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Power Quality Enhancement in a Grid-Integrated Solar-PV System with a Hybrid UPQC Control Strategy

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ABSTRACT

The supply grid network has been periodically experiencing frequent problems with Power Quality (PQ), and these problems have gotten worse over time due to the rise of electrical appliances. Thus, supplying consumers with electricity in the custom of sinusoidal voltages and currents that have adequate magnitudes and frequencies near the common point of coupling (PCC) stays one of the Utility system's main responsibilities. Thus, in order to improve PQ in the supply grid network, this article examines the practice of solar-PV coordinated Unified Power Quality Conditioner (UPQC).

By means of optimizing the utilization of solar energy and improving PQ, the Solar-PV fed UPQC contributes clean, renewable energy to the grid and solves environmental problems at the same time. This study presents Adaptive Leaky Least Mean Square (AL_LMS) algorithm-based control techniques for UPQC, which include both traditional Proportional-Integral (PI) and Adaptive Neuro Fuzzy Inference System (ANFIS) controllers for UPQC series and shunt active converter switching. This method gets the reference signals with switching on the shunt and series voltage source converters (VSCs) of UPQC by means of iteratively updation of the weights. Accordingly, PQ consternations for instance, voltage sag and swell of load voltage and harmonic distortions of grid current are reduced when control techniques have been applied to solar-PV fed UPQC. This work is carried out in MATLAB/Simulation software, and also the results of simulations demonstrate that the suggested ANFIS controlled AL_LMS algorithm is the most effective at improving power quality while adhering to IEEE-519 Standards when applied to a solar-PV fed UPQC.

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تحسين جودة القدرة لمنظومة الطاقة الشمسية الكهروضوئية المتكاملة بالشبكة مع استراتيجية التحكم الهجينة في UPQC .

ملخص: تتعرض شبكة الإمداد الكهربائية بشكل دوري لمشاكل متكررة في جودة القدرة، وقد تتفاقم هذه المشاكل مع مرور الوقت بسبب التوسع في استخدام الأجهزة الكهربائية. وبالتالي، فإن تزويد المستهلكين بالكهرباء بجهد وتيارات جيبية ذات مقادير وترددات كافية بالقرب من نقطة الاقتران المشتركة (PCC) يظل أحد المسؤوليات الرئيسية لنظام المرافق. من أجل تحسين جودة القدرة في شبكات الإمداد، فإن هذه الورقة تتناول كيفية تحسين جودة القدرة الموحدة المتسق بالطاقة الشمسية الكهروضوئية (UPQC). من خلال تحسين استخدام القدرة الشمسية وتحسين معلم PQ، تساهم UPQC التي تغذيها الطاقة الشمسية الكهروضوئية بالطاقة النظيفة والمتجددة في الشبكة وتحل المشكلات البيئية في نفس الوقت. تعرض هذه الدراسة تقنيات التحكم المستندة إلى خوارزمية المربع الأقل تسربًا (AL_LMS) لـ UPQC، والتي تشمل كلاً من وحدات التحكم التقليدية للتكامل النسبي (□□) ونظام الاستدلال العصبي الغامض التكيفي (ANFIS) لسلسلة UPQC وتبديل المحول النشط. تحصل هذه الطريقة على الإشارات المرجعية من خلال تشغيل محولات مصدر الجهد التسلسلي والتحويلي (VSCs) الخاصة بـ UPQC عن طريق التحديث التكراري للأوزان. وفقًا لذلك، يتم تقليل مخاوف PQ على سبيل المثال، وتبلد الجهد وتضخم جهد الحمل والتشوهات التوافقية لتيار الشبكة عندما يتم تطبيق تقنيات التحكم على UPQC التي يتم تغذيتها بالطاقة الشمسية الكهروضوئية. تم تنفيذ هذا العمل باستخدام برنامج MATLAB/Simulation ، كما أظهرت نتائج عمليات المحاكاة أن خوارزمية AL_LMS المقترحة للتحكم في ANFIS هي الأكثر فعالية في تحسين جودة الطاقة مع الالتزام بمعايير IEEE-519 عند تطبيقها على UPQC التي يتم تغذيتها بالطاقة الشمسية الكهروضوئية.

الكلمات المفتاحية – جودة الطاقة، نظام الطاقة الشمسية الكهروضوئية، خوارزمية UPQC، AL_LMS، وحدة تحكم ANFIS.

1. INTRODUCTION

Nowadays, the usage of Renewable Energy Sources (RES) for energy generation, for e.g., solar-PV systems and wind systems, has become more popular owing to the exhaustion of traditional energy sources and their adverse impacts on the environment. The network interplay of these RES for enhanced system performance is currently a prominent focus by the industry and academia studies. The popularity of RES has grown in comparison to traditional energy sources because of their accessibility, environmental friendliness, and declining costs [1]. Conversely, over the past few decades, the incorporation of numerous controlling devices, information processing devices, renewable energy sources, and sensitive power electronics equipment to the distribution system has resulted in an abrupt rise in the demand for power, moments distribution networks experiencing a notable increase in PQ problems [2]. In a distributed system, PQ set a critical part in guaranteeing the proper operation of associated devices and the entire system's viability. Thus, voltage quality and current quality are important. PQ problems, like voltage sag, voltage swell, harmonics, and flicker, can lead to disruptions, damage to sensitive equipment, and reduced efficiency in power supply systems had been discussed by [3]. By this context, the application of PQ Enhancement (PQE) techniques has gained significant attention to mitigate power disturbances and voltage fluctuations. To improvise the functionality and stability of electric power systems, resolve issues with the PQ, numerous devices and technologies have been proposed and put into practices [4]. In [5, 6] proposed Flexible AC Transmission Systems (FACTS) devices that are cutting-edge technological solutions for enhancing voltage regulation, besides stable and immediate apparent controlling of active and reactive powers at the fundamental frequency. Supplementary methods rely on distinctive power apparatuses that provide a range of alternatives, such as both shunt and series compensation of active along with reactive power to enhance PQ, voltage control in associate with performance at fundamental and harmonic frequencies w.r.t. steady-state and dynamic situations [7]. UPQC is regarded as a customized power device that has emerged as a promising solution in alleviating both Voltage and Current PQ issues to electrical supply systems and it can be installed at the PCC in the distribution network. Its primary objective is to ensure continuous PQ improvement by regulating voltage and mitigating various PQ issues for example voltage sags, swells, and harmonics. It consists of two components: active power filter in series (SeAPF) and in the shunt (ShAPF) with a common DC link. The SeAPF is responsible for compensating voltage-related conflicts, such as sags and swells, while ShAPF mitigates current-related issues, such as harmonics and reactive power demand and makes regulations of DC-link voltage [8].

The increasing integration of RES, particularly Solar-PV systems, into the power grid has brought profuse aids in terms of sustainability and reduced carbon emissions as reviewed by [9]. Several advantages can be realized by integrating solar-PV system with UPQC. Firstly, Solar-PV system can serve as a clean RES, reducing inevitability on traditional fossil fuel-based electricity generation and contributing to a more sustainable electricity supply. Secondly, the PV system can provide dynamic support to the active power, enabling the UPQC to perform voltage regulation under different load conditions and maintain a stable power grid stated by the authors [10, 11]. To switch both series compensator and shunt compensator, respectively, a reference load voltage signal and source current signals must be generated via the proper control structure for UPQC. Conventional time-domain techniques like Instantaneous Symmetric Component Theory (ISCT), Synchronous Reference Frame (SRF or d-q-0) technique, Instantaneous Reactive Power (IRPT or p-q) Theory had been utilized in several studies [12-15]. The performance of these classical algorithms formed on p-q and d-q-0 theories are unsatisfactory when the load is unbalanced owing to insignificant performance of low pass filters. Several frequency domain methods are realized by means of Wavelet Transform and the Fast Fourier method, but these approaches consume a more memory, elasticities slower response, and require additional computational efficacy as revised by [16]. Soft Computing Techniques based control schemes (e.g. Neural Networks) are likewise used to distinguish and categorize power quality issues stated in [17]. As a means of lowering THD in Solar-PV system, study [18] suggests a strategy that focuses upon the Leaky LMS adaptive filter algorithm. The input's signal harmonic content is significantly lowered by the suggested filter and delivered to the load. Therefore, control schemes combined with state-of-the-art power electronics equipment afford a durable supporting for managing PQ issues [19, 20].

In the proposed Solar-PV fed UPQC integrated to grid system, the main objective is meant to address the PQ challenges brought on by the 3-Φ non-linear load. In order to conjecture the reference signals meant to directive together shunt and series VSCs of UPQC, controlled approaches based on AL_LMS algorithm with typical PI and ANFIS controllers are conferred to approximation the voltage and current references in functioning together series and shunt compensators. The proposed ANFIS controller gives superior condition than the traditional PI controller as the adaptive leakage parameter feature of the AL_LMS method offers higher performance in both steady-state and dynamic circumstances without drift of weighted parameters exceeding the limits. So, the performance of the Solar-PV fed UPQC is thereby enhanced by fast and more precise estimate of the reference signals used for switching the VSCs for alleviating PQ problems.

2. SYSTEM MODEL DESCRIPTION

The suggested system paradigm features UPQC with Solar-PV system in a grid coupled mode, which is schematically represented in Figure 1. The series converter element of UPQC is connected in series to the supply grid via a connecting inductor (Lse) and a 3-Φ series injection transformer (Tse). An interface inductor (Lsh) couples the shunt VSC component to the load point in parallel, and a capacitor (Cdc) bridges the two compensators. A Solar-PV constituent is allied with a reversal block diode to the DC Capacitor linkage. The addition of ripple filters (Rr & Cr) eliminates the high frequency component of voltage caused by VSC switching. The 3-Φ non-linear load (diode-bridge rectifier) is connected to the system for analyzing the PQ issues.

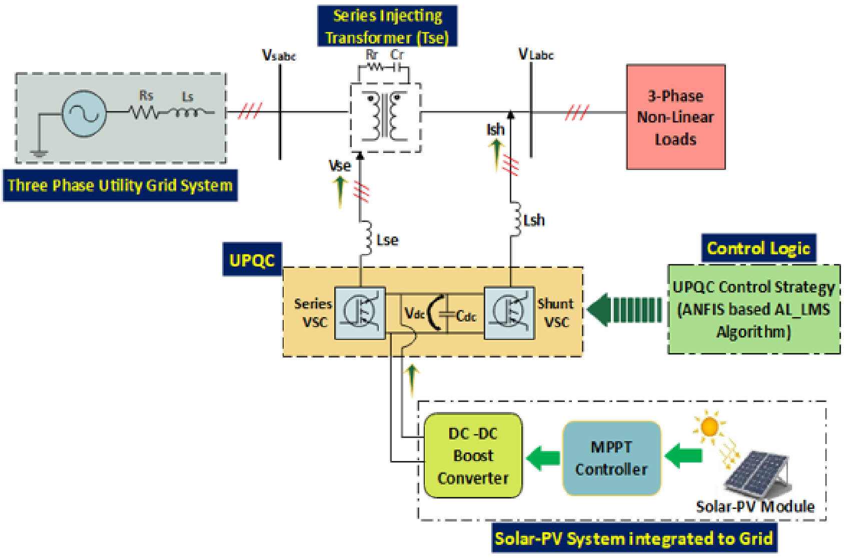

Figure 1. Illustration of a proposed Solar-PV fed UPQC system model.

3. CONTROL SCHEMES FOR UPQC

Here, Shunt VSC of UPQC is inured reducing the harmonics in the network source current and retains DC-link voltage at the significant level. Additionally, it helps PCC meet its demand for reactive power. The load voltage's harmonics, Voltage sag and swell are all reduced thru the series VSC. To switch both series and shunt compensators, respectively, a reference load voltage signal and source current signals must be generated via the proper control structure for UPQC as described below.

3.1. Adaptive Leaky LMS (AL_LMS) Method

In a customized filtering application, a modified conventional LMS method called as the Adaptive Leaky LMS (AL_LMS) algorithm
[21, 22] is employed. In this context of adaptive filtering, the determination is to found an optimal set of filter coefficients (weights) that minimizes the eeriness amongst the desired output and the filter's output. Here, in applied AL_LMS algorithm, a leakage factor is introduced to regulate the rate at which the filter coefficients are updated, thus achieving a trade-off between tracking speed and stability. The mathematical equation [23] correlated to AL_LMS and its estimator are described by below equations (1) and (2).

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

$$Y(t)=W^{T}(t).X(t) \qquad ....(2)$$

Where
X(t): Input vector at time step 't';
W(t): Weighted vector of filter constants at the time step 't';
μ: Step-size or erudition rate, controlling the adaption rate;
λ(t): The leakage factor, which can vary at each time step 't' based on system conditions;
E(t): The instantaneous error signal at time step 't', defined as desired output 'D(t)' minus

predicted output 'Y(t)', i.e.:

$$E(t) = D(t) - Y(t) \qquad ....(3)$$

The cost function Fc(t) is specified by:

$$F_c = E^2(t) + \left[\lambda(t).W^T(t).W(t)\right] \qquad ......(4)$$

Updating of weights are accomplished such that it attains a minimal value. The weight update expressions are obtained thru the equations (5) to (8).

$$W(t+1) = W(t)\left[1-2\mu(t).\lambda(t)\right] + \left[2\mu(t).E(t).X(t)\right] \qquad ....(5)$$

$$\lambda(t+1) = \lambda(t) - \left[2\mu(t).\rho.E(t).X^T(t).W(t-1)\right] \qquad ......(6)$$

$$\mu(t+1) = \left[\alpha.\mu(t)\right] + \left[\lambda(t).R^2(t)\right] \qquad ....(7)$$

$$R(t) = \left[\beta.R(t-1)\right] + \left[(1-\beta).E(t-1)\right] \qquad ....(8)$$

Here:
R(t): Autocorrelation between E(t) & E(t-1);
β: Exponential weighing parameter used to control averaged estimated time, so that $0 < \beta < 1$;
α and ρ: Time convergence control constraints such that $0 < \alpha < 1$ and $\rho > 0$.
Here, in this research, Solar-PV fed UPQC can be controlled adaptively by using the AL_LMS algorithm to produce appropriate reference signals for operating the device. The main objective is to ensure that UPQC effectively compensates for power quality issues by adaptively adjusting the control signals based on the instantaneous measurement of the electrical parameters. The above technique measures the deviation between the measured and anticipated values of these parameters. The disparity between both of these values represents the PQ error, and the reference signals are then adaptively adjusted to eliminate the error [24]. Employing the error signal and a learning rate (μ) to calculate adaptation rate, this method adjusts the reference signals consistently. The UPQC's operations are managed by the modified reference signals that the algorithm produces. To address the power quality issues, this entails producing the proper compensating signals and the operation progresses by a feedback loop through constant adjustment of its control signals by the UPQC in response to shifting electrical circumstances within the system.

