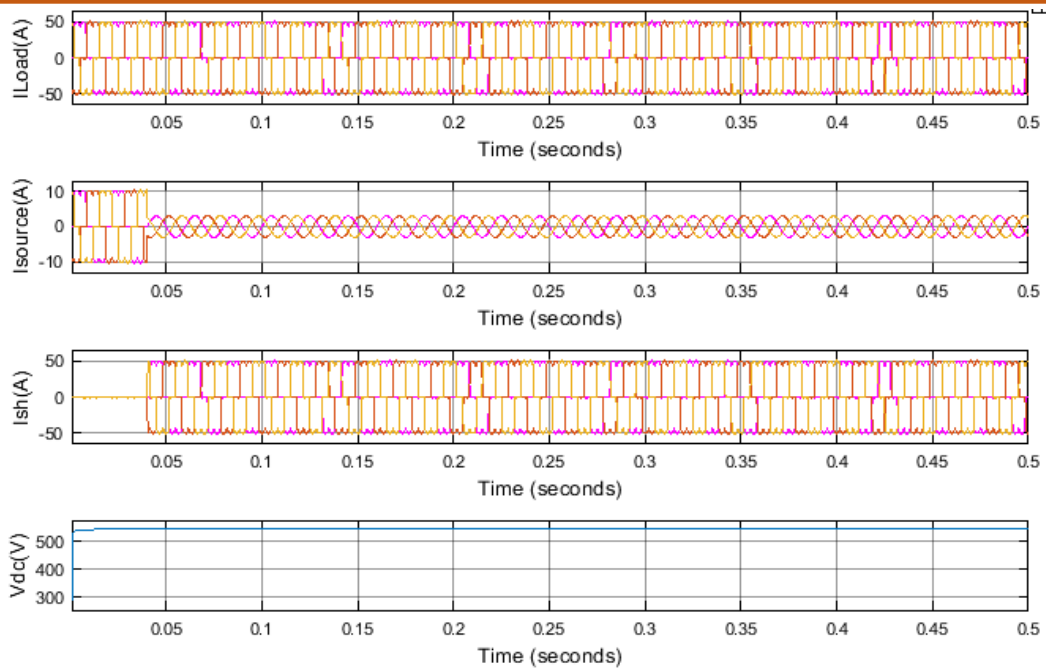


Figure 12. Shunt VSC performance toward non-linear loads using a custom PI controller

