SIMULATION OF TEN-SWITCH UPQC FOR NONLINEAR LOAD

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Abstract—This paper presents a control method based on a synchronous-reference frame (SRF) to compensate the power-quality (PQ) problems that occur in a three-phase four-wire unified PQ conditioner (UPQC) under unbalanced as well as distorted load conditions. The proposed system is also extended with an energy storage device called super capacitor. This super capacitor is used to improve the performance of the UPQC. The proposed UPQC system can improve the various power quality parameters at the point of common coupling on the power distribution systems under unbalanced as well as distorted load conditions. The simulation results are obtained using the Matlab/Simulink Environment. They are discussed in detail to support the proposed SRF-based control method presented in this paper. The proposed approach is also validated through the experimental study with the UPQC hardware prototype.

Index Terms—Active power filter (APF), phase locked loop (PLL), harmonics, power quality (PQ), synchronous reference frame (SRF), unified power-quality (PQ) conditioner (UPQC), Super capacitor.

I. INTRODUCTION

UNIFIED POWER-QUALITY (PQ) conditioner (UPQC) systems are under wide study by many researchers as an eventual method to improve the PQ in electrical distribution systems [1]–[11]. The main objective of an UPQC is to eliminate the disturbances that affect the performance of the critical loads in power systems. Therefore, the UPQC is one of the most powerful solutions to improve PQ to large-capacity loads which are sensitive to the supply-voltage-imbalance distortions [3]. It consists of two inverters that share one common dc link, and capable of compensating the voltage sag and swell and the harmonics in current and voltage. It can also be used to control the power flow and voltage stability. The UPQC designed with the combination of a series active power filter (APF) and a shunt APF can also compensate for the voltage interruptions if it has some energy storage or battery element in the dc link [4]. The shunt APF is usually connected in parallel to the loads and compensates

for all current-related problems. Some of them include the power factor improvement, reactive power compensation, current harmonic compensation, dc-link voltage regulation, neutral current compensation and load unbalance compensation. The series APF is connected in series with a transmission line through a series transformer (ST). It acts as a voltage-controlled source and can compensate all voltage-related problems. Some of them include voltage sag, voltage swell, flicker, voltage harmonics, etc. [2], [3]. In this paper, a synchronous-reference-frame (SRF)-based control technique is proposed for the UPQC system and it is optimized without using the transformer voltage, load, and filter current measurement. This technique reduces the numbers of the current measurements and thereby the system performance is improved. In the proposed technique, various parameters like load voltage, source voltage, and source current are measured. They are then evaluated and tested under different conditions like unbalance and distorted load with the use of Matlab/Simulink software. The proposed SRF-based control technique has also been validated through experimental study.

II. UPQC

The UPQC is used for harmonic elimination along with compensation of voltage and current to improve the PQ, at the point of common coupling (PCC) to protect the harmonic sensitive loads connected to it. In the research on UPQC, it is clear that the UPQC is utilized mainly to solve PQ problems simultaneously [12]–[15]. Fig. 1 represents a basic system configuration of a general UPQC with series and shunt APFs. The main aim of the series APF in UPQC is to obtain harmonic isolation between the load and supply. It has the capability of voltage imbalance compensation as well as the voltage regulation and harmonic compensation at the PCC. The shunt APF is mainly used to absorb the current harmonics, to compensate for the reactive power, and to regulate the dc-link voltage between both APFs.

III. SRF

The conventional SRF method is generally used to extract the harmonics contained in the supply voltages or currents. For compensating the current harmonics, the distorted currents are first transformed into a two-phase stationary coordinate using $\alpha-\beta$ transformation (same as that in the $p-q$ theory). After this transformation, the stationary frame quantities are further

transformed into the synchronous rotating frames using the cosine and sine functions from the phase-locked loop (PLL). The sine and cosine functions help in maintaining the synchronism with the supply voltage and current. Like the $p-q$ theory, the harmonics and fundamental components are separated easily using the filters and are transferred back to the $a-b-c$ frame of reference as the reference signals for the filter. The conventional SRF algorithm is also commonly known as the $d-q$ method, and it is based on the transformations $a-b-c$ to $d-q-0$ (parks transformation), which is for active filter compensation [13]. Several APF and UPQC application works which have been presented in the literature are about improving the performance of the compensator [14]–[20]. In the technique of SRF-based APF in three-phase four-wire (3P4W) system applications, the voltage and current signals are generally transformed into the conventional rotating frame $(d-q-0)$. In the proposed SRF method, the transformation angle (ωt) is used to represent the angular position of the reference frame which is said to be rotating with a constant speed in synchronism with the three-phase ac voltage. Where in the nonlinear load conditions, harmonics and reactive currents of the load are determined by the PLL algorithms. Then, the currents with the same magnitude and reverse phase are produced and injected to the power system to compensate for the neutral current, the harmonics, and the reactive power. The $\alpha-\beta-0$ coordinates are stationary in the stationary reference frame, while in the SRF method $d-q-0$ coordinates rotate synchronously with the supply voltages. Thus, it is observed that the angular position of the supply voltage gives the angular position of the SRF as well[13]–[20]. In 3 Phase 4 Wire systems, since the direct axis current component id of the current in the "d" coordinate is in phase with the voltage. It corresponds to the positive-sequence current. However, quadrature axis current component iq of the current in the "q" coordinate is orthogonal to the id component of the current. It corresponds to the negative sequence component of the reactive current. Further, the $i0$ component of the current, which is orthogonal to both id and iq, corresponds to the zero-sequence current component. If the iq component is negative, then the load has inductive reactive power. In other words, if iq is positive, then the load has capacitive reactive power. In a 3P4W nonlinear power systems, the id and iq components of the currents include both oscillating components and average component sas shown in

$$i_d = \tilde{i}_d + \bar{i}_d \quad i_q = \tilde{i}_q + \bar{i}_q. \qquad (1)$$