3.2. Proposed Scheme for Shunt VSC

The Figure 2 below depicts the suggested controller representation of shunt VSC. The technique aims to manage DC-link voltage while generating a balanced sinusoidal grid/source current. Initially, the instantaneous phase voltages (v_{sa}, v_{sb} and v_{sc}) at PCC for each phase are sensed. Following that, the phase amplitude of the PCC voltage (V_{sp}) is then calculated as labeled in equation (9).

$$V_{sp} = \sqrt{\tfrac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \qquad ....(9)$$

The Equation (10) defines the voltage source in-phase unit templates.

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

The equation (11) represents the quadrature unit templates of voltage using in-phase unit templates.

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

$$v_{qc} = -\frac{\sqrt{3}}{2} v_{pa} + \frac{1}{2\sqrt{3}}(v_{pb} - v_{pc}) \qquad \text{...............}(11)$$

In terms of the control method, the PV array and the grid provides the needed dynamic power for the load. Moreover, the grid allows for the inherent losses of the UPQC by maintaining the constant voltage across DC-link. Error signal (E_{dc}) is obtained and delivered to PI controller with the purpose of minimizing error, after corelating the measured DC-link capacitor voltage (V_{dc}) and anticipated DC-link voltage (V_{dcref}) were provided from MPPT of Solar-PV output.

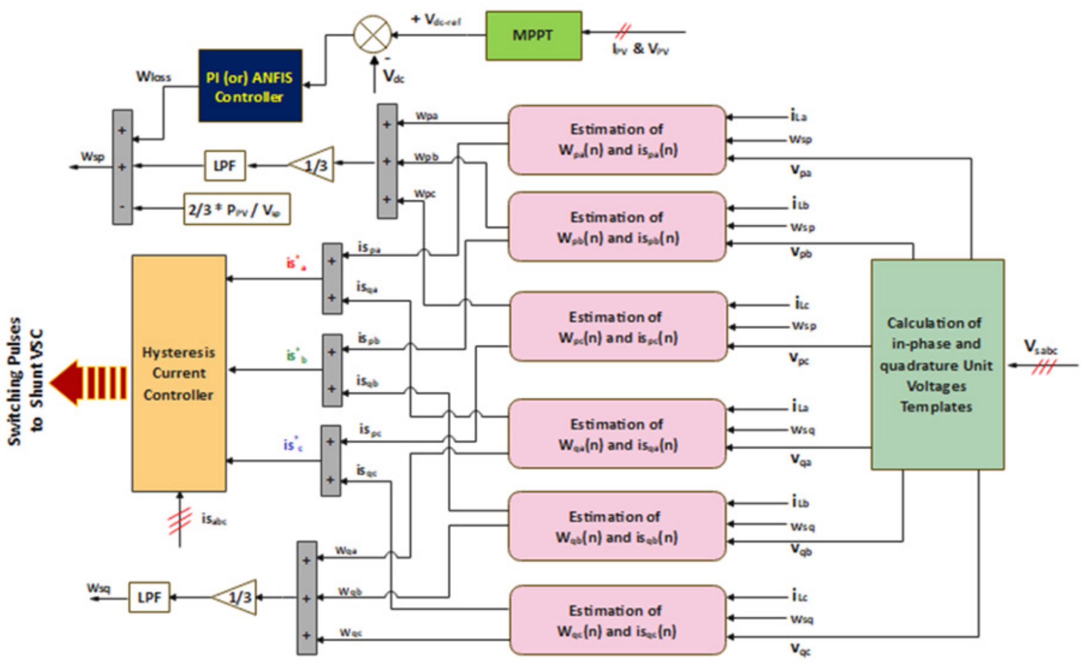

Figure 2. Proposed Schematic Control Diagram of Shunt VSC.

Thus, equations (12) & (13) yield the necessary loss component (W_{loss}) and expressed as:

$$E_{dc}(t) = V_{dcref}(t) + V_{dc}(t) \qquad \text{................}(12)$$

$$W_{loss}(t+1) = W_{loss}(t) + K_p\left[E_{dc}(t+1) - E_{dc}(t)\right] + K_i.E_{dc}(t+1) \qquad \text{......}(13)$$

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

$$W_{pv} = \frac{2}{3}.\frac{P_{PV}}{V_{sp}} \qquad \text{..........}(14)$$

Now, with the use of basic weight update expressions given in above equations (5) to (8), the essential component of active load current for phase "a" may be expressed as follows:

$$W_{pa}(t+1) = W_{pa}(t)\left[1 - 2\mu_{pa}(t).\lambda_{pa}(t)\right] + \left[2\mu_{pa}(t).E_{pa}(t).v_{pa}(t)\right] \qquad \text{.........}(15)$$

$$\lambda_{pa}(t+1) = \lambda_{pa}(t) - \left[2\mu_{pa}(t).\rho.E_{pa}(t).v_{pa}(t).W_{pa}(t-1)\right] \qquad \text{............}(16)$$

$$\mu_{pa}(t+1) = \left[\alpha.\mu_{pa}(t)\right] + \left[\lambda_{pa}(t).R_{pa}^2(t)\right] \qquad \text{..........}(17)$$

$$R_{pa}(t)=\left[\beta.R_{pa}(t-1)\right]+\left[(1-\beta).E_{pa}(t).E_{pa}(t-1)\right] \quad ....(18)$$

The Error prediction will remain now as:

$$E_{pa}(t)=i_{La}(t)-v_{pa}(t).W_{pa}(t) \quad ....(19)$$

Where iLa is load current of phase 'a'. Likewise, shunt VSC's phases "b" and "c", active component weights (W_{pb} and W_{pc}), leakage factors (λ_{pb} and λ_{pc}), step sizes (μ_{pb} and μ_{pc}), error autocorrelation (R_{pb}, R_{pc}), and anticipated error (E_{pb}, E_{pc}) can all be updated at any given moment, in a manner akin to that of the phase "a". As a result, the weighted average of the basic active component (W_{pave}) is given by equation (20).

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

The reference grid current's active components (i_{spa}, i_{spb}, and i_{spc}) and total weight of active component (W_{sp}) are computed as:

$$W_{sp}=W_{pave}+W_{loss}-W_{PV} \quad ....(21)$$

$$i_{spa}=W_{sp}.v_{pa}\,;\quad i_{spb}=W_{sp}.v_{pb}\,;\quad i_{spc}=W_{sp}.v_{pc} \quad ......(22)$$

Similarly, the reactive components of load current are computed using vector voltage templates for quadrature units and the accompanying updated weights for the reactive current components are stated as equation (23).

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

In this case, the weight of the entire reactive components (Wsq) equals the weight average of the fundamental reactive components. Hence, by adding the elements in above equations (22) and (23), the resultant reference source's currents extracted are determined as:

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

Henceforth, comparing the resultant references currents (i^{*}_{sa}, i^{*}_{sb}, and i^{*}_{sc}) to the measured source's currents (i_{sa}, i_{sb}, and i_{sc}) of the system, along with the acquired erroneous signals, the Hysteresis Current Controller (HCC) provides in generating the anticipated switched signals to operate the shunt VSC of UPQC for mitigating the PQ issues.

3.3. Proposed Scheme for Series VSC

The representation of schematic control for series compensator is shown in Figure 3.