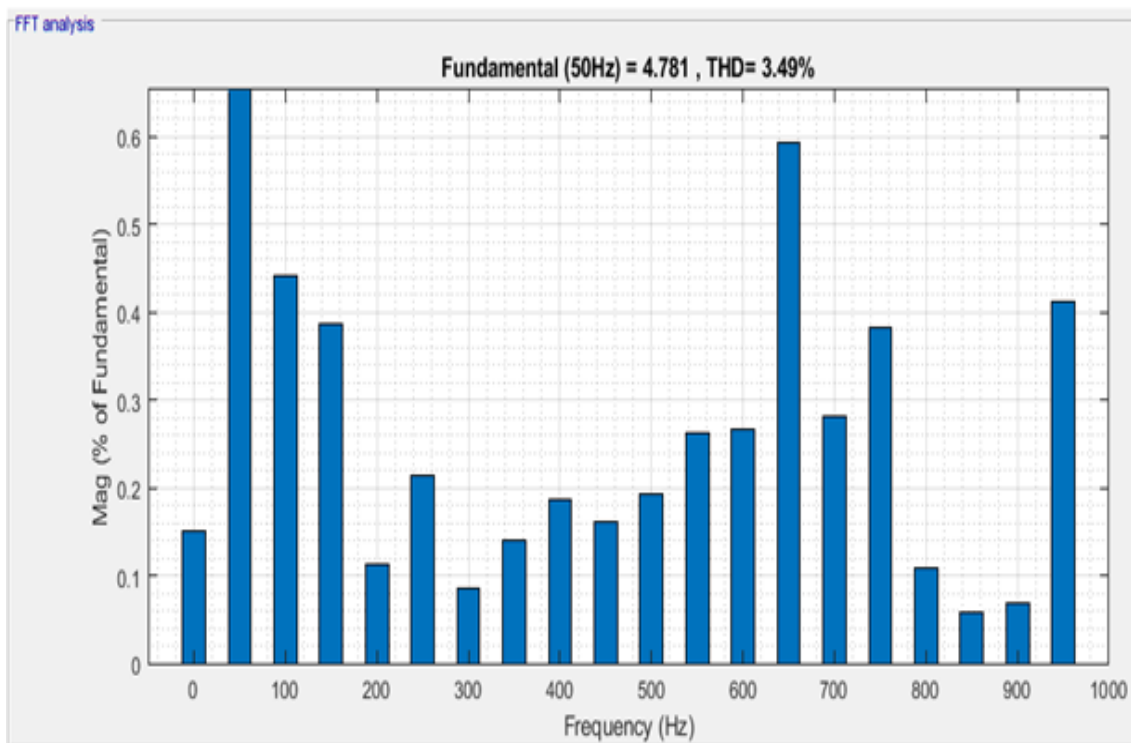


Figure 13. Source's current %THD with custom PI control

Table 3. %THD assessment of proposed UPQC controller methods

% THD with Proposed AL_LMS Algorithm			
Parameters	Types of Controller		
	With PI Controller [22]	With Fuzzy Controller [23]	With ANFIS Controller
Load Voltage (For Sag and Swell)	2.41%	2.29%	0.94%
Grid/Source Current (For Non-Linearities)	3.49%	3.38%	0.98%

