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Unified Power Quality Conditioner Model Based with Series and Shunt Filters

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ABSTRACT

With the increase of the complexion in the power distribution system, it is very possible that several kinds of power quality disturbances are happened in a power distribution system simultaneously.This paper proposes a unified power quality conditioner (UPQC) including a series and a shunt active power filter (APF) to compensate harmonics in both the distorted supply voltage and nonlinear load current. In the series APF control scheme, a proportional-integral (PI) controller, meanwhile a PI controller and are designed in the shunt APF control scheme to relieve harmonic currents produced by nonlinear loads. The DC voltage is maintained constant using Two degree of freedom proportional integral voltage controller (2DoFPI). The performance of the proposed UPQC is significantly improved compared to the conventional control strategy. The feasibility of the proposed UPQC control scheme is validated through the simulations.

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1. INTRODUCTION

The distributed generation of power supply quality has increasing demand either connected to the conventional grid, smart grid or micro grid [1]. The compensation of the load current and the distortion of the source voltage is the main objective of Unified Power Quality Conditioner (UPQC) in the power distribution system [2]. The difficultiess in the power distribution system have been given rise according to the broad use of nonlinear loads such as electric welders, adjustable speed drives and switching power supplies in industrial applications. The harmonic nonlinear currents loads into the networks and consequently distort the voltage waveform at the point of common coupling (PCC) due to the system impedances [3]. The deficiency in operation of electrical and electronic devices disturbances to voltage waveform can result in problems related to the specifications of these devices and industrial equipment. A constant sine wave form,frequency and symmetrical voltage with a constant RMS value to continue the production are needed in any operation precisely.This yield in improvement of efficiency,eliminate variations in the industry and reduce complexity of the extra instruments that lead to more distortion in the voltage waveform [4].

To avert the this problem and to preserve the loads from distortions, the harmonic the voltage and current components of must be fully compensated. Passive filters and shunt active power filters (APFs) are regularly used to relieve harmonic currents [5]. The evaluation of the current components ensure the effectiveness of control algorithm to eliminate the undesirable source-end current components with respect to higher harmonics, reactive power and negative sequence components of the load current [6]. Another APF connected in series to insert a voltage, which is added at a point of common coupling (PCC) such that the load end the voltage remains unchanged by any voltage disturbance, whereas the shunt APF is sufficient to compensate for load reactive power demand and unbalance, to delete the harmonics from regulate common DC link voltage and to supply current [7]. A new technique to install relieving equipment that can preserve the both purposes, the utility as well as to the customer. Thus with the implementation of custom power devices in the distribution side, power quality is improved [8]. Many UPQC techniques have been expanded to relieve harmonic currents and voltages such asPQ theory, wavelet transform, neural networks, fuzzy algorithm, Fourier transform theory, State feedback control law, power angle control concept [9].

The Unified Power Flow Controller (UPFC) is a second generation FACTS device, which enables independent control of active and reactive power besidesimproving reliability and quality of the supply [10].

The modern techniques in industry leads to a fast development in the power grid systems and the experts pay more attention to how to delete the voltage and current harmonics. Active Power Filter (APF) is an active tool to reduce the influence of harmonics, shunt APF for harmonic current, series APF for harmonic voltage and it is mainly used in low voltage low capacity applications [11]. In order to have minimum distortion in the load voltage, the difference between the load voltage and the reference voltage (error) must be zero [12]. The error produced is then delivered to a hysteresis controller to produce the required gate signals for series APF as can be shown in Figure 1.

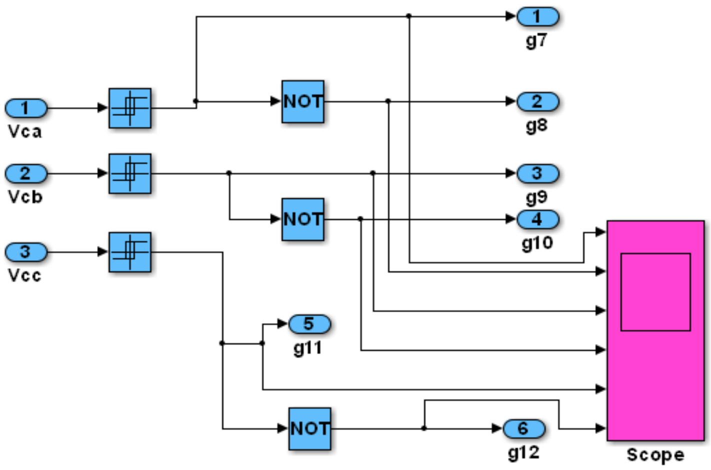

Figure 1. Hysteresis Controller

The performance of hysteresis controllers are powerful and simple to implement, but they are difficult to design, due to the varying switching frequency,the control specification is limited by the trade-off between the hysteresis band and switching frequency.
Control specification may be better when the hysteresis band is designed to be small. Nowadays the improvements in the power lectronics makes the switching frequency high, then, the switching loss is increased.

$$V_{ca} = \sqrt{2/3} * V_{alpha} \tag{1}$$

$$V_{cb} = \sqrt{2/3} * ((-0.5 * V_{alpha}) + ((\sqrt{3}/2 * V_{beta})) \tag{2}$$

$$V_{cb} = \sqrt{2/3} * ((-0.5 * V_{alpha}) - ((\sqrt{3}/2 * V_{beta})) \tag{3}$$

Valpha and Vbeta voltage components are generated after active and reactive powers (p,q) are implemented using Matlab/Simulink as in Figure 2.With the following input values:

$$V\_{alpha} = ((P * i\_{alpha}) - (q * i\_{beta})) \tag{4}$$

$$V\_{beta} = ((P * i\_{beta}) + (q * i\_{alpha})) \tag{5}$$

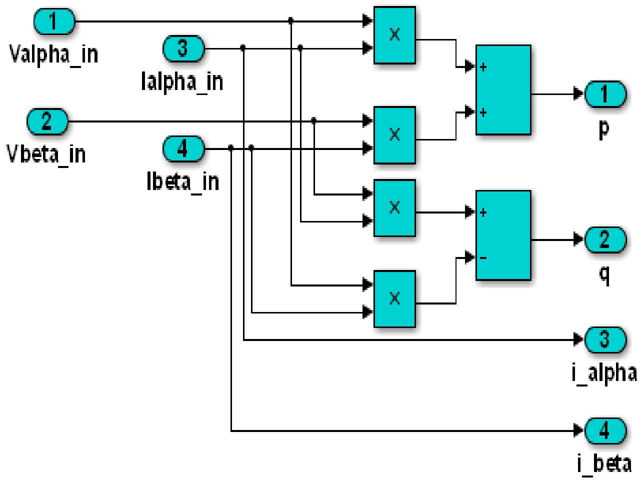

Figure 2. Simulink Generate Alpha and Beta Current Coponents

The instantaneous sampling of load current and source voltage and current are used to provide the compensation voltage through the UPQC series inverter and provides conditioning current through the shunt inverter.