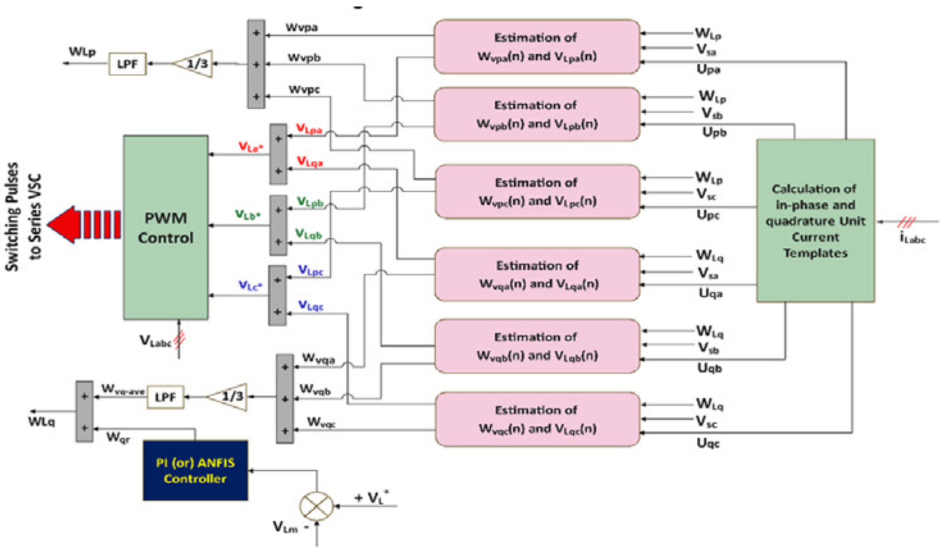

Figure 3. Schematic Control Representation for Proposed Series VSC.

The control objective is to achieve the desired magnitude and sinusoidal waveform of the load voltages. The proposed AL_LMS algorithm is used to estimate the reference load voltages, as shown below. The magnitude (ILp) of the 3-phase load currents (iLa, iLb, and iLc) are determined by sensing them, and their unit templates are provided by equations (25) and (26) correspondingly.

$$I_{Lp} = \sqrt{\tfrac{2}{3}(i_{La}^2 + i_{Lb}^2 + i_{Lc}^2)} \qquad \text{........(25)}$$

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

To compute the quadrature current unit templates, these in-phase unit templates are employed, which can be specified as:

$$u_{qa} = \frac{-u_{pb} + u_{pc}}{\sqrt{3}}; u_{qb} = \tfrac{\sqrt{3}}{2}.u_{pa} + \tfrac{1}{2\sqrt{3}}(u_{pb} - u_{pc});$$

$$u_{qc} = -\tfrac{\sqrt{3}}{2}.u_{pa} + \tfrac{1}{2\sqrt{3}}(u_{pb} - u_{pc}) \qquad \text{...............(27)}$$

Now, phase 'a' load voltage's in-phase weighted component (W_{vpa}) has been calculated according to basic weighted updated expressions and are given by following equations (28) to (32) below.

$$W_{vpa}(t+1) = W_{vpa}(t).\left[-2\mu_{vpa}(t).\lambda_{vpa}(t)\right] + \left[2\mu_{vpa}(t).E_{vpa}(t).u_{pa}(t)\right] \qquad \text{....(28)}$$

$$\lambda_{vpa}(t+1) = \lambda_{vpa}(t) - \left[2\mu_{vpa}(t).\rho.E_{vpa}(t)\right].\left[u_{pa}(t).W_{vpa}(t-1)\right] \qquad \text{............(29)}$$

$$\mu_{vpa}(t+1) = \left[\alpha.\mu_{vpa}(t)\right] + \left[\lambda_{vpa}(t).R_{vpa}^2(t)\right] \qquad \text{..........(30)}$$

$$R_{vpa}(t) = \left[\beta.R_{vpa}(t-1)\right] + \left[(1-\beta).E_{vpa}(t).E_{vpa}(t-1)\right] \qquad \text{..........(31)}$$

Estimated Error will be found as:

$$E_{vpa}(t) = V_{sa}(t) - \left[u_{pa}(t).W_{vqa}(t)\right] \qquad \text{..........(32)}$$

where, V_{sa} is the source voltage of phase 'a'. Similarly, phases "b" and "c," in-phase weights component (W_{vpb} and W_{vpc}), leakage factors (λ_{vpb} and λ_{vpc}), step size (μ_{vpb} and μ_{vpc}), error auto correlation (R_{vpb} and R_{vpc}), and error prediction (E_{vpb} and E_{vpc}) can all be tuned in an alike way at any instant in series VSC. The weighted average of the in-phase component, denoted as W_{vpave}, is derived using the equation (33) below.

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

The following are the measured constituents of the in-phase reference load voltage:

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

Similar to this, the weights of the load voltage's quadrature components (Wvqa, Wvqb, and Wvqc) are estimated using the suggested AL_LMS scheme. The weighted average reactive component is represented in the equation (35) below.

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

Now, a loss component (Wqr) is considered in this instance in order to normalize the load voltage and is expressed as:

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

A PI/ANFIS controller receives the error signal produced by comparing the magnitudes of the rated load voltage (V_L^*) and the measured load's voltages (V_{La}, V_{Lb}, and V_{Lc}). This allows the controller towards maintaining the intended load voltage magnitude, as indicated by the following equations.

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

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

The expression for the reference load's voltage overall quadrature weight component (W_{Lq}) is:

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

The following equation describes the overall quadrature component of the reference load voltage.

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

Consequently, the significant reference load voltages to each of the three phases are provided as:

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

Eventually, the variance is sent to a PWM generator for the purpose of providing switching pulses to the series VSC by relating the reference and calculated load voltages. Henceforth, the series component of UPQC is done for enhancing PQ issues.

3.4. Adaptive Neuro Fuzzy Inference System (ANFIS) Control

An additional neural-based technique that associate the benefits of Fuzzy Logic and Neural Networks is so-called Adaptive Neuro Fuzzy Inference System (ANFIS) [25]. It's often used to improve the performance and efficacy of control systems, comprising a neural network plus a fuzzy system. The fuzzy inference system (FIS) parameters were changed via the neural network as in Figure 4.

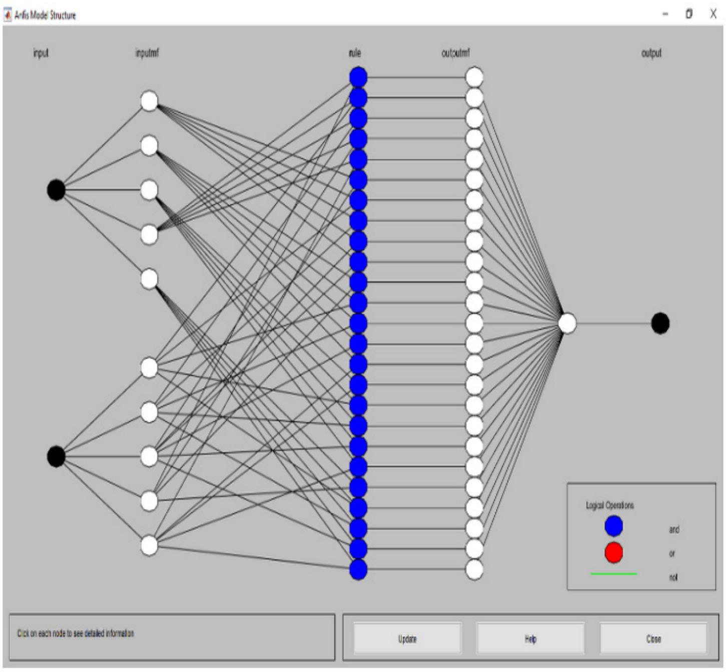

Figure 4. ANFIS Model Structure.

Utilizing actual voltage's and current's signals as input variables and compensating voltage's and current's as output variables, a customary fuzzy rules set was generated by the FIS. The system's interpretation of these variables plays an important role since improper tuning could cause the data to be either overfit or underfit.

A hybrid approach that blends the mean square error (MSE) method and the least-squares (LS) method can be custom towards modifying the parameters of the ANFIS model. The training process intentions to minimalize the training error [26]. All over the training phase, the parameters of the neural network and fuzzy inference system are changed to lower the error between the expected and real compensatory voltages and currents. The trained ANFIS model was judged with a set of validation data to determine its accuracy in predicting the required compensating voltages and currents under various operating conditions. After training and validation, include the ANFIS model within the governing system. Make the required connections between the ANFIS inputs such as Error(e) and Change-in-Error(ce) and the ANFIS outputs (such as control signal) after replacing the PI controller with the ANFIS controller as given in Figure 5 and 6.

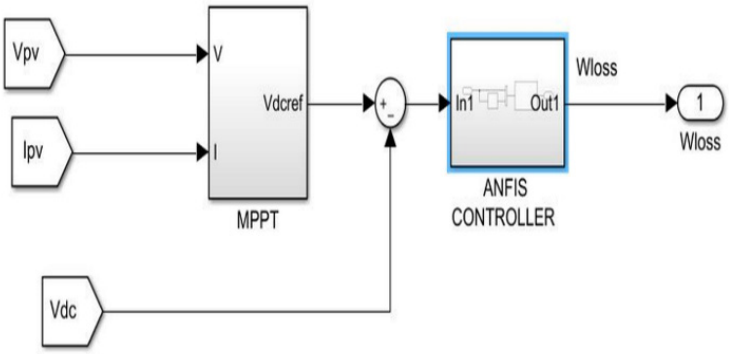

Figure 5. ANFIS Control Strategy in Shunt VSC.

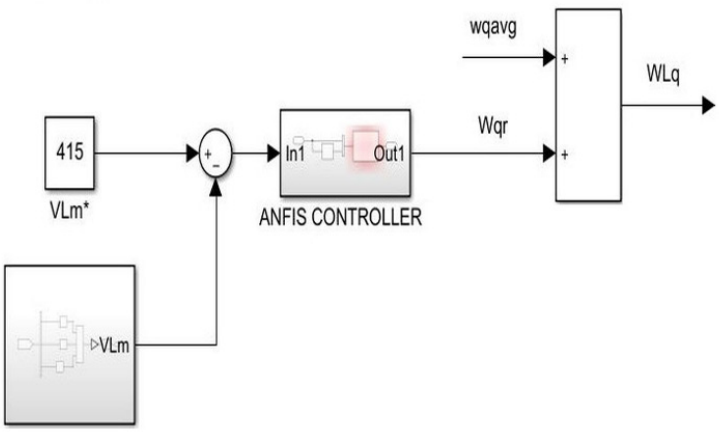

Figure 6. Series VSC ANFIS Control Strategy.

4. RESULTS AND DISCUSSIONS

The anticipated Solar-PV coordinated UPQC configuration is modeled in the MATLAB/ Simulink software and then simulated for examining the performance analysis of Non-linear load condition, Voltage Sag and Swell situations using the presented AL_LMS algorithm with conventional PI and ANFIS controllers' strategies as depicted in Figure 7.

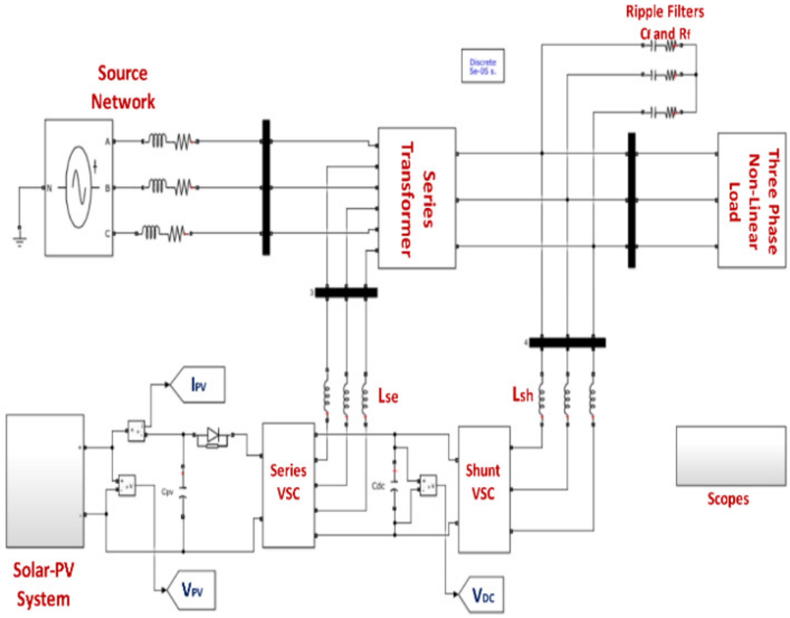

Figure 7. Simulation diagram of proposed Solar-PV-UPQC system.

The parameters used to simulate the described system are tabulated below.

Table 1. System Parameters.

Parameters	Values
Supply Grid Voltage (Vs)	415V (L-L)
Coupling inductors (L_{se} and L_{sh})	1.5mH
DC-link capacitor (C_{dc})	8000µF
DC-link Voltage (V_{dc})	700 V
Gains (K_P & K_I) of Shunt VSC	2 & 0.1
Gains (K_P & K_I) of Series VSC	4 & 800
Solar-PV MPPT voltage and current	700V, 60A
Non-linear load	15KW, 7.2KVA

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

4.1.1. Using Conventional PI Controller

The following illustrates how effectively the UPQC's series VSC performed under voltage sag and swell situations with the traditional PI controller-based AL_LMS algorithm. A rated load voltage was achieved due to the mitigation of 0.5 Per Unit voltage dip on t=0.1Sec and 1.2 Per Unit voltage swell at t=0.3Sec respectively by the series VSC of UPQC.

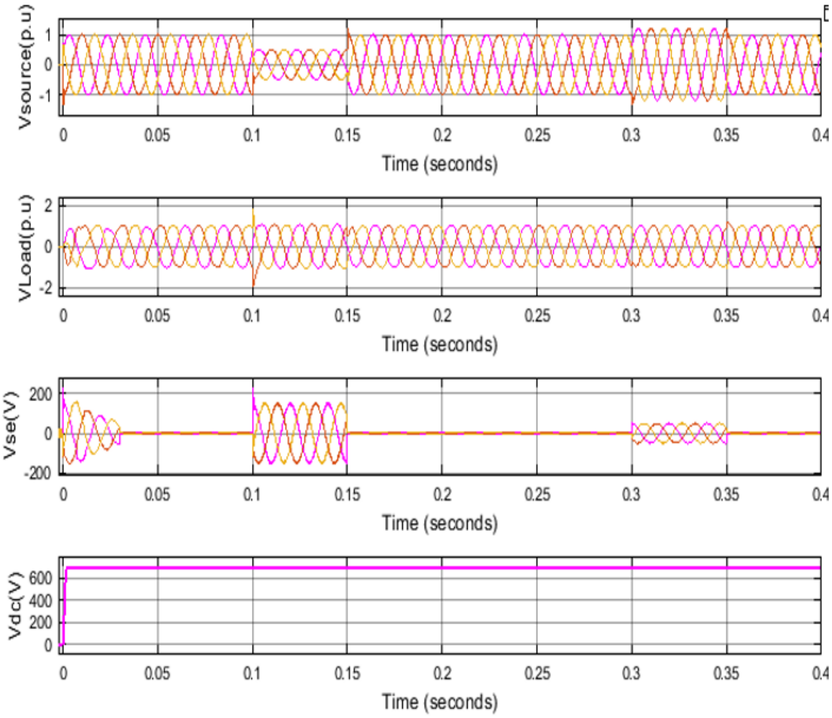

Figure 8. Compensation of Voltage Sag and Swell conditions with PI Controller based AL_LMS algorithm for UPQC.

As depicted in Figure 9, the load's voltage %THD by means of conventional PI controller applied to UPQC is obtained as 2.41%. Further, it is investigated with ANFIS controller for better enhancement of power quality, as shown below.

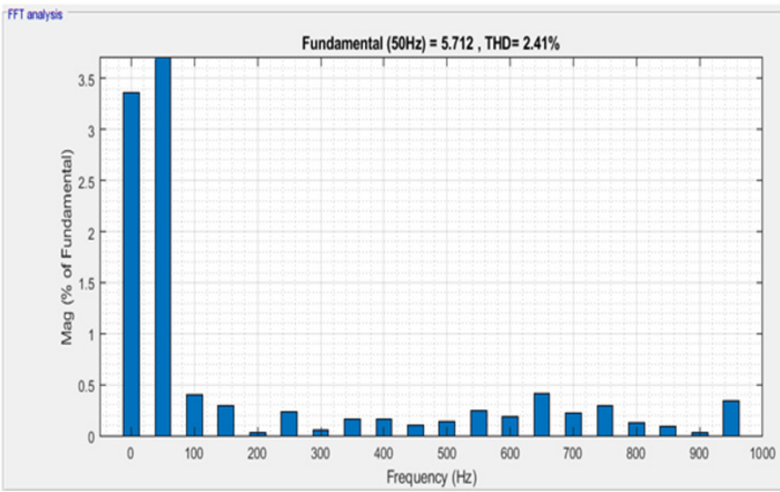

Figure 9. %THD of Load voltage by conventional PI controller.

4.1.2. Using ANFIS Controller based AL_LMS algorithm

The following graph shows how well the series component of UPQC performed under voltage sag and swell situations applying the suggested ANFIS controlled AL_LMS algorithm. A 0.5 P.U. voltage sag and a 1.2 P.U. voltage swell has formed at t=0.1 and 0.3 seconds, respectively, which could be alleviated by UPQC's series VSC and thus resulting rated load's voltage.

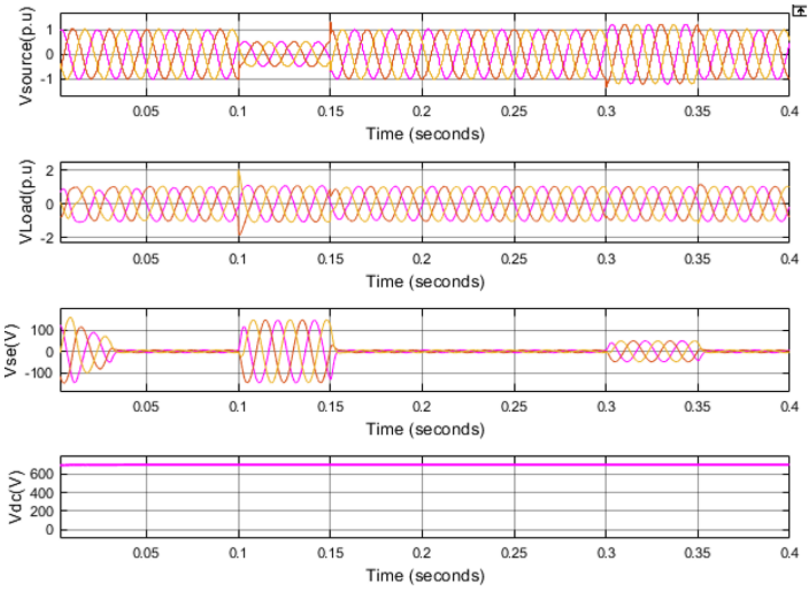

Figure 10. Compensation of Voltage Sag and Swell conditions using ANFIS controlled AL_LMS algorithm.

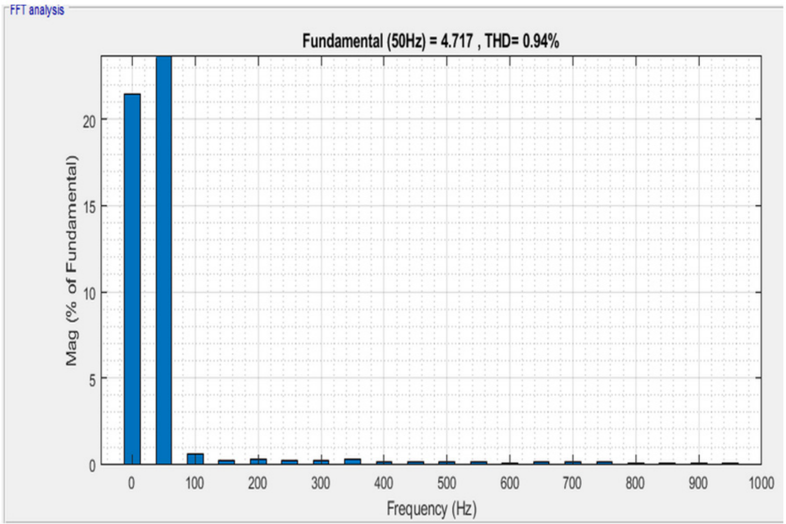

Figure 11. %THD of Load Voltage from proposed ANFIS controlled AL_LMS algorithm.

It can be viewed that with the enhanced %THD performance, the proposed ANFIS controlled AL_LMS algorithm more effectively recompenses voltage sag and swell. The attained %THD of load voltage is 0.94%, whereas the traditional PI controller gives %THD of 2.41%, as displayed in the harmonic spectrum Figure 11.

4.2. Performance Analysis of Shunt VSC for Non-linear load condition

The figures below show how well shunt VSC performs under non-linear load's conditions. In terms of the control strategy, the Solar-PV array and the grid work together to fulfil the load's active power requirement and uphold the DC-link voltage by a significance value. The outputs of both control strategies are expressed below.

4.2.1. Using Conventional PI controller-based AL_LMS algorithm

Figure 12 shows how, before t=0.04Sec, the network grid/source current becomes captivated with the harmonics produced by the non-linear loads. When UPQC is linked to the network at t=0.04

sec, its shunt VSC balances out the non-linearities introduced into network grid/ source current, producing a sinusoidal grid current. The obtained source current's THD is 3.49%, as seen in the harmonic spectrum's Figure 13 below.

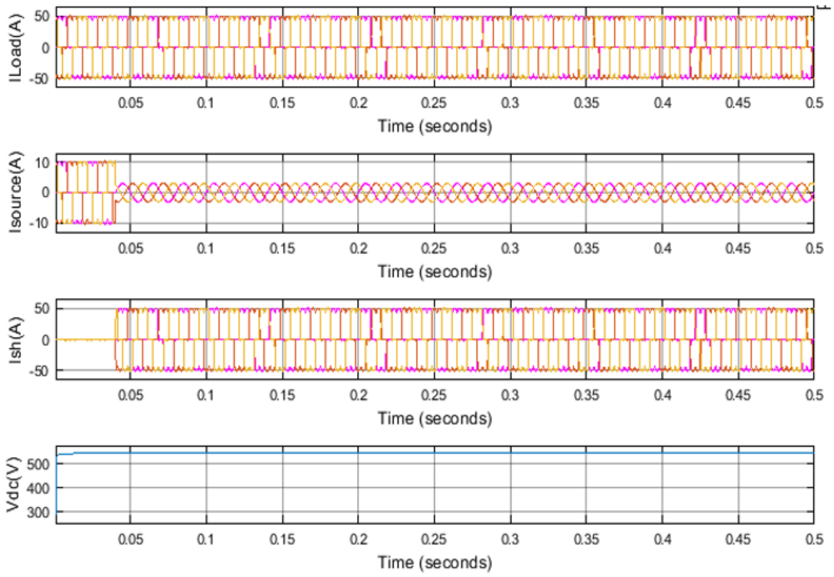

Figure 12. Performance of Shunt VSC to Non-linear loads by conventional PI controller-based AL_LMS algorithm.

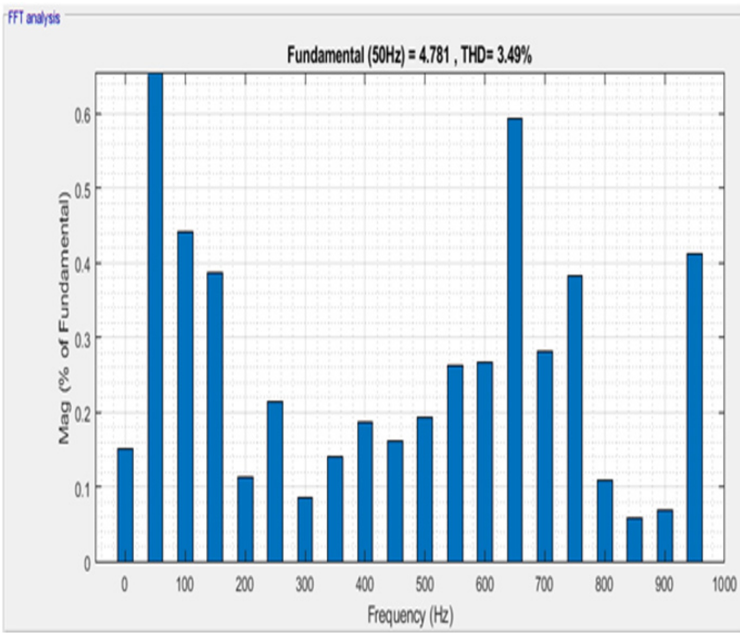

Figure 13. %THD for source current with conventional PI controller.

4.2.2. Using ANFIS controller-based AL_LMS algorithm

The suggested ANFIS controller further reduces the disparities in the source/grid and load currents with compared to the PI controller-based AL_LMS algorithm. Moreover, the shunt VSC of UPQC maintains the constant DC-link voltage at t=0.04Sec while compensating for the non-linearities obsessed by the system's source current, producing a sinusoidal grid current.

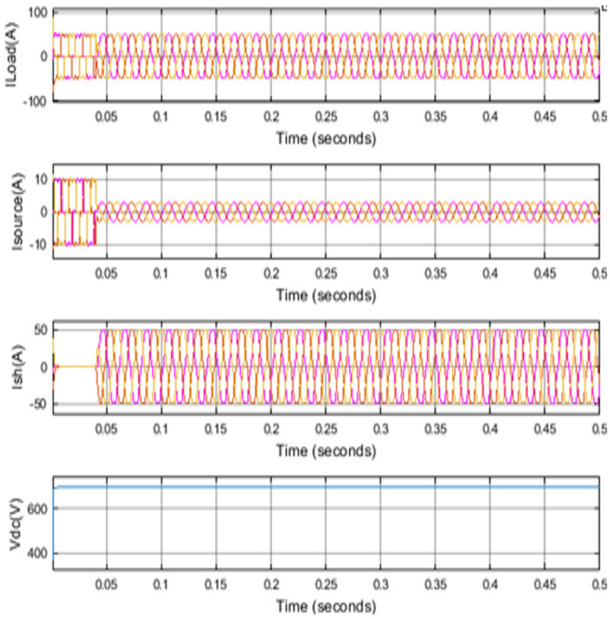

Figure 14. Performance of Shunt VSC to Non-linear loads by ANFIS controller-based AL_LMS algorithm.

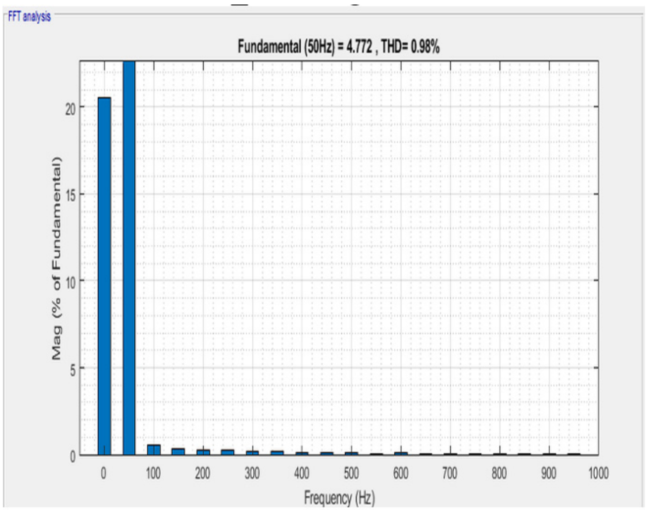

Figure 15. %THD for source current with proposed ANFIS controller-based AL_LMS algorithm.

As seen in Figure 15, the %THD come to be in the network grid/source current is 0.98%, compared to 3.49% in the conventional PI controller. As such, it can be demonstrated that the ANFIS controlled AL_LMS algorithm provides a greater power quality enhancement.

The Table 2 below inferences %THD of Load voltage owing to Sag and Swell conditions and also, it can be known that the %THD of Source/grid Current because of Non-linear loads out showed by both conventional PI and ANFIS controllers-based AL_LMS algorithm. The PQ has enhanced with proposed ANFIS controller-based AL_LMS algorithm compared to the PI controller.

Table 2. %THD assessment of proposed UPQC controller strategies.

Proposed AL_LMS algorithm		
Parameters	With PI Controller	With ANFIS Controller
Load Voltage (For Sag and Swell)	2.41%	0.94%
Grid/Source Current (For Non-linearities)	3.49%	0.98%

5. CONCLUSIONS

An adaptive control strategy has proposed in this paper based on ANFIS controller-based AL_LMS algorithm for amelioration of the power quality issues with Solar-PV fed UPQC in the distributed network. The system's performance is assessed by ANFIS controller comparing with the conventional PI controller for %THD of non-linear load condition, voltage sag and swell conditions. The ANFIS controller-based AL_LMS algorithm have achieved better results in these conditions by generating proper reference currents to the both shunt and series VSCs of UPQC. Even in instances of sag and swell situations, the load voltage is satisfactorily kept at its nominally rated voltage and also %THD of source current been reduced significantly and made sinusoidal for non-linear load currents. Furthermore, the suggested strategy assists to meet the active power requirement for loads by capturing solar-PV energy and consequently, the load burden upon the network grid is reduced.

Further work will be involved incorporating optimization methods for better tuning of PI controller of UPQC and also multi-level inverter topologies could be implemented for UPQC to augment the PQ of the system.

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REFERENCES

[1] Warner, Kevin J., and Glenn A. Jones. "The 21st Century Coal Question : China, India, Development, and Climate Change." Atmosphere, vol. 10, no. 8, p.476, Aug. 2019. https://doi.org/10.3390/atmos10080476.

[2] Alam, Md. Shafiul, et al. "High-Level Penetration of Renewable Energy Sources in to Grid Utility : Challenges and Solutions." IEEE Access, vol. 8, pp. 190277–99, 2020. https://doi.org/10.1109/ACCESS.2020.3031481.

[3] Bollen, Math H. J. Understanding Power Quality Problems : Voltage Sags and Interruptions, IEEE Press, 2000.

[4] Chilakapati, Lenin, T.Gowri Manohar, "Microgrid Power Quality Enhancement with Adaptive Control Strategies: A Literature Survey." Przegląd Elektrotechniczny, vol. 1, no. 3, pp. 115-119, Mar. 2024. https://doi.org/10.15199/48.2024.03.21.

[5] Hingorani, Narain G., and Laszlo Gyugyi. Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, IEEE Press, 2000.

[6] M. M. Khaleel, et.al., "A Review of Fuel Cell to Distribution Network Interface Using D-FACTS : Technical Challenges and Interconnection Trends," International Journal of Electrical and Electronic Engineering & Telecommunications, Vol. 10, No. 5, September 2021, pp. 319-332. ttps://doi.org/10.18178/ijeetc.10.5.319-332

[7] Chawda, Gajendra Singh, et al. "Comprehensive Review of Distributed FACTS Control Algorithms for Power Quality Enhancement in Utility Grid with Renewable Energy Penetration." IEEE Access, vol. 8, pp.107614–34, 2020. https://doi.org/10.1109/ACCESS.2020.3000931.

[8] Satish, Raavi, et al. "A Comprehensive Power Quality Mitigation Tool: UPQC." In Power

Quality in Microgrids: Issues, Challenges and Mitigation Techniques, Springer Nature Singapore, 2023, vol. 1039, pp.47–68. https://doi.org/10.1007/978-981-99-2066-2_3.

[9] Jha, Kanchan, and Abdul Gafoor Shaik. "A Comprehensive Review of Power Quality Mitigation in the Scenario of Solar PV Integration in to Utility Grid" E-Prime - Advances in Electrical Engineering, Electronics and Energy, vol. 3, p.100103, Mar.2023. https://doi.org/10.1016/j.prime.2022.100103.

[10] Agarwal, Nirmal Kr., et al. "Review on Unified Power Quality Conditioner (UPQC) to Mitigate Power Quality Problems." In 2nd Global Conference for Advancement in Technology (GCAT), IEEE, 2021, pp. 1–7. https://doi.org/10.1109/GCAT52182.2021.9587586.

[11] Ray, Pragnyashree, Pravat Kumar Ray, and Santanu Kumar Dash. "Power Quality Enhancement and Power Flow Analysis of a PV Integrated UPQC System in a Distribution Network." IEEE Transactions on Industry Applications, vol. 58, no.1 2022, pp.201–211. https://doi.org/10.1109/TIA.2021.3131404

[12] Diab, Ahmed M., et al. "Fast and Simple Tuning Rules of Synchronous Reference Frame Proportional - Integral Current Controller." IEEE Access, vol. 9, 2021, pp. 22156–70. https://doi.org/10.1109/ACCESS.2021.3054845.

[13] Ahmad, Shameem, et al. "DQ-Axis Synchronous Reference Frame based p-q Control of Grid connected AC Microgrid." In IEEE International Conference on Computing, Power and Communication Technologies (GUCON), IEEE, 2020, pp. 842–47. https://doi.org/10.1109/GUCON48875.2020.9231080.

[14] Lenin Babu, Chilakapati, and T.Gowri Manohar. "Control Strategies for Mitigating Power Quality Issues in Renewable Energy Coordinated Microgrid- A Comprehensive Review." in Proc. International Conference on Hydro and Renewable Energy, India, vol. 391, Springer Nature Singapore, 2024, pp. 417–28. https://doi.org/10.1007/978-981-99-6616-5_47.

[15] Bajaj, Mohit, and Amit Kumar Singh. "Grid Integrated Renewable DG Systems : A Review of Power Quality Challenges and State-of-the-art Mitigation Techniques." International Journal of Energy Research, vol. 44, no. 1, Jan. 2020, pp. 26–69. https://doi.org/10.1002/er.4847.

[16] Singh, Nivedita, et al. "Feature Extraction and Classification Techniques for Power Quality Disturbances in Distributed Generation : A Review." IETE Journal of Research, vol. 69, no. 6, Aug. 2023, pp. 3836–51. https://doi.org/10.1080/03772063.2021.1920849.

[17] Abdulkader, Rasheed, et al. "Soft Computing in Smart Grid with Decentralized Generation and Renewable Energy Storage System Planning." Energies, vol. 16, no. 6, Mar. 2023, p. 2655. https://doi.org/10.3390/en16062655.

[18] Devena, Nageswari, Geetha mahalakshmi Gengi, Bindu Kollappapillai Vijayammal, Kowselya Sujstha Reghuraman, Divyabharathi Gunaselvam, and Jayabharathi Balaraman. "Improvement of Power Quality using Variable Leaky Least Mean Square Controller With Adaptive Shunt Active Filter for Non-Linear Loads." In AIP Conference Proceedings, vol. 2857, no. 1. AIP Publishing, 2023. https://doi.org/10.1063/5.0164334.

[19] Jadeja R, Ved A, Trivedi T, Khanduja G. "Control of Power Electronic Converters in AC microgrid." in Microgrid Architectures, Control And Protection Methods, Springer International Publishing, Cham, 2020, pp 329–355. https://doi.org/10.1007/978-3-030-23723-3_13

[20] A. L. Bukar, C. W. Tan, D. M. Said, A. M. Dobi, R. Ayop, and A. Alsharif, "Energy Management Strategy and Capacity Planning of an Autonomous Microgrid: Performance Comparison of Metaheuristic Optimization Searching Techniques," Renewable Energy Focus, vol. 40, Mar. 2022, pp.48–66. https://doi.org/10.1016/j.ref.2021.11.004.

[21] Lenin Babu, Chilakapati, and Tenepalli Gowri Manohar. "An Improved Power Quality in a Renewable Energy-Based Microgrid System using Adaptive Hybrid UPQC Control Strategy." International Journal of Experimental Research and Review, vol. 36, Dec. 2023, pp. 217–31. https://doi.org/10.52756/ijerr.2023.v36.022.

[22] Ray, Pragnyashree, and Pravat Kumar Ray. "Design and Control of PV-UPQC using Variable Leaky LMS based Algorithm for Power Quality Enhancement." In 3rd International Conference on Energy, Power and Environment: Towards Clean Energy Technologies, IEEE, 2021, pp. 1–6. https://doi.org/10.1109/ICEPE50861.2021.9404514.

[23] Bag, Aurobinda, Subudhi, B., and Ray, P. K. "An Adaptive Variable Leaky Least Mean Square Control Scheme for Grid Integration of a PV System." IEEE Transactions on Sustainable Energy, vol. 11, no. 3, July 2020, pp. 1508–15. https://doi.org/10.1109/TSTE.2019.2929551.

[24] Chilakapati, Lenin Babu, and T. Gowri Manohar. "Control Strategies for Enhancing Power Quality with Unified Power Quality Conditioner in a Solar-PV Integrated Utility System." International Journal of Experimental Research and Review, vol. 35, Nov. 2023, pp. 1–15. https://doi.org/10.52756/ijerr.2023.v35spl.001

[25] Renduchintala, Udaya K., Pang, C., Tatikonda, K. M., and Yang, L."ANFIS-Fuzzy Logic Based UPQC in Interconnected Microgrid Distribution Systems : Modeling, Simulation and Implementation." The Journal of Engineering, vol. 2021, no. 1, Feb. 2021, pp. 6–18. https://doi.org/10.1049/tje2.12005.

[26] Kenjrawy Hassan, et.al.,"New Modulation Technique in Smart Grid Interfaced Multilevel UPQC-PV Controlled via Fuzzy Logic Controller." Electronics, vol.11, no.6, Mar.2022, p. 919. https://doi.org/10.3390/electronics11060919.