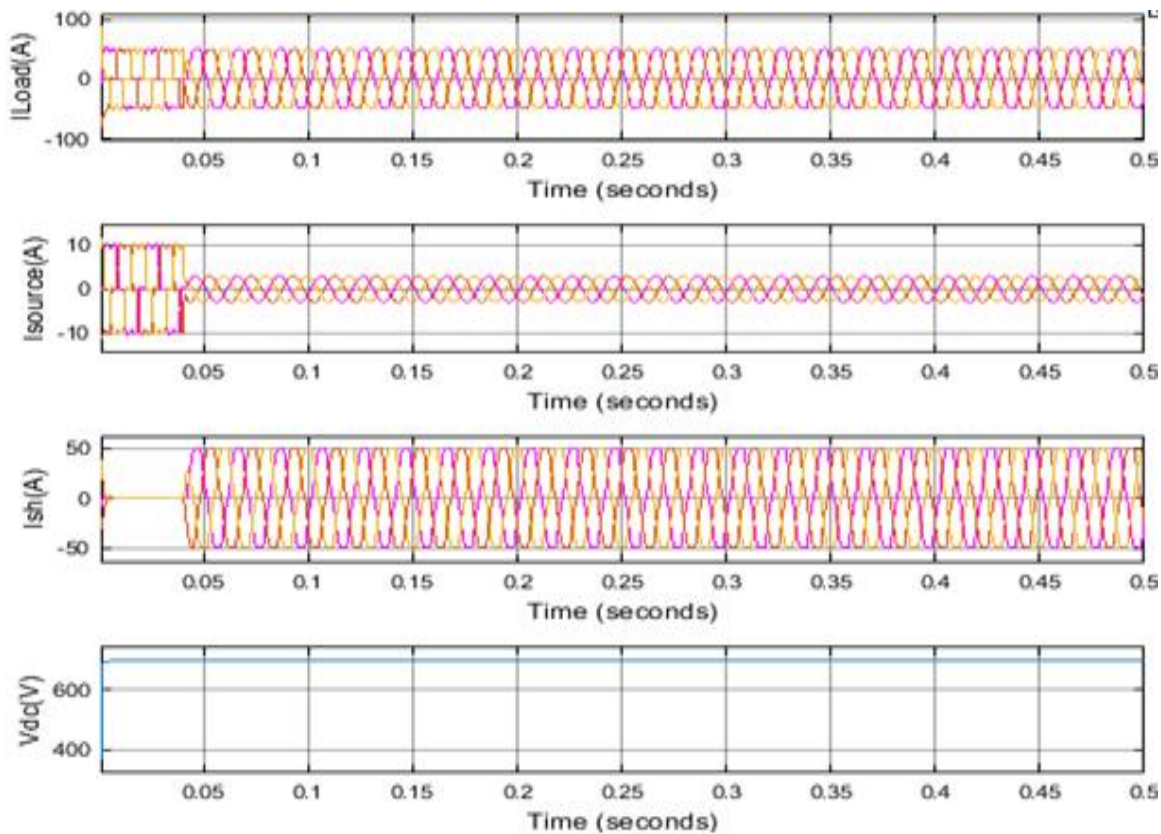


Figure 14. Presentation of ANFIS controlled Shunt-VSC toward Non-linear loads

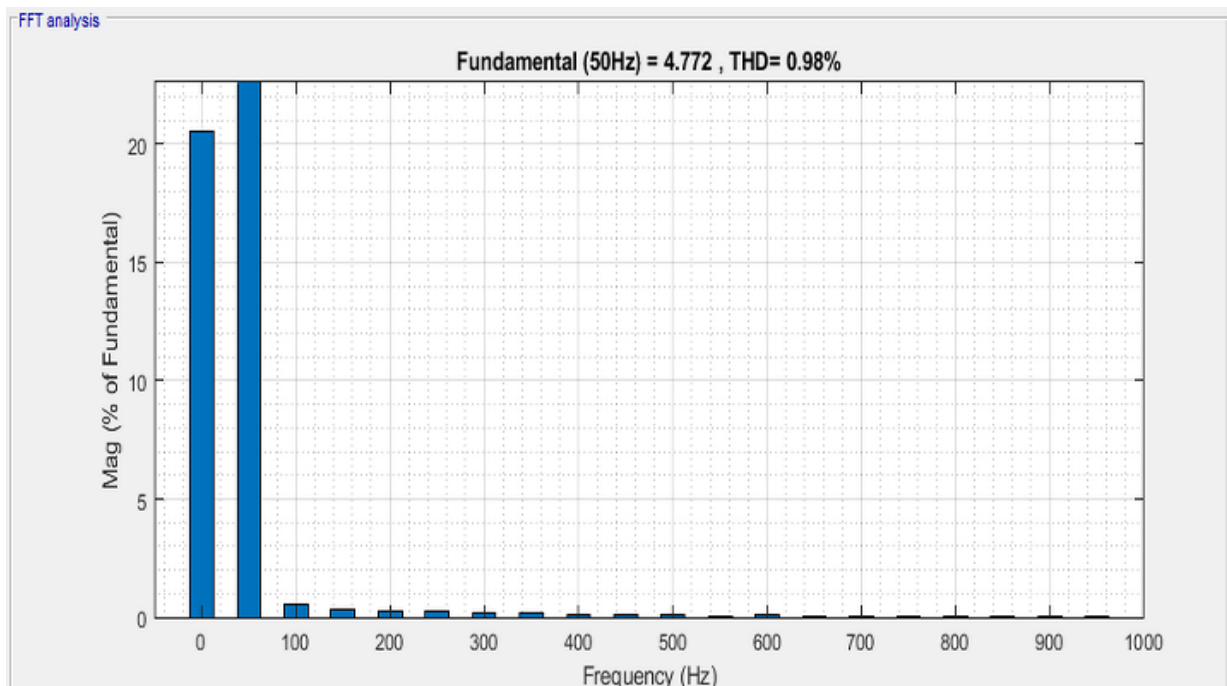


Figure 15. Proposed ANFIS control for source's current THD

From the figure 16, it is observed that the Solar-PV power is meeting the required load demand while the remaining power is fed to the main grid, resulting in the effective utilization of energy resource.

It can be seen from figure 17 that the required reactive power is met by the UPQC resulting in the lower burden on the main grid system.

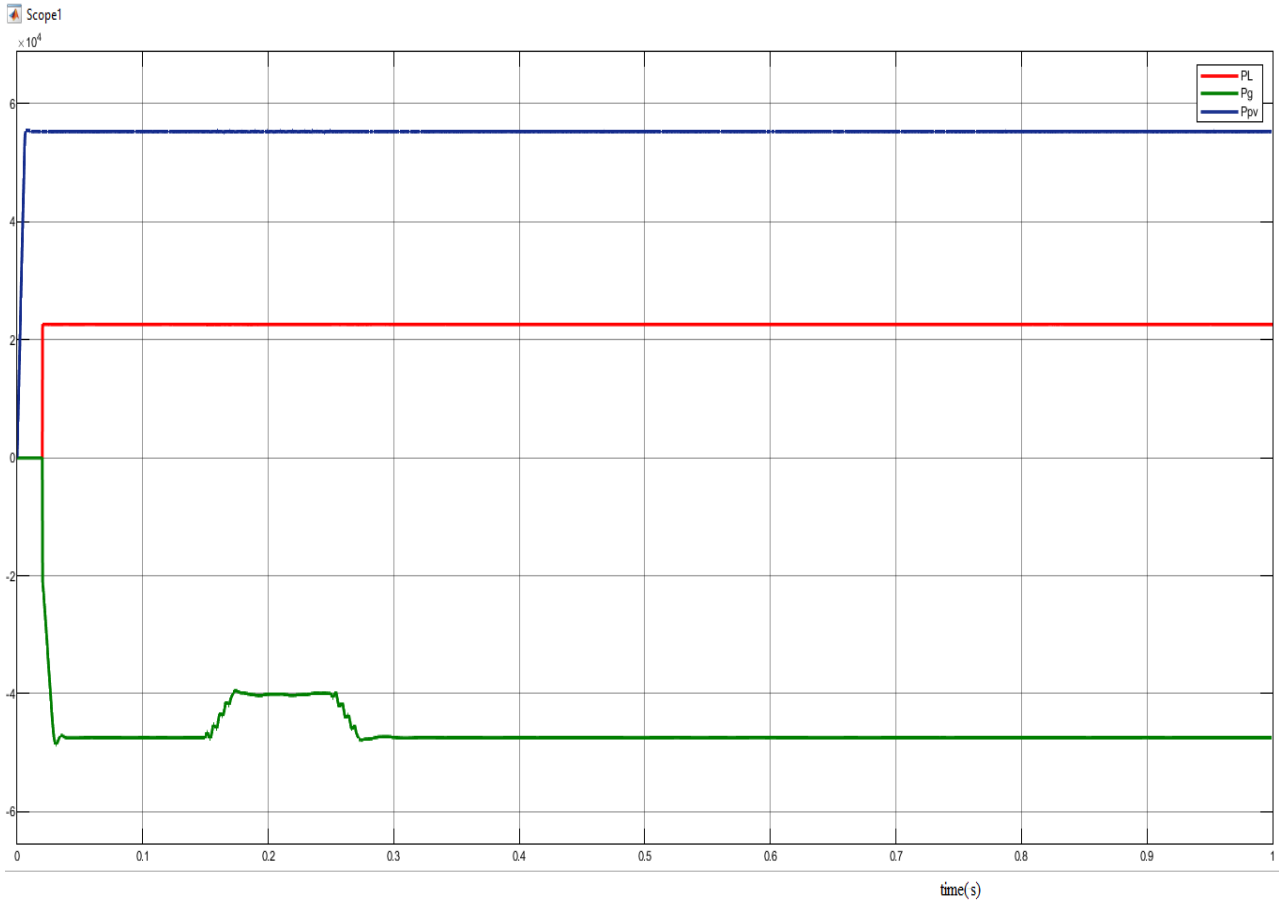


Figure 16. Active power flows of the system

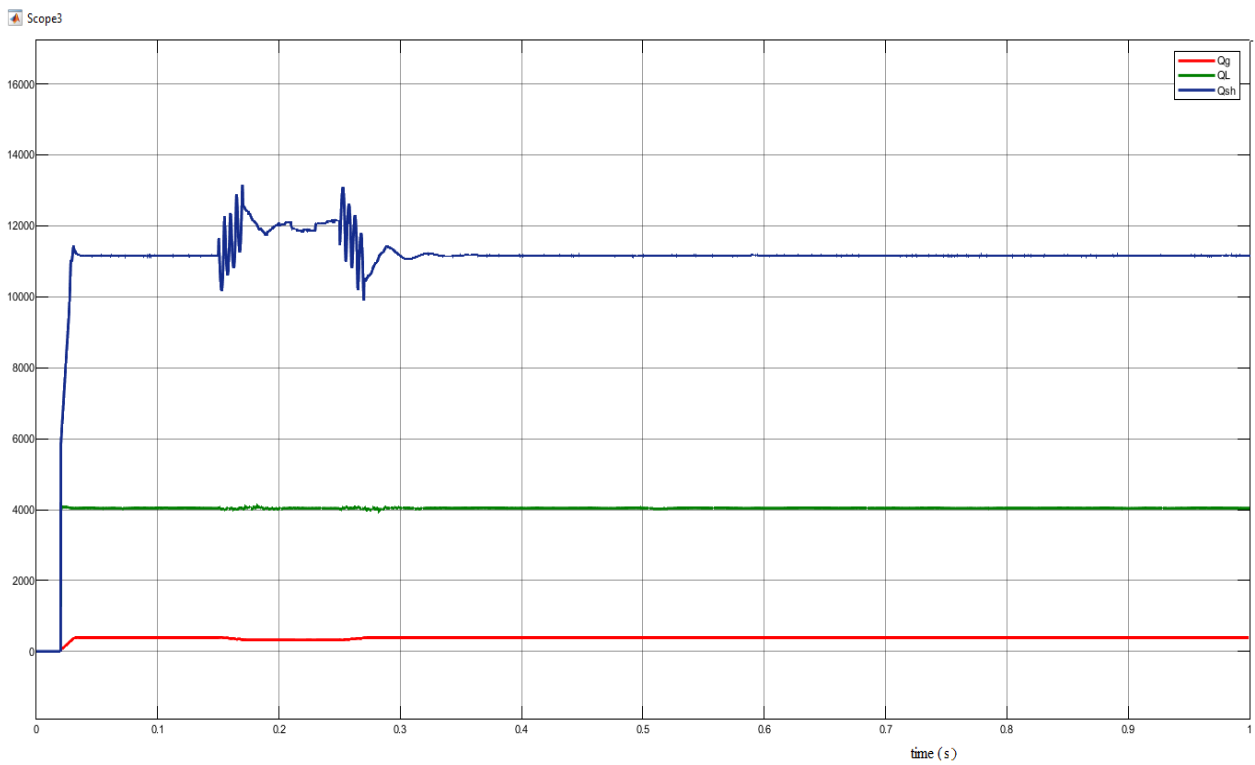


Figure 17. Reactive power flows of the system

## 5. Conclusion and Future Scope

Herein the study, an adaptive control method relied on the AL\_LMS algorithm thru the ANFIS controller is anticipated to solve the power quality problem of solar photovoltaic power supply UPQC in decentralized networks. The system performance can be evaluated by comparing the %THD of the ANFIS controller with that of a conventional PI controller under the conditions of nonlinear load, voltage sags and swells. In these cases, better results are achieved by using the AL\_LMS algorithm, which is based on the ANFIS controller and generates appropriate reference currents for parallel and series VSC of UPQC. The load voltage is efficaciously upheld at the nominal rated voltage even during sags and surges. In addition, the THD percentage of the source's current remains significantly reduced and becomes sinusoidal for the nonlinear load current. Moreover, the proposed method helps in utilizing solar-PV energy to meet the load active power demand, in so doing tumbling the power grid's burden. With the intention of enlightening the power quality of the system, UPQC can adopt a multi-level converter topology and might incorporate optimization techniques to improve the regulation of the PI controller in the further research.

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#### Authors Contribution Statement

Chilakapati Lenin Babu: Original draft, writing and formatting, methodology and conceptualization, software modeling of the system and T. Gowri Manohar: Research Supervision, Methodology, Reviewing and Suggestions.

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#### Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

#### Has this article screened for similarity?

Yes

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