The reference currents are compared with their shunt inverter output currents, in a hysteresis type PWM current controller. A suitable controlling method has been selected for the simulation and the rating of series and shunt inverters has been calculated through loading calculations of these inverters applying phasor diagram to increase the design accuracy. If nonlinear loads are used in a system, as given in Figure 2, the load current is composed of the fundamental component (i_f) and harmonic components (i_h) as follows:

$$i_L = i_f + i_h + I_{L1} \sin(\vartheta) \quad (6)$$

The compensated supply current to sinusoidal and in phase with the supply voltage, the traditional control methods regularly involve harmonic detection and current regulation stages [13]. The Simulink implementation of series active filter can be illustrated as in Figure 3.

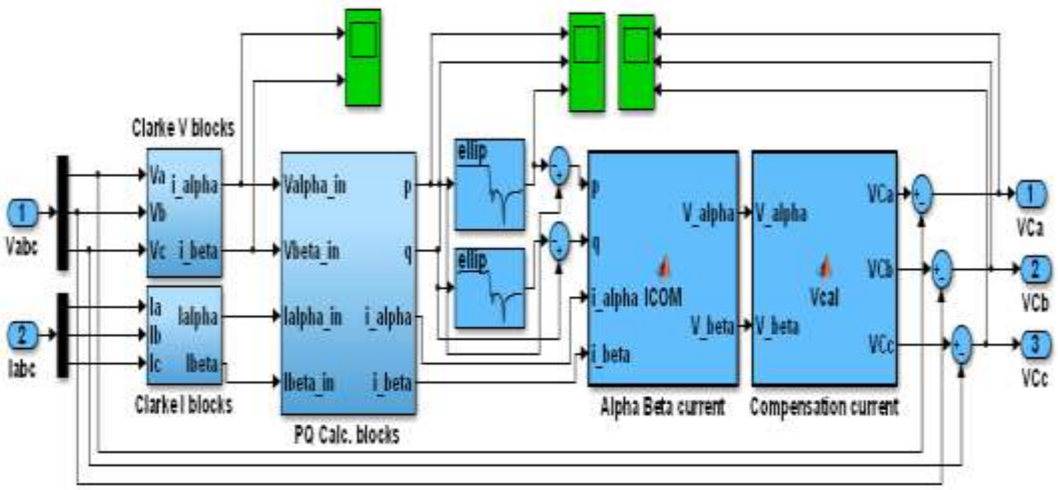

Figure 3. Seriesactive filter preperation signal Simulink implementation

Harmonic detectors are achieved by using two Elliptic low pass filter (LPF). Control scheme of series active filter can be shown in Figure 3. This unit is composed of the following blocks, Clarks transformation for voltage and current to prepare the data for the power calculation block.

The phase locked loop (PLL) are used to obtain smooth sinusoidal waveform using a second order elliptic filters. Let the load current (I_{Labc}) and dq components of current elliptic filter be the input to generate the reference current components of phase a, phase b and phase c as can be shown in Figure 4.

Figure 4 shows that, the reference current components generated through a Clark transformation block will be compared to the actual load current components to be form the error signal of the hysteresis controller.The signal obtained from the hysteresis controller is the input to the inverter. According to the usage of these hysteresis current controllers, the stabilization of the UPQC can be obtained. To detect the compensated current, the reference current has to obtain. PLL value is improved by means of RMS value. RMS of load active current can be obtained by the following formula:

$$RMS_{f(t)} = \sqrt{1/T \int_0^T f^2(t)\,dt} \quad (7)$$

The design of the shunt APF is to operate as a controlled current source whose output current would be automatically controlled [14] as can be shown in Figure 4.