The oscillating components of id and iq of the current correspond to the harmonic currents, and the average components of the current correspond to the active (id) and reactive (iq) currents [13], [14], [20]. In the balanced, linear three-phase systems, the load voltage and current signals consist of only fundamental positive-sequence components. However, in nonlinear unbalanced load conditions, the fundamental component has all positive, negative, and zero-

sequence components. In APF applications, to compensate the harmonics the fundamental positive-sequence components of the signals should be usually separated.
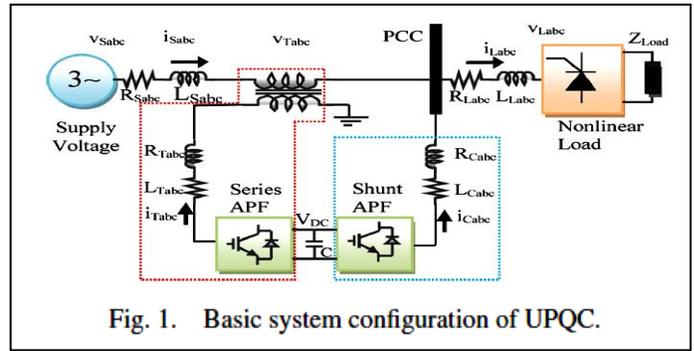

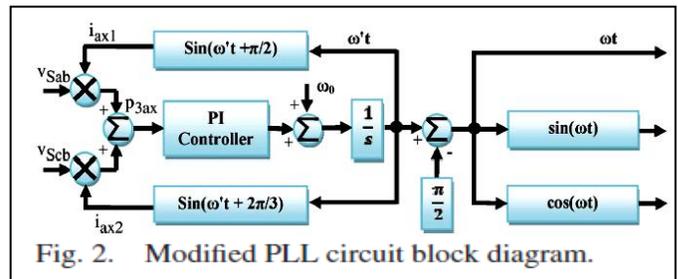Fig. 1.   Basic system configuration of UPQC.

Fig. 2.   Modified PLL circuit block diagram.

IV. SRF-BASED CONTROL ALGORITHM

Among the various APF control methods in the literature, the SRF-based control method is seen as one of the most conventional and the most practical methods [11], [12], [14]–[17]. The SRF method gives excellent characteristics but it requires the decisive PLL techniques. A new technique based on the SRF method along with modified PLL algorithm is presented in this paper. The performances is compared with the conventional SRF method under both unbalanced and distorted load conditions. The SRF control method proposed here uses $a-b-c$ to $d-q-0$ transformation equations, filters, and the modified PLL algorithm as shown in Fig. 2. The technique of sensing of the source current only to realize an SRF-based controller or any other type of controller for shunt APF is not new. This controller of this kind can be found in the literature [24]–[28]. The SRF-based controller with the modified PLL for the UPQC for 3P4W topology proposed as well as the SRF-based controller implemented for the series APF is not presented in the literature. The proposed method therefore is novel, simple and easy to implement and offers the less current measurement. Therefore, it can be run efficiently in the DSP platforms. Hence, the proposed controller with modified PLL algorithm efficiently improves the performance of the UPQC under unbalanced as well as distorted load conditions.
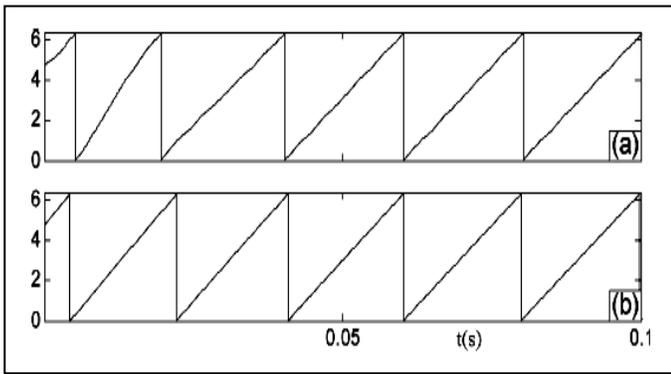
Fig. 3.   Transformation angle (ωt) waveforms for the (a) conventional and (b) modified PLL algorithms.

A. Modified PLL

Several PLL algorithms are used with the SRF and other control methods in APF applications [13]–[16], [19]–[22]. The conventional PLL circuit can also work properly under distorted and unbalanced system voltages. However, a conventional PLL circuit has disadvantages such as low performance for highly distorted and unbalanced system voltages. In this paper, the modified PLL circuit is shown in the Fig. 2 and it is used for the determination of system voltage signals' positive sequence components. The reason for modifying the conventional PLL is to improve the UPQC filtering performance under unbalanced and extremely distorted voltage conditions. The simulation results according to the transformation angