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Intelligent Control of UPQC for Enhancing Power Quality in PV Integrated Smart Grids Using ANFIS Controller

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ABSTRACT: Power quality issues has become significant tool in recent power distribution systems due to the occurrence of loads and devices, based on power electronics. To mitigate the effects of power quality disputes, Flexible Alternating Current Transmission System (FACTS) devices are crucial. In this instance, a photovoltaic (PV) integrated Unified Power Quality Conditioner (UPQC) for enlightening power quality in electrical power system and improves power factor on load side. UPQC is controlled by Adaptive Neuro-Fuzzy Interference System (ANFIS) controller. A High gain Quadratic Boost Converter (QBC) assimilates this research for stepping-up voltage from PV and enhance the act of powering the DC-link. The Whale Optimization Algorithm (WOA)-Proportional Integral (PI) controller which enhances the performance of converter by optimally tuning the PI parameters. Thus power quality issues overcome by enhanced UPQC and results are analysed through MATLAB/Simulink. The proposed system achieves 95% efficiency with reduced Total Harmonic Distortion (THD) of 1.52% indicating improved power quality.

Keywords: Photovoltaic, High gain Quadratic boost converter, WOA-PI, UPQC, ANFIS controller.

1. Introduction

Power quality has developed an acute concern in recent electrical systems due to the cumulative complexity and sensitivity of electronic devices and industrial equipment. Common power quality issues including, voltage fluctuations, harmonic distortion, voltage sag/swell, which results in serious consequences including equipment failure, reduced operational lifespan. These challenges impact not only utilizes but also end users underscoring the robust need for power quality monitoring [1]. In recent years researchers focused on improving power quality in electrical power system.

For mitigating power quality problems, FACTS devices are used. FACTS is a collection of power electronic devices which enhances or control power flow and voltage in AC electrical power system. Some of FACTS devices such as Dynamic Voltage Restorer (DVR), Static Var Compensator (SVC), Static Synchronous Series Compensator (SSSC),Thyristor Controlled Series Reactor (TCSR),Thyristor Controlled Series Compensator (TCSC)[2]. DVR which mitigate all the voltage-related power quality issues but it has limited capacity and complexity [3].Static Synchronous Compensator (STATCOM) is a shunt compensation device that suppress all the current-related power quality issues but it is more expensive and sensitivity to grid disturbance. [4]

Static Var Compensator (SVC) is type of FACTS which regulates voltage and reactive power and enhances load modulating capability and improving overall system stability and performance. SVC improves power quality issues but its initial cost is higher and requires greater maintenance [5]. The enhancement of transmission efficiency and stability and to improve voltage profile Static Synchronous Series Compensator (SSSC) is used. SSSC is a control loop stability that increases transmission capacity and power factor correction but it requires transformer maintenance [6]. Thyristor Controlled Series Reactor (TCSR) which act as a series capacitor, it control impedance in electrical circuit and power flow. It limits computational cost and has reconstruction efficiency and accuracy [7].Electrical networks commonly use Thyristor Controlled Series Compensator (TCSC) method which is robust and impartially valued sequences. FACTs device with excellent performance that enables precise, dependable power flow regulation of power lines. Even though TCSC is one of the device that increase in the transient stability of power system still it meets high network losses and cost efficiency [8]. To address the limitations in this work UPQC is implemented for overturn voltage ripple in DC-link due to the effect of low frequency with dynamic performance.

To control the UPQC operations, controllers are used. Some of the controllers including Artificial Neural Network (ANN), PI controller, and so on. PI controllers overcome power quality issues especially in non-linear loads and dynamic conditions. But it is computationally intensive and has high THD [9]. ANN controller provides a better dynamic performance with high power factor but it requires power hardware [10]. Hence the proposed work prefers ANFIS controller which is used to control and modelling processes of complex and nonlinear systems.

Furthermore, the powered AC supply to the load suggest power quality issues. In this paper a high gain QBC is introduced for enhancing PV output. The converter steps-up the voltage and optimized by WOA-PI by tuning PI parameters thereby regulating the voltage from the converter to achieve better performance and efficiency.

2. Recent works

Noor Zanib *et al* (2022) [11] have developed UPQC for the performance analysis of RES based generation and distribution system for power quality improvement through ANN based PI controller. It improved power quality issues as harmonic reduction, and power factor due to parallel-series power line conditioning facilities. However, it has faster dynamic response but has average THD value and costlier.

Luis A. Paredes *et al* (2023) [12] have implemented FACTS based resilient microgrids to enhance dynamic voltage stability. The dynamic performance of the device is relatively analysed by DSTATCOM. It's operating response is faster for compensating reactive power, improves stability of voltage in dynamic and static conditions, avoids dynamic voltage fluctuations, and control the voltage module. Nonetheless, with assimilation of DSTATCOM, it is revealed that the reactive power fluctuates temporarily for a few cycles and recovers proficiently, and achieves better performance.

Donghun Lee *et al* (2024) [13] have proposed DC-DC buck converter under reinforcement learning based control for improving time delay in controllers. Proportional-Integral-Derivative (PID) has been widely used for its easy implementation and wide applicability. To emulate the typical delay in a Digital Signal Processor (DSP), this system integrates a pulse-delay module. It enhances overall performance of system and efficiency at a reasonable cost. Nevertheless, the existence of non-linearities and hidden dynamics poses insistent and substantial challenges.

Niklas Langmaack *et al* (2023) [14] have offered decentralized control of power supply based artificial swarm intelligence approach of DC-DC converter. It regulates pure high stability voltage and it has possibility to implement a very fast and robust carrier shift optimization under a very simple communication among neighbouring agents. Although it helps to maintain voltage levels within desired limits, but it faces potential stability issues and high cost.

Sisir Kumar Yadav *et al* (2024) [15] have introduced optimization of online tuning of PI in real time of UPQC-DG using PSO. The PSO-based method provide superior capacity to reduce steady-state errors and enhance dynamic response as well. However it is simple, effective, higher reliability and less loss but it is costlier and has less efficiency.

Therefore, to overcome the power quality issues the proposed work efficiently employed an ANFIS controller based UPQC in PV integrated distribution network.

The proposed work contributes as:

- ❖ PV system is an electrical system which converts sunlight into electricity using photovoltaic cells.
- ❖ High gain-Quadratic boost converter enhances the voltage from PV system which achieves higher voltage.
- ❖ WOA optimized PI controller optimizes by tuning the PI parameter to achieve better performance of the converter.
- ❖ UPQC is applied to overcome power quality issues and improve stability and reliability in power system.
- ❖ ANFIS controller is essential for managing the flow of power and ensuring optimal power quality in UPQC.

3. Proposed System

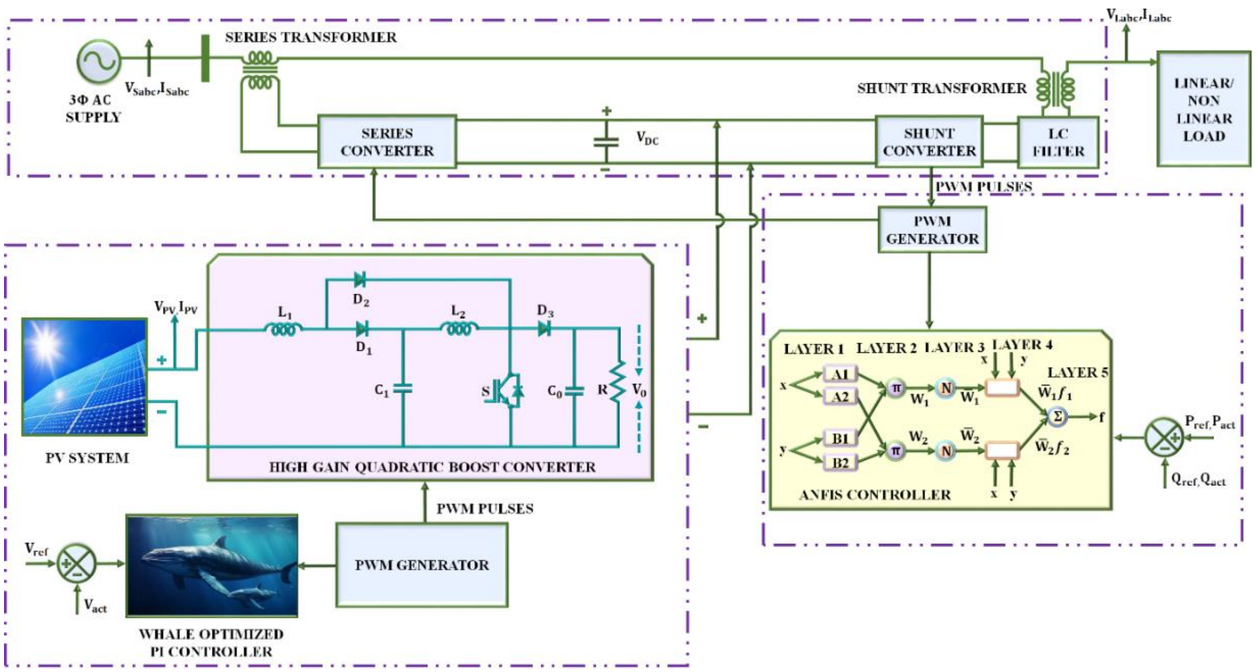

Figure 1: *Proposed block diagram*

The direct supply of 3ϕ AC supply to load produces power quality issues. This constraints overcome by UPQC appliance as shown in Figure 1. UPQC setup consist of series and shunt converter where the series converter mitigates voltage related issues and shunt converter removes current associated issues. The UPQC operations are controlled by integrating ANFIS controller. ANFIS controller succeeds the power flow and ensures power quality in UPQC which achieves a desired control signal and better performance. The control signal from controller is fed to PWM generator producing PWM pulses, thereby adjusting series and shunt converter's operation. In between the two converters a DC-link capacitor is applied. The DC-link is powered from PV system which is unstable due to its environmental condition. Therefore the voltage from PV is low, it is stepped up by high gain QBC. The converter rises the voltage and thereby charging the DC-link capacitor. The output voltage from converter is regulated by WOA-PI. The optimization of WOA-PI by tuning the PI parameters to achieve better performance. The optimized signal is fed to another PWM generator that generates switching pulses to converter for voltage regulation. The converter output power is fed into the DC bus. Hence power quality issues are mitigated using UPQC device in the electrical power system.

3.1 Modelling of UPQC

Generally UPQC consist of series and shunt active filter combination. The purpose of series active filter is to reduce harmonic isolation among transmission and distribution system. UPQC has both series and shunt side which realizes the compensation of voltage and current. The series and shunt converters allows UPQC to recover voltage and current quality. The series active filter removes voltage imbalance from the load terminal voltage.

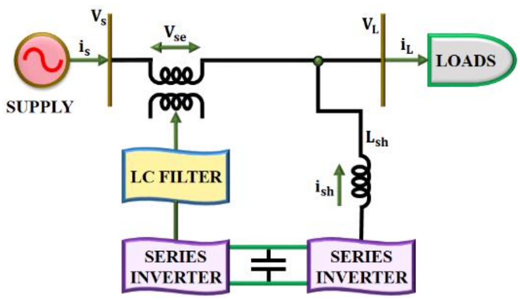

Figure 2: *UPQC block diagram*

The DC link voltage regulation accomplished by shunt active filter, thus leading to a major decline of DC capacitor's capability and captivates current harmonics, to recompense reactive power and negative-sequence current. It is quite dissimilar in determination, operation, and control strategy for transmission system. Thus high-frequency switching ripples generated by shunt and series inverters are eliminated by LC filters. UPQC is unified to manage voltage sag and ensure seamless operation in grid/load applications.

To obtain a stabilized power quality under varying load condition in UPQC system, a sophisticated ANFIS controller is quite necessary.

3.2 ANFIS Controller

The ANFIS is a hybrid structure integrating the methodologies of fuzzy logic and neural networks. The development of ANFIS has become a widely used tool in the control of non-linear systems. It has the capacity to human mimics' decision making process. The elementary ANFIS structure is illustrated in Figure 3.

The adaptive structure allows for learning of relationships between input and output. The ANFIS combines data-driven learning process with fuzzy rules. The feature enables ANFIS to demonstrate superior performance in modelling process of linear /non-linear loads. Consequently, the system is able to make predictions with minimal errors and considerably faster than other systems.

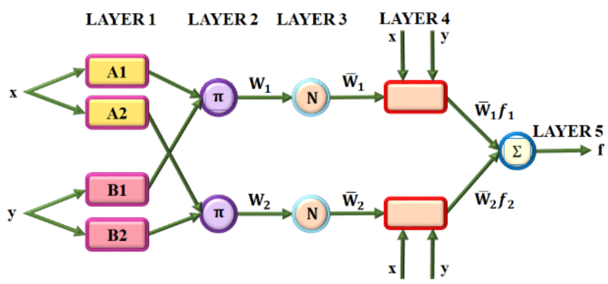

Figure 3: *ANFIS architecture*

Therefore the ANFIS controller enhances optimal power flow by mitigating voltage sags/swell, harmonics and reactive power issues.

Consequently the dc-link in the UPQC generally powered through PV system and the operation of PV is discussed as below.

3.3 PV system

The corresponding circuit of PV system is signified by a single diode to photo generated current. Here I_{pv} is the input current of PV, I_d denotes the current flowing through diode, where $R_p$and R_s is the series and parallel resistance. The output current and voltage is determined as I and V.

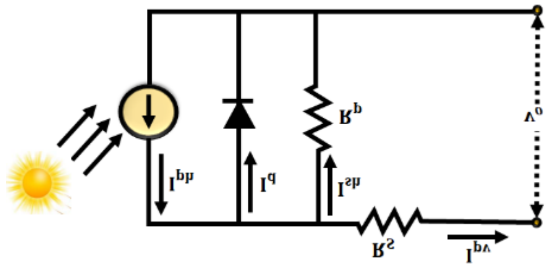

Figure 4: *Equivalent circuit of PV*

From figure 4. The outputs from PV cell is equated as,

$$I = I_{PVCELL} = I_{SCELL}\left[exp\frac{(qv)}{\alpha KT} - 1\right] \qquad (1)$$

$$I = I_{PV} - I_o\left[\,exp\,\frac{(v+R_S \cdot I)q}{\alpha V_k} - 1\right] - \frac{(v+R_S \cdot I)}{R_p} \qquad (2)$$

I_{PV} represents the PV cell current, T is ambient temperature, $\propto$ is the ideality factor, I_O is saturation current,

$$I = I_{PV} - I_o\left[\,exp\,\frac{(v+R_S \cdot I)q}{\alpha KT \cdot N_s} - 1\right] - \frac{(v+R_S \cdot I)}{R_p} \qquad (3)$$

The output current and voltage is denoted as I and v, thermal voltage $V_k = \frac{KT}{q}$, where N_s is the number of series PV cells, q is the charge of electron, R_s and R_p are the series and shunt resistance.

Subsequently to increase the output voltage generated from PV, High gain QBC is applied in the proposed topology, which is described below.

3.4 High gain Quadratic Boost Converter

The high gain (QBC) is a DC-DC converter that step-up voltage from PV. It achieves higher output voltage from low input voltage and draws current without ripples from sources. The increased independence enhances the overall performance of the system. The circuit diagram is shown in Figure 5.

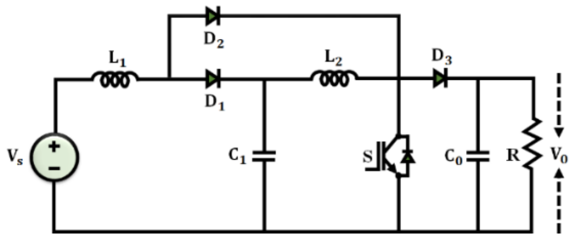

Figure 5: *Circuit for Quadratic boost converter*

The circuit consist of a switch s, two inductors L_1, L_2, a capacitor C_1, C_0, a diode D_1, D_2, D_3. By activating the switch, the inductor L_1, the input source, thereby capacitor C_1 turned ON for charging the inductor L_2. The energy stored in the inductor is discharged by load. The converter operates at two modes in continuous conduction mode.

Modes of operation

(A)Continuous Conduction Mode (CCM)

Based on the converter's modes of operations CCM displays two modes. The circuit diagram for CCM modes of operation shown in Figure 6(a) & 6(b).

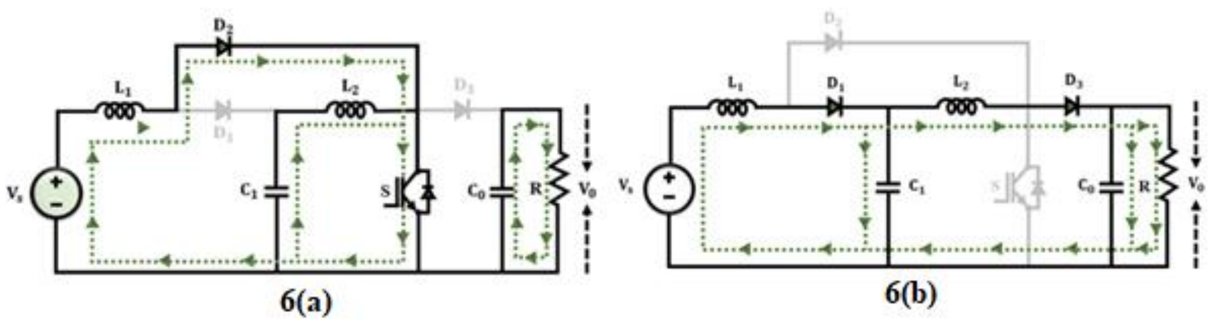

Figure 6(a): *Mode 1 and 6(b) Mode 2*

Mode 1:

When the switch s, is ON, the diode D_2 act as forward bias condition while diodes D_1 D_3 act as reverse bias condition. Input source V_s charges the inductor L_1 and L_2 is charged through capacitor C_1. The power is delivered through capacitor C_o to the load. It represents that the input source V_s is equal to the voltage across L_1. Similarly voltage across inductor L_2 is equivalent to voltage across capacitor C_1.

Therefore $$V_O = V_{C_O} \quad (4)$$

Mode 2:

When the switch s is OFF, the diodes D_1 , D_3, act in forward bias condition and the diode D_2 act in reverse bias condition. Here the capacitor C_1 is charged using the input source and inductor L_1. Using load the inductors L_1, L_2 get discharges. The voltage gain is calculated in CCM is given by,

When the switch s is ON,

$$V_{L_1} = V_S \quad (5)$$

$$V_{L_2} = V_{C_1} \quad (6)$$

When the switch s is OFF,

$$V_{L_1} = V_S - V_{C_1} \quad (7)$$

$$V_{L_2} = V_{C_1} - V_{C_o} \quad (8)$$

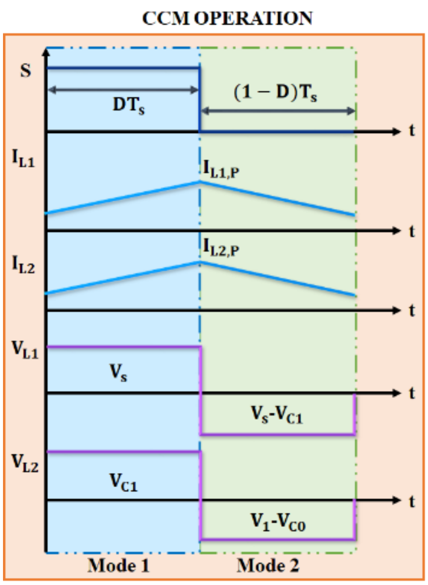

Figure 7: *Theoretical waveform of QBC in CCM*

The inductor L_1, volt-second stability is given by,

$$dV_S + (1-d)\left(V_S - V_{C_1}\right) = 0$$

$$V_{C_1} = \frac{V_S}{(1-d)} \quad (9)$$

Volt-second stability through the inductor L_2, is expressed as

$$d\left(V_{C_1}\right) + (1-d)\left(V_{C_1} - V_{C_o}\right) = 0$$

$$V_{C_o} = \frac{V_{C_1}}{(1-d)} = \frac{V_S}{(1-d)^2} \quad (10)$$

Substituting the values of (11) in (5)

$$V_O = \frac{V_S}{(1-d)^2} \quad (11)$$

The converter gain in CCM is given by,

$$M = \frac{V_O}{V_S} = \frac{1}{(1-d)^2} \quad (12)$$

The theoretical waveform of high gain QBC for CCM modes of operation is shown in Figure 7 and for the regulation of converter output, WOA-PI optimization is necessary as discussed below.

3.5 Optimization of WOA-PI

PI controller is a feedback control system which regulate the outputs from the converter to provide a steady voltage and simplicity in implementation. To achieve better performance the PI parameters are fine-tuned utilizing WOA algorithm.

WOA is a metaheuristic algorithm which is stimulated by hunting strategy of whales with methodological steps like encircling prey, bubble net attacking method and searching for prey. The algorithm based on the concept of whales that dives down in water and starts to swim towards the surface by creating bubbles in spiral loop around the prey.

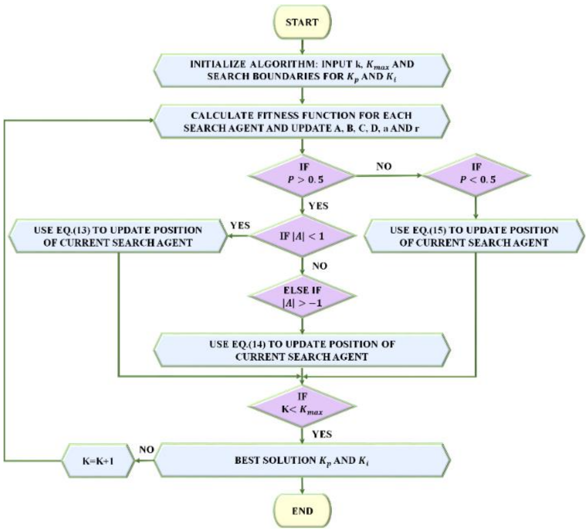

Figure 8: *Flowchart for WOA algorithm*

Normally the humpback whale knew the exact position of prey and encircles it. WOA consider the best solution as its prey and search for a better solution. The characteristics of Whale is mathematically derived in the equations as given by,

$$\vec{D} = \left|\vec{C} \cdot \vec{X} * (k) - \vec{X}\,(k)\right| \qquad (13)$$

$$\vec{X}(k+1) = \vec{X}(k) - \vec{A} \cdot \vec{D} \qquad (14)$$

The vector coefficients are $\vec{A}$ and $\vec{C}$, $\vec{X} * (k)$ indicates the earlier best location of whale, $\vec{X}(k+1)$ is the current position of whale, $\vec{D}$ signifies the distance among prey and the whale.

$$\vec{A} = 2\,\vec{a} \cdot \vec{r} - \vec{a} \qquad (15)$$

$$\vec{C} = 2 \cdot \vec{r} \qquad (16)$$

The value of $\vec{a}$ decrease from 2 to 0, the arbitrary variable ranges from 0 to 1.

By reducing the value of $\vec{a}$ the mechanism of encircling prey is performed. The objective function is written as

$$Maximize\ P(d)\ Expose\ to\ d_{min} \le d \ge d_{max} \qquad (17)$$

WOA optimization enhances the efficiency of the system as well as reduces the power loss. To control PWM pulse, the mathematical expression is given by,

$$d_i(k+1) = d_i(k) - A \cdot D \qquad (18)$$

The objective function evaluated using equation (22)

$$P\left({d_i}^k\right) > P\left({d_i}^{k-1}\right) \qquad (19)$$

To obtain a steady state outputs, the equation (23) is computed by,

$$\frac{P^k - P^{k-1}}{P^k} \ge 0.1 \qquad (20)$$

The flowchart in Figure 8 enlightens the WOA process by tuning the parameters of PI which achieves a better performance of converter. Therefore the power quality issues in UPQC has mitigated by ANFIS controller according to an initial power source from PV which is enhanced by high gain QBC with WOA-PI optimization method.

4. Results and discussion

According to the research UPQC introduced in this research to progress the power quality in power system which includes high gain QBC with WOA-PI and ANFIS controller. The overall results are obtained through MATLAB which is a versatile platform used in various simulation, modelling and data analysis. The following Table illuminates parameter specification for the proposed topology.

Table 1: *Parameter specification*

Parameter	Rating
PV System	
Rated Power	$10kW$
Open Circuit Voltage	$37.25V$
Short Circuit Current	$8.95A$
No. of panels connected in series	3
No. of panels connected in parallel	2
Switching frequency	$10kHz$
High gain quadratic boost converter	
Switching frequency	$10kHz$
Inductor L_1, L_2	$4.7mH$
Capacitor C_1	$22\mu F$
Capacitor C_O	$2200\mu F$
LC filter	
$\boldsymbol{L_f}$	$2mH$
$\boldsymbol{C_f}$	$100\mu F$

Constant condition

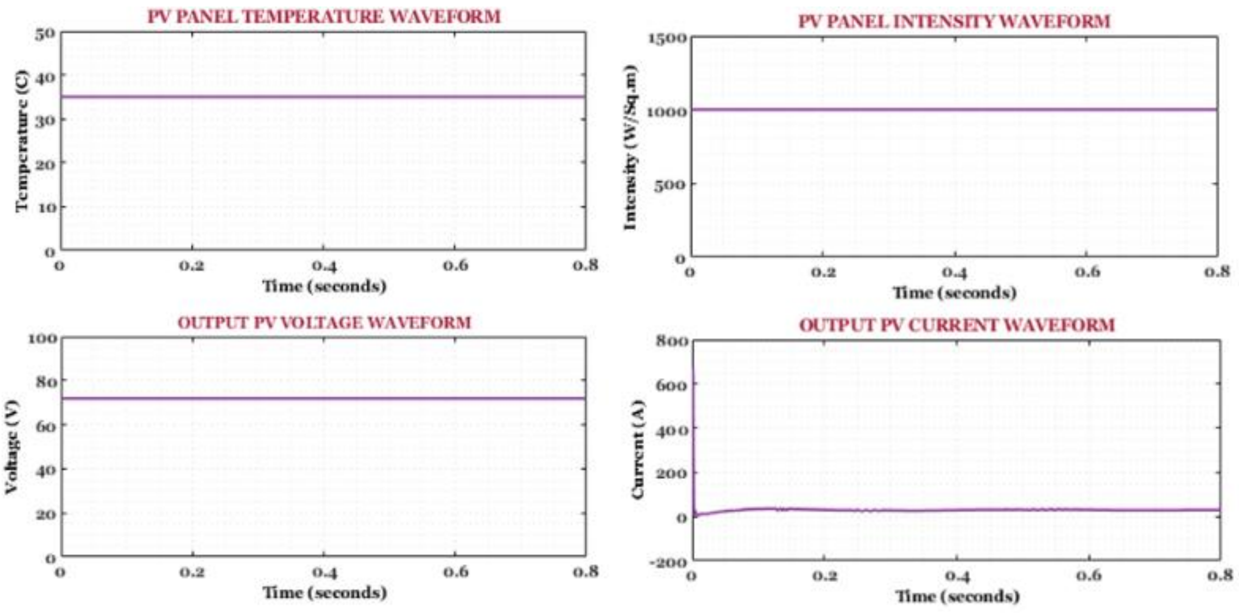

Figure 9: *PV Panel waveform*

Figure 9 presents PV panel waveform of temperature, intensity, voltage and current. The temperature waveform showing $35° C$ under constant condition. The PV panel intensity waveform showing $1000W/sq.m$. PV panel's output is obtained based on the temperature and intensity. Therefore the attained PV output voltage is $75V$ and the output current from PV panel is $20A$ which is maintained constantly.

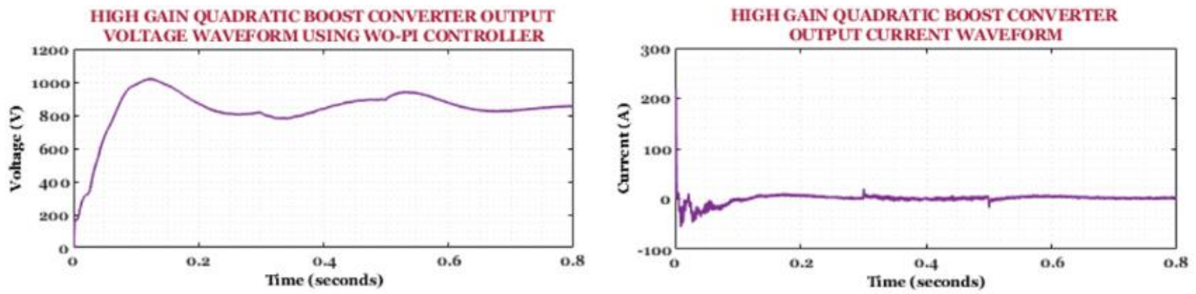

Figure 10: *Output waveform of High gain QBC using WOA-PI*

Figure 10 characterizes the output voltage and current waveforms of High gain QBC using WOA-PI. The output voltage waveform increases to $980V$ with a rise time of $0.1s$ where the voltage fluctuations takes place from $0.1s$ to $0.7s$. It reaches $810V$ which becomes stable at a quick settling time of $0.7s$.Similarly the output current waveform stabilizes approximately $3A$ of output current respectively.

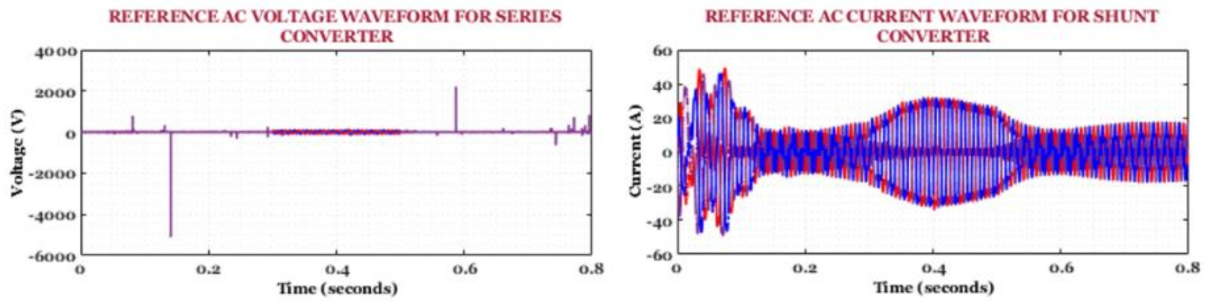

Figure 11: *Reference AC voltage for series and current for shunt converter waveform*

Figure 11 shows the waveform of reference AC voltage for series and current for shunt converter. The series converter mitigates voltage related issues in UPQC. The reference AC voltage of series converter waveform shows a reliable voltage of $900V$ with less voltage fluctuations. The shunt converter overcomes the current-related issues in UPQC. The waveform of reference AC current for shunt converter visualize some ripples of current at initial stage between $50A$ to $-50A$ and then it stabilizes to $18A$ by $0.6s$.

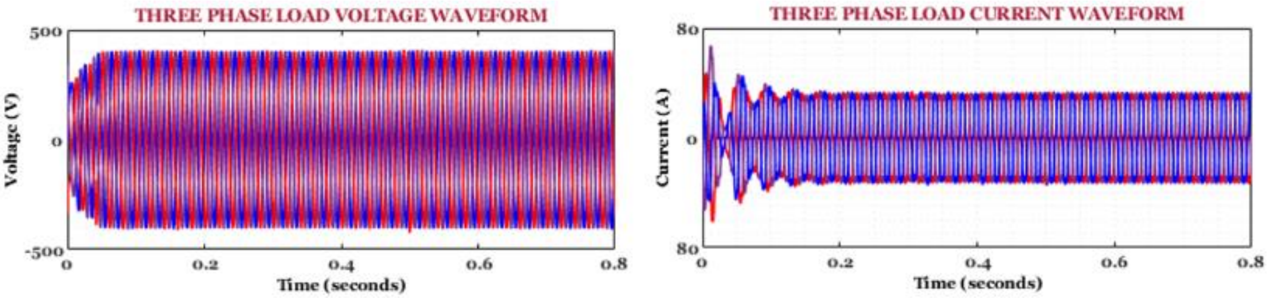

Figure 12: *Waveform of three phase load voltage and current*

Figure 12 represents 3φ load voltage and current waveform. The waveform of 3φ load voltage shows the fluctuations between $400V$ to $-400V$. The waveform of 3φ load current shows oscillation period around 80 and-80A at 0 to $0.2s$. After $0.2s$ current waveform gets stabilizes to $30A$ respectively.

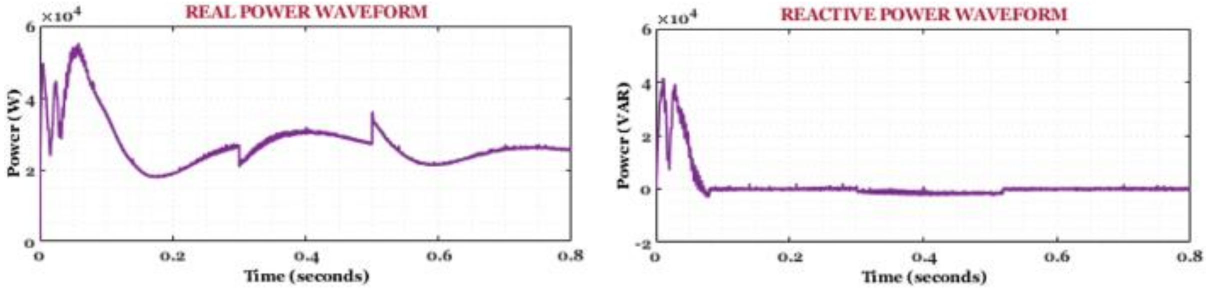

Figure 13: *Waveform of Real power and reactive power*

Figure 13 illustrates real and reactive power waveform. The real power waveform shows voltage swell occurs at $0.1s$ and voltage sag takes place at $0.2s$ Normally real power is nothing else, power consumed by resistive loads and hence the attained power is 3kW at a settling time of 0.7s. While the reactive power is that power oscillates between source and load.

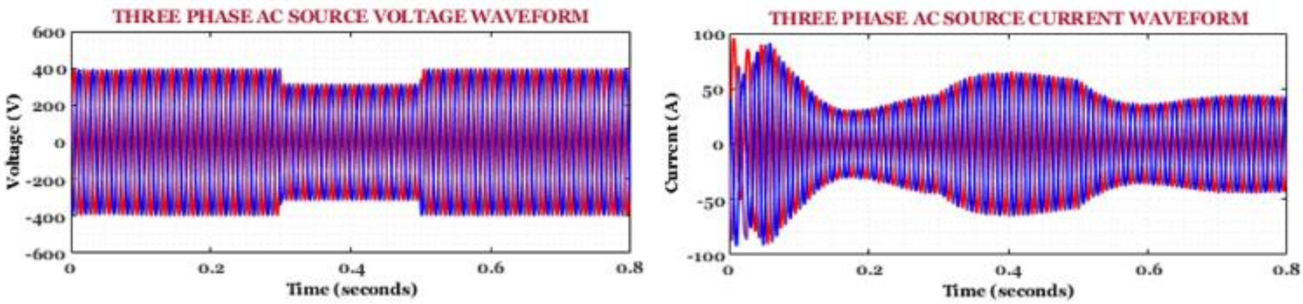

Figure 14: 3φ *AC source voltage and current waveform*

Figure 14 demonstrates 3φ AC source voltage and current waveform. The 3φ AC source voltage waveform displays stable voltage of $400v$ which fluctuates between $300V$ during $0.1s$ to $0.5s$. Yet again after $0.6s$ the steady state voltage is achieved. Initially the 3φ AC source current waveform is inaccurate but it stabilizes after $0.6s$ to form a sinusoidal waveform.

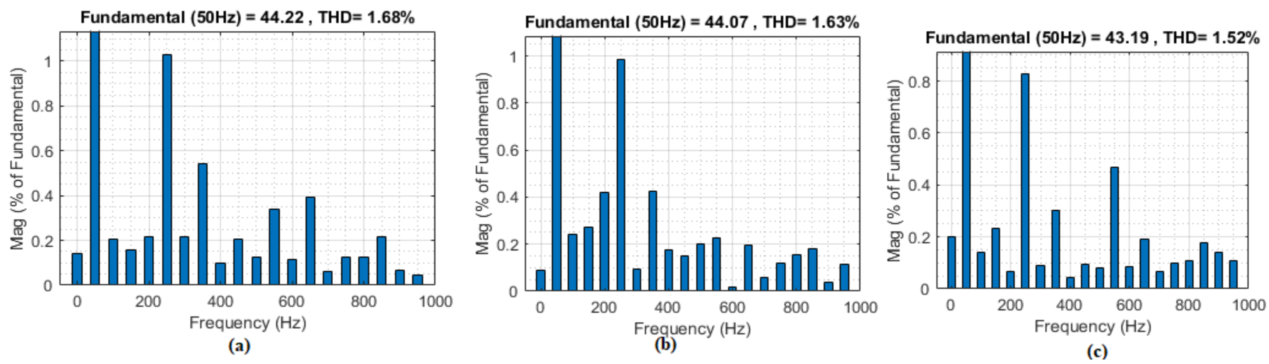

Figure 15: *THD Waveform*

Figure 15 presents the THD waveform. In figure 15(a) the THD value is 1.68% , following figures 15(b)&15(c) shows the THD value is 1.63% and 1.52% respectively .The low THD value indicates the minimum level of harmonic distortion in the system output, enlighten the efficiency and power quality generated by the proposed system.

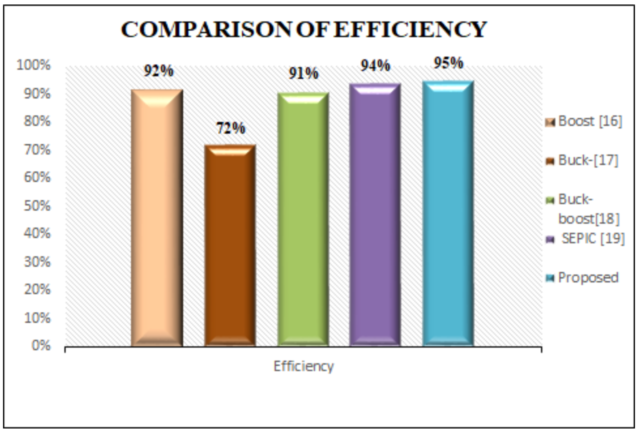

Figure 16: *Efficiency comparison*

Figure 16 shows the efficiency comparison between converters. The high gain QBC significantly increases the voltage greatly than a standard DC-DC converter by cascading two converter stages. The efficiency of proposed high gain QBC converter attained a greater efficiency compared to other converters. Comparing with various converter's efficiency such as boost [16] gained 92%, buck [17] reached 72%, similarly buck-boost [18] attained 91% and SEPIC [19] achieved 94%. Subsequently the proposed converter achieved about 95% of efficiency respectively.

Table 2: *Comparative analysis of control approaches*

Control approach	Total harmonic distortion (THD)
PSO [20]	3.21%
PI [21]	3.7%
PI-PID [23]	2.5%
Proposed	1.52%

Table 2 shows the THD comparison of control approaches. The proposed controller regulates the overall control parameters of UPQC with reduced THD of 1.52%. Compared to PSO [20] control approach which has THD level as 3.21%, progressively. Hybrid controller [21] ranges THD is 2.32%. The proposed control approach attained reduced THD compared to others. Hence comparing with PSO and Hybrid controllers, the proposed control approach is more dynamic and has greater performance with reduced harmonic distortion.

5. Conclusion

This research aims to enhance the power quality and improved efficiency gain by retaining PV based High gain QBC for UPQC with ANFIS controller. The proposed high gain QBC steps-up the voltage from PV and provides greater efficiency. The WOA-PI optimizes by tuning the parameters of PI controllers to achieve better performance of the converter. UPQC improves the power quality of electrical power system by recompensing voltage and current disturbances. UPQC has improved the system efficiency, reduced power quality issues with reduced THD value. The proposed scheme enhances the UPQC performance by means of an ANFIS controller which optimizes the control parameters of UPQC thereby ensures overall flow of power and power quality problems. Consequently the proposed topology results are simulated using MATLAB and the achieved efficiency of the converter is 95%. Successively the overall investigation supports to the progression of enhancing efficiency of proposed system with reduced THD of 1.52% and converter outputs as $810V\ and\ 3A$ along with improved power quality, meanwhile the performance of UPQC is superior compared to existing.

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