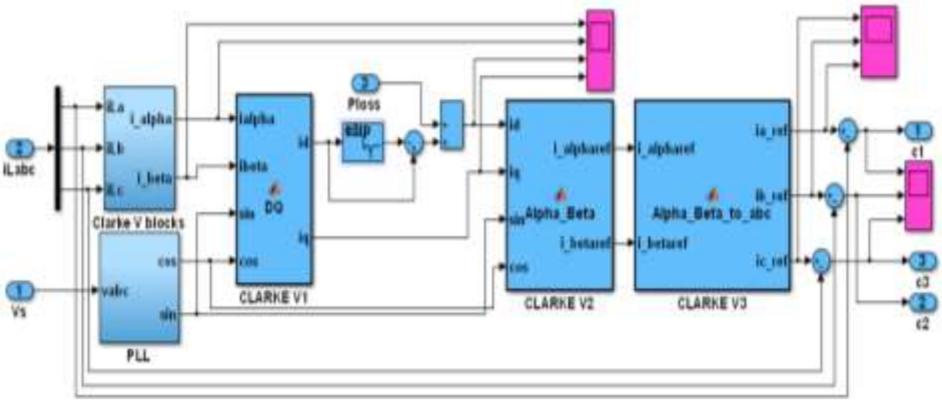

Figure 4. Shunt Filter Signal Preperation

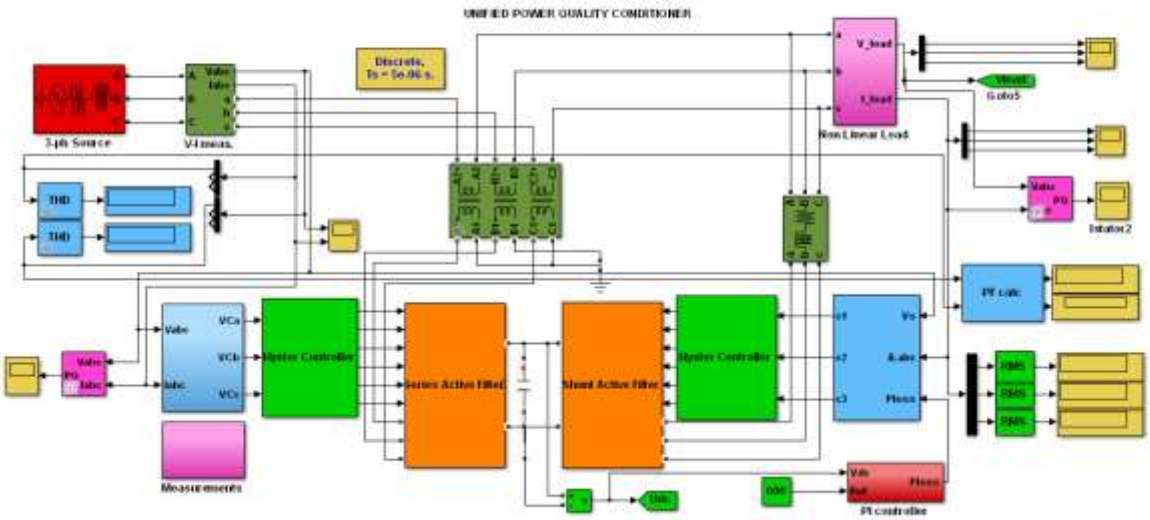

Figure 5. proposed algorithm of UPQC

Hysteresis controllers good control performance cannot be realized since switching ripples appear in the load voltage and the supply current. To improve the performance of the UPQC, this paper proposes a two degree of freedom proportional-integral (2DOFPI) controller to compensate the DC voltage with voltage regulation for the nonlinear load. In the series active filter control scheme, a PI controller satisfies good response. Simulation of the UPQC proposed control scheme is investigated through Matlab/Simulink (R2013a).

2. BASIC STRUCTURE OF UPQC

As mentioned earlier, UPQC is composed of series and shunt APF, the series and shunt APF use same energy storage so as to facilitate the structure and reduce the cost of UPQC. This can help in protect the critical load from voltage quality problems and eliminates the harmonic current produced by load. Most of the systems suffer from unbalance in the load as well as presence of reactive power in the power source which should be avoided or minimized. Normally the reactive power comes from inductive loading. Power Factor (PF) is a commonly used parameter for presence of reactive power. It is explained in IEEE standard that power factor is an important parameter for presence of reactive power in a system. PF is defined as the ratio of the active power (P) and apparent power (S), where their relationship with reactive power (Q) satisfies the equation:

$$S = P + Q \tag{8}$$

in harmonic free system. [15]. Figure 5 shows the block diagram of the proposed UPQC scheme. As shown in Figure 5, the new proposed control scheme without any harmonic detectors. Supply current and voltage are measured and compensated to be sinusoidal. Due to the harmonic detection absence in the proposed control scheme, the accuracy and the steady state performance of the UPQC can be improved significantly.

The control system of UPQC controller is comprised of three following parts [16]:

1. DC link voltage control
2. Shunt inverter control
3. Series inverter control

The Simulink implementation of the proposed algorithm can be illustrated as in Figure 5.

2.1. DC Voltage Link Control

A function of the PI controller is tracking the error exists between the actual and reference values of capacitor voltage to control the D.C link voltage as shown in Figure 5. A large value in P gain make the rise time so small which inversely proportional to the band width. This make the control system sensitive to any parameter variation and lead to instability and so much reduction decreases the responding speed of control system. I gain of controller try to eliminate the steady state error of (SSE) in the voltage control system. If this gain value is large, the resulted SSE is corrected faster and too much increase in its value ends in overshoot in system response [17].

2.2. Shunt Inverter Control

The UPQC shunt inverter controlling block diagram shown in Figure 4 using synchronous reference frame theory where the load currents are (I_{La} , I_{Lb} I_{Lc}). Clark transformation is used for transfer load currents into dq0 frame. As mentioned in first section ,the smooth sinusoidal waveforms are obtained using PLL. Here, the currents are divided into AC and DC components. The active part of current is id while iq represent the reactive one. AC and DC elements can be derived by a Elliptic low pass filter. Controlling algorithm corrects the system's power factor and compensates the all current harmonic components.

$$\begin{aligned} i^*_{fd} &= i_{ld} \\ i^*_{fq} &= i_{lq} = i_{sd} \\ i_{sq} &= 0 \end{aligned} \tag{9}$$

The average value of DC voltage can be reduced due to the following reasons:

1. Switching frequency
2. Power received from the DC link capacitors.
3. Distortions such as unbalance conditions
4. Sudden changes in load current.

2DoFPI controller is necessary in order to compensate the error between the actual and reference voltages of the shunt capacitor. As shown in Figure 6, the reference currents are transferred into abc frame through reverse conversion of synchronous reference frame Clarke V2 and Clarke V3 as in Figure 4. Resulted reference currents (Iaa*, Ibb* and Icc*) are compared with the output currents of shunt inverter (I_{La} , I_{Lb} and I_{Lc}) in and generate (c1, c2, c3). The Pulse width Modulation (PWM) signals is generated by inverter applying these signals to shunt inverter's power switch gates [18].

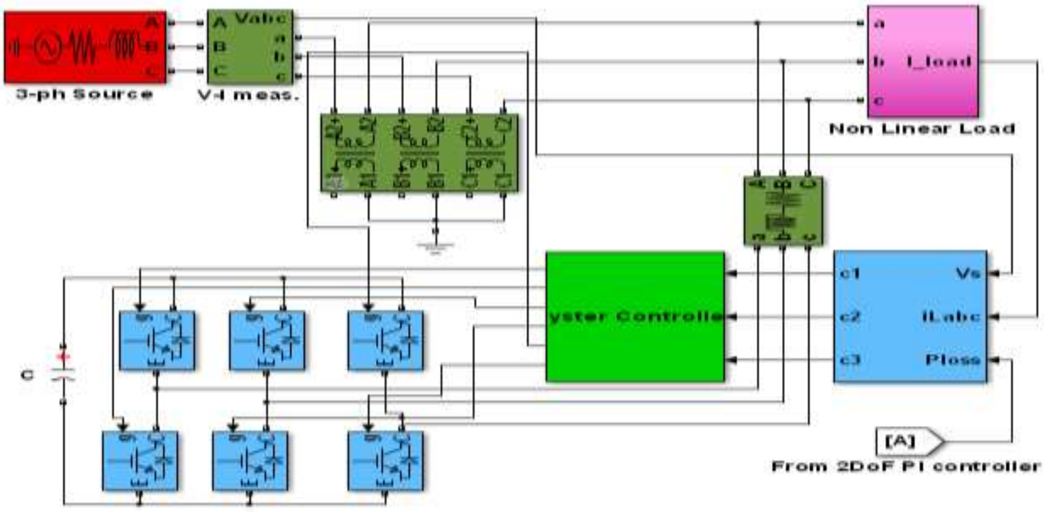

Figure 6. Shunt inverter control block diagram

The use of current control mode, only theneed to control the inverter output current tracking the voltage of the grid, while setting the sizeof the output current, you can achieve the stability of the parallel operation, the control methodis relatively simple and the results are better, so it has been widely used [19].

2.3. Series inverter control

The series inverter is shown in Figure 7. The PWM method is used to obtain better response of series inverter [19]. Sinusoidal voltage controlling strategy of load is used to control the series part of UPQC. The voltage distortions and 3-phase load voltage can be maintained with smooth sinusoidal waveform, through precise controlling of the duty cycle of the series inverter.

The synchronous reference frame theory is applied to achieve that aim. In this method the desired value of load phase voltage in d-axis and q-axis is compared with the load voltage and the result is considered as the reference signal. The controlling circuit of series inverter is shown in Figure 7. PWM method is used to perform best response of series inverter [20]-[21].

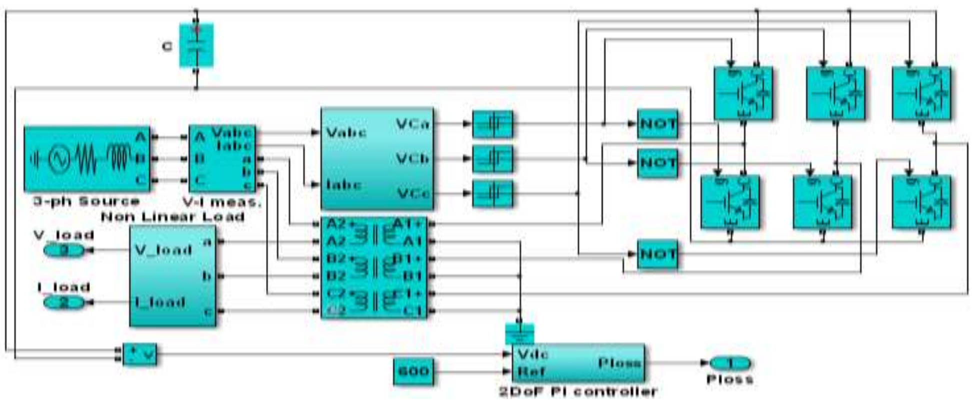

Figure 7. Series inverter control block diagram

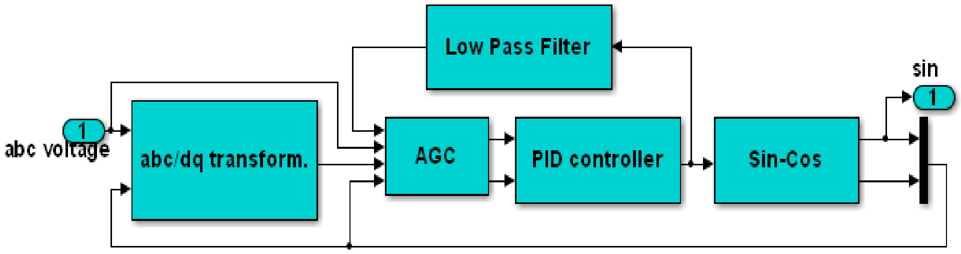

Figure 8. Block diagram of the improved PLL scheme

The conventional PLL is unable to operate smoothly under upnormal supply voltage condition. In this paper an improvement PLL is developed. LPF is added before the PLL block and automatic gain controller (AGC) as shown in Figure 8 to reject the effect of the harmonics in source and load voltages. The LPF is used in the dq frame, so that the slugish performance of LPF can be avoided. The phase angle should be detected precisely to avoid the system to spike or overshoot that lead to deterioration in the system performance.

3. ANALYSIS AND DESIGN OF 2DOFPI CONTROLLER &VOLTAGE REGULATOR

3.1. Analysis and Design of the Proposed 2DoFPI Controller

The new 2DOF PID controller can be described in the complex variable domain by the relation (10) [20].

$$U(s)=K\{bW(s)-Y(s)+\frac{1}{T_I s}[W(s)-Y(s)]+T_D s[cW(s)-Y(s)]\} \quad (10)$$

where:

U(s), W(s), Y(s), K, TI, TD, b, c is the Laplace transform of the u(t), the Laplace transform of the reference input w(t), the Laplace transform of the actual output y(t), the controller gain, the integral time, the derivative time, the set-point weight of the proportional term, the set-point weight of the derivative term respectively.

Both set-point weights can change in the interval from 0 to 1. The control system with the 2DOF controller (11) can be transformed in the system in Figure9 with the input filter with the transfer function.

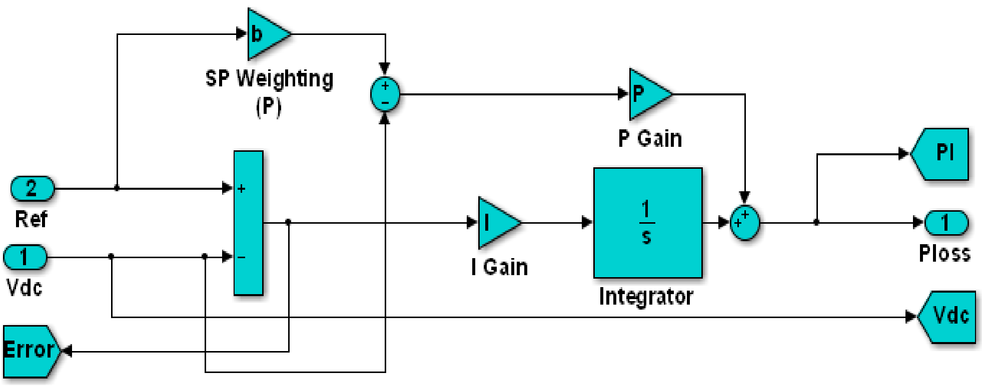

Figure 9. 2DoFPI controller with DC voltage

$$G_f(s)=\frac{W'(s)}{W(s)}=\frac{cT_I T_D s^2+bT_I s+1}{T_I T_D s^2+T_I s+1} \quad (11)$$

and the standard PID controller with the TF.

$$G_C(s)=K(1+\frac{1}{T_I s}+T_D s)=K+\frac{r-1}{s}+r_1 s) \quad (12)$$

The 2DOF PI controller can be developed when b=c=1 and TD = 0 according to (11 and 12). 2DoFPI closed loop control system is shown in Figure 10.

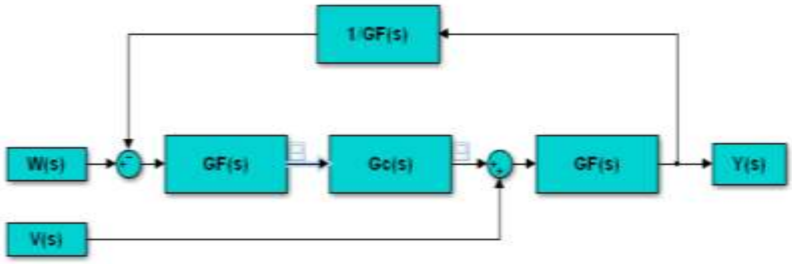

Figure 10. 2DoF control system block diagram

The output power losses according to the 2DoFPI can be shown in Figure 11 which is completely constant. The algorithm switching frequency is lower than of the hysteresis controller so that the power loss is reduced in the steady state region as shown in the second part of the Figure 11.

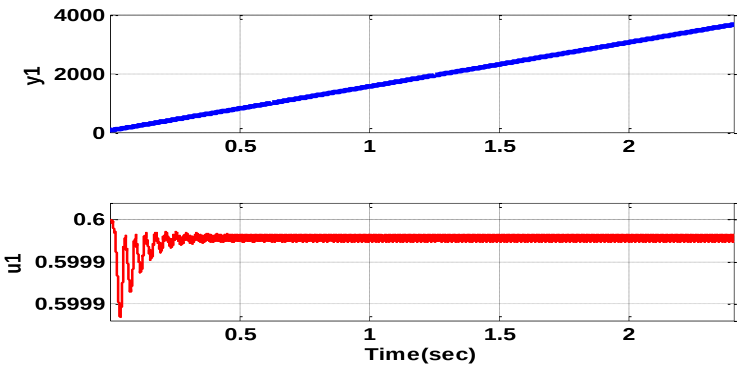

Figure 11. 2DoFPI controller output(Power loss)

3.2. Analysis and Design of the Voltage Regulator

A fixed output voltage is the main purpuse of voltage regulator to produce a constant magnitude regardless of changes to its input voltage or load conditions [22]. The require of switching regulators means to vary their output voltage in response to input and output voltage changes. PWM approach is to controls the input to the associated power switch, which controls it's on and off time (duty cycle). The output voltage that filtered through a requalator is fed back to the PWM controller to control the duty cycle. The feedback applied to the PWM controller is used to stabilized the output voltage when the filtered output tends to change the duty cycle. The proposed voltage regulator in shown in Figure 12.

The rational structure of the both 2DOF PID and PI controllers as numinator and denominator helps to overcome the problems take parts in the system. The nominator part of the closed loop transfer functions can removes the unsatisfactory overshoots and steady state error in control system. The tuning of the 2DOF parameters can be easly perform as the set-point changed in the interval from 0 to 1 [23]. The 2DoFPI controller is so powerfull to compensate the DC-link voltage variation and maintain the output to desired value. In the high frequency, its laborus for the convetional PI controller to remove undesired components of harmonic currents generated by shunt APF. The transfer function of the proposed 2DoFPI controller is obtained as in (13).

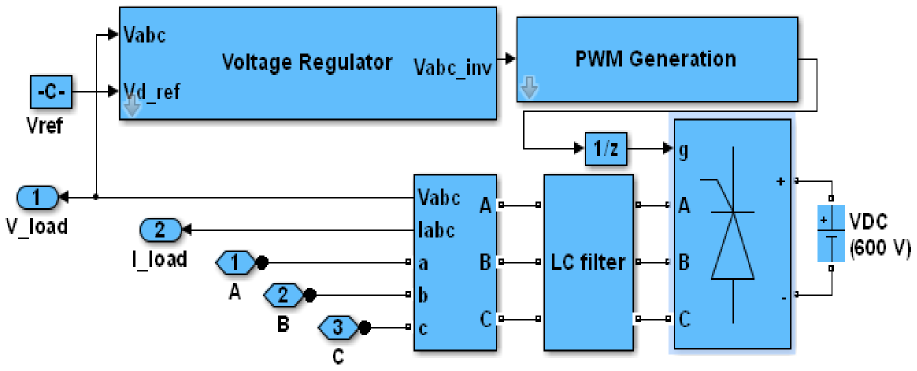

Figure 12. Proposed Voltage regulator

$$G(s)=8.6820*\frac{1+3.7219s}{3s^2+4.499s+1} \quad (13)$$

Both shunt and series inverters share a common dc link. Normally the shunt inverter is used to regulate the dc link at a reference value. The UPQC may be expanded with a PWM current source inverter that uses same energy form the dc link [24]. The voltage regulation and PWM blocks is shown in Figure 13.

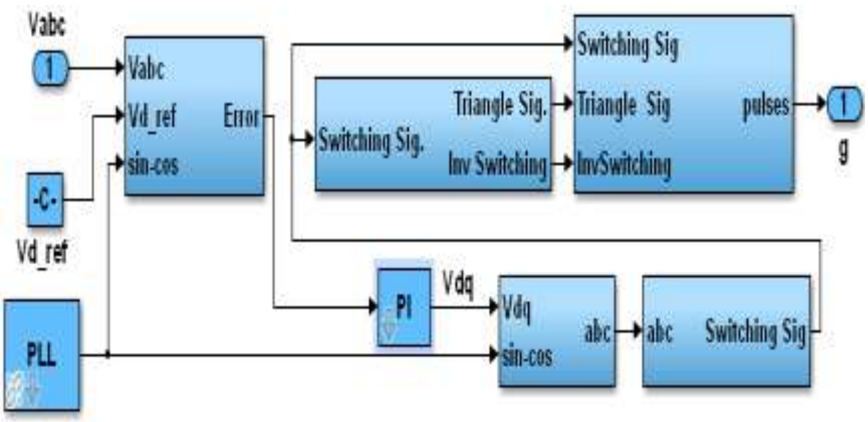

Figure 13. Voltage regulation and PWM blocks details

In this scheme the reference voltage q-axis as in (14)

$$V_{q\_ref}=0 \quad (14)$$

With currier frequency 2Khz

To generate triangle signal the, Output a repeating sequence of numbers specified in a table of time-value pairs.Values of time should be monotonically increasing as in the following sequence. [0 1/Fc/4 3/Fc/4 1/Fc] and the corresponding output values should be as [0 -1 1 0].

4. SIMULATION RESULTS

The Matlab/Simulink used to assessment of the proposed algorithm [25]. At the beginning, the simulation model consists of a conventional UPQC with a nonlinear load. The nonlinear load is supplied with distorted 200 V source as in the Figure 14. Figure 15 shows conventional nonlinear current that should be compensated.

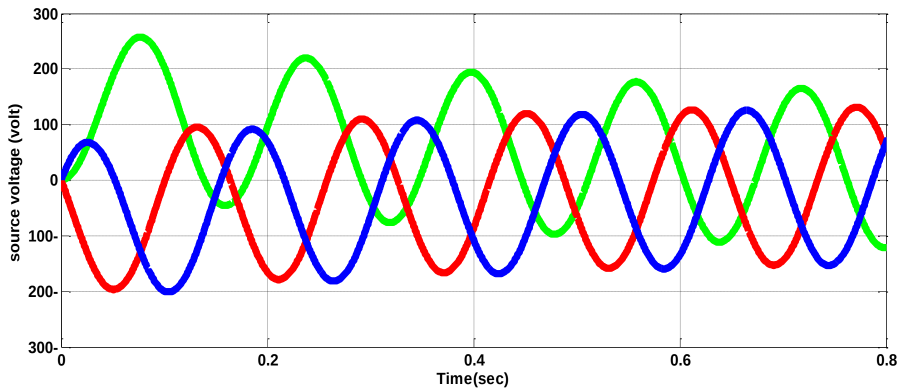

Figure 14. Simulation results with the conventional control scheme

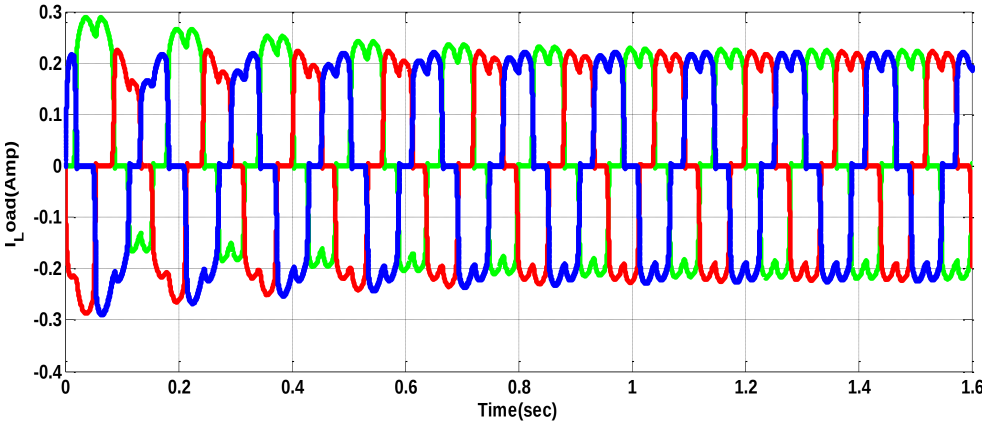

Figure 15. Load current with the conventional control scheme

The total harmonic distortion (THD) factor of distorted source is 7% as in Figure 16.

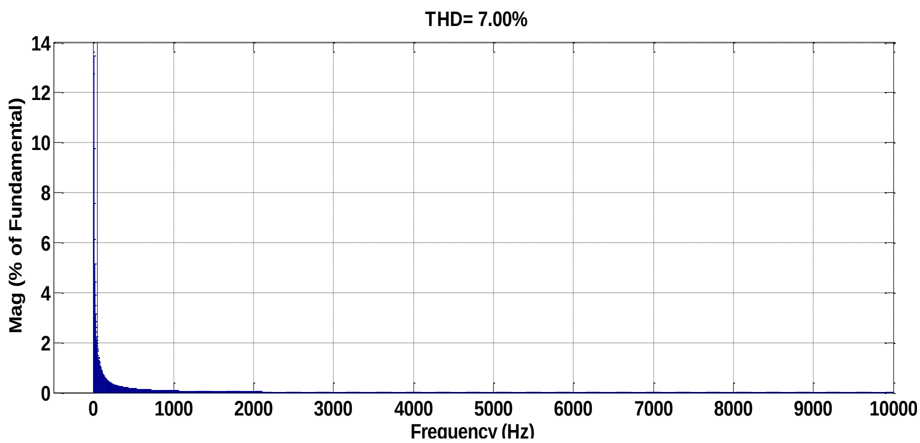

Figure 16. THD when UPQC is not connected to the system

To investigate the effectiveness of the proposed algorithm, the UPQC a reacts against theload nonlinear load current variation between (100-125)% change to relieve harmonics in load current and to ensure better response in both load voltage and supply current. The current waveform during the variation is shown in Figure 17. Absolutely it's better than Figure 15.

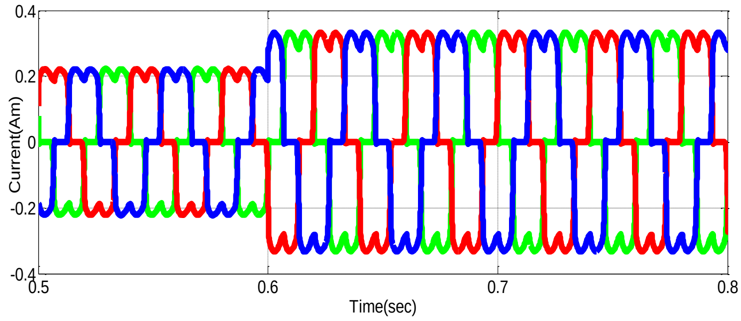

Figure 17. Current nonlinear load response during the load variation

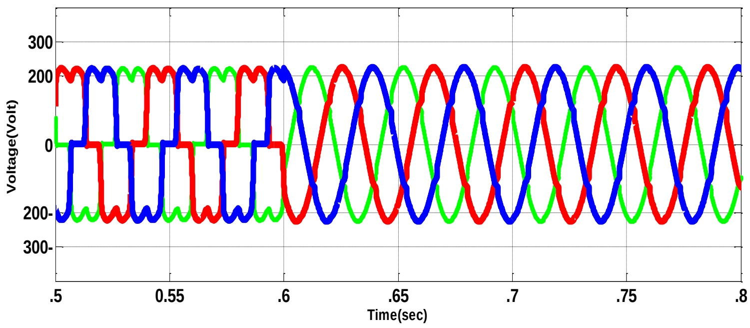

Figure 18. Voltage compensation when UPQC is connected to the system

The effectiveness of the proposed scheme can be also verified by switching ON-OFF of the UPQCsystem.After 0.6 sec the UPQC is switch ON, the voltage waveform of the load can be shown as in Figure18. The load voltage is completely compensated and it's clearly can be shown as pure sinusoidal waveform after 0.6 sec. The load voltage is completely compensated which proves the effectiveness of the proposed algorithm as in Figure 19.

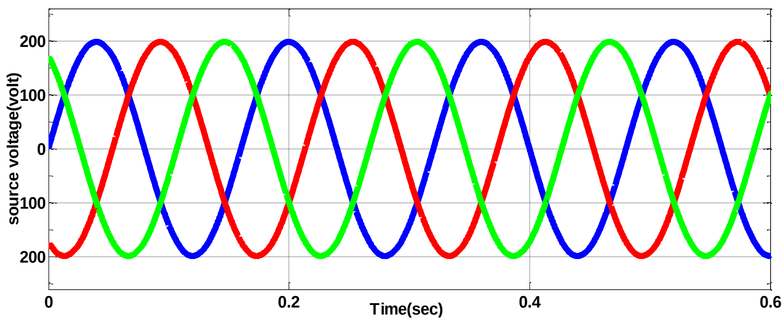

Figure 19. Load voltage when UPQC is connected to the system

The total harmonic distortion (THD) factor of compensated load voltage is 0.00005% as in Figure 20.

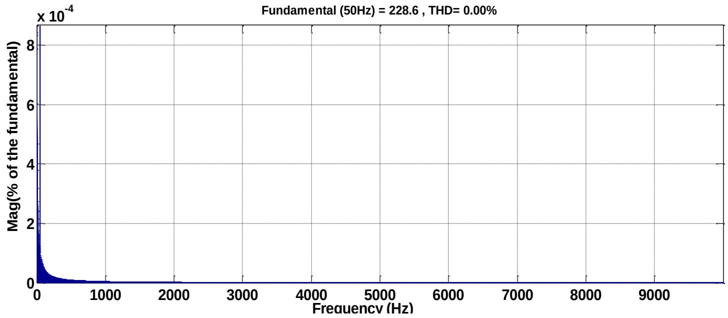

Figure 20. THD of the load voltage with UPQC

The THD is reduced from 7% to 0%, the load voltage is improved using the proposed UPQC for reduction of the harmonics. The dc voltage is maintained at a constant value which is equal to the reference value Vdc=600 V by using 2DoFPI voltage controller as can be shown in Figure 21. This result is much better than results reported in [26]-[27]. This controller is used in the DC voltage loop for reduction of unwanted power loss inside the inverter [28].

The powerfullof the proposed control algorithm can be demonstrated with Figure 22. In Figure 22, the load current is compensated after 0.6 sec with the turn-on of UPQC with increasing 125% of the nominal load. This result is much better than results reported in [29]The Simulation results of the proposed regulator scheme can be shown the following Figures. The timing sequence to control the IGBT can be illustrated in Figure 23. The V_{dq} generated in the regulator unit which is combined with PI controller to generate both m-index and Vabc of the nonlinear load van be shown in Figure 24.

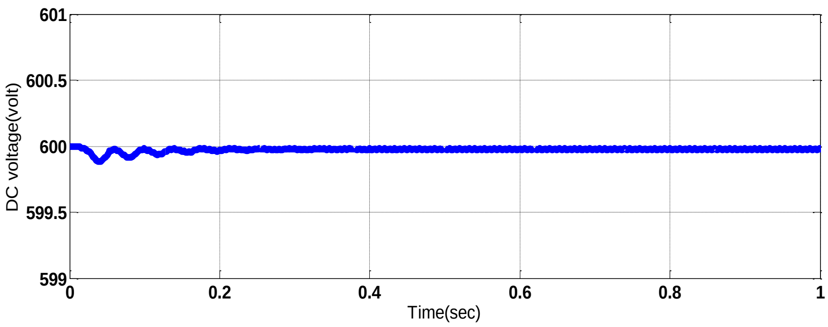

Figure 21. DC voltage simulation results with the proposed control scheme

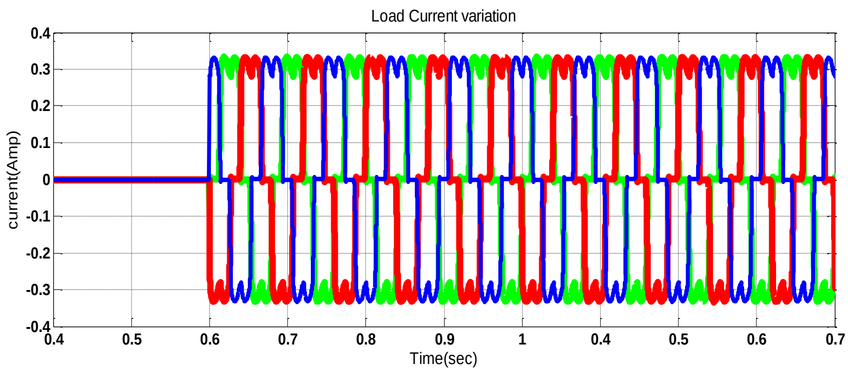

Figure 22. Load current variation with the proposed control schem

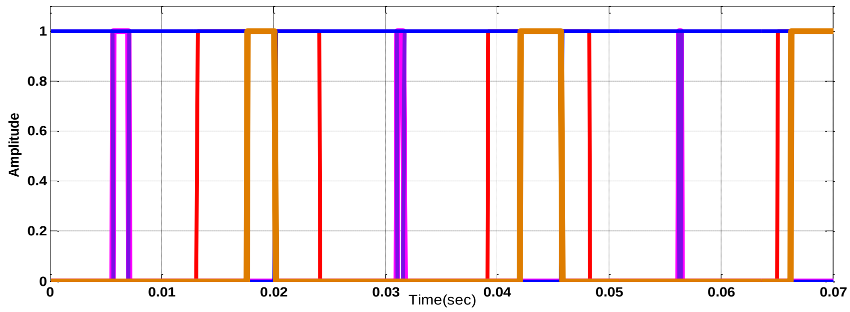

Figure 23. Pulses of the voltage regulation unit

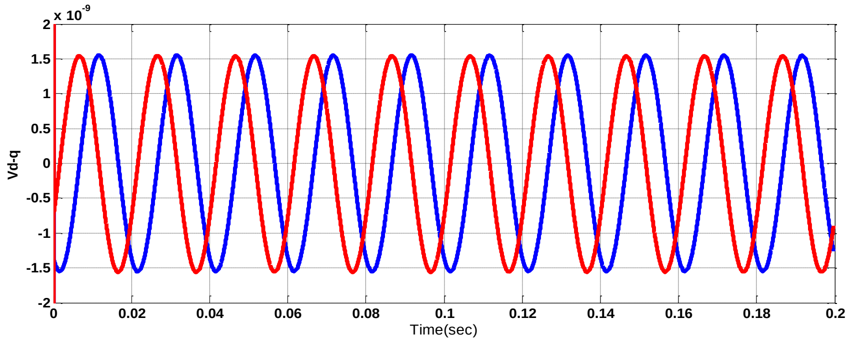

Figure 24. V_{dq} before PI controller of the regulation unit

The V^*_L reference voltage is captured with derived unit vector. Park's transformation is used to converts load voltages (V_{La}, V_{Lb}, V_{Lc}) from abcfram to rotating dqo frame using a PLL [30]. The angular position (w*t) used for generation of the PWM can be shown in Figure25. The simulation figures of the voltage regulation unit proves the effectevness of the proposed scheme.

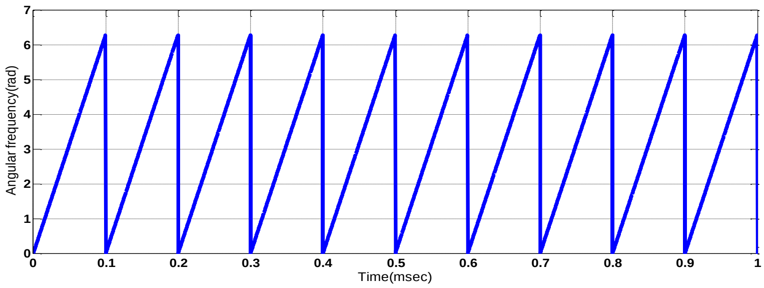

Figure 25. Angular position (ωt) of voltage regulation unit

The stability of the system may be characeterized by eigenvalues. The energy of the any stateof the UPQC system can be defined by Hankel singular values. According to Hankel, larger energy states preserves most of its characteristics in terms of stability, frequency, and time responses. For a stable state space system (A, B, C, D), its Hankel singular values are defined as [31]-[32].

$$\delta_H = \sqrt{\lambda_i (PQ)} \tag{15}$$

where:

P, Q, λ are controllability, observability grammians and Eigen value respectively satisfying:

$$AP + PA^T = -BB^T \tag{16}$$

$$A^T Q + QA = -C^T C \tag{17}$$

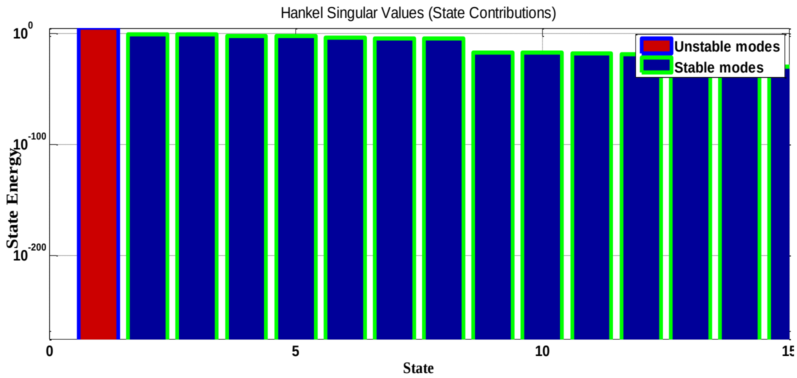

Figure 26. State contribution of the proposed scheme

Figure 26, shown that, most of the energy of system stored in states 1 through 15 which ensures that the system preserves most of its dynamic response. The detail system parameters are given in Table I.

Table I. System Parameters

	Parameters	Value
Source	Voltage	200 Vrms
	Frequency	50 Hz
Nonlinear Load	3-phase AC inductance	1 mH
	Diode resistance	1m Ω
DC-Filter	Voltage	600 V
	Capacitance	20mF
Shunt Filter	Filter inductance	3.5 mH
Series Filter	Filter inductance	1.3 mH

5. CONCLUSION

In this paper, control the UPQC with voltage regulation was proposed with the aid of the 2DoFPI and improvement of PLL unit. The proposed control strategy was investigated and the design of the 2DoFPI and voltage regulation to generate and control the PWM. The proposed algorithm provides smooth performance with good responses during the load variations. The sinusoidal load voltage and supply current are the final results which are compensated smoothly during all period of operation of the UPQC with lowest values of THD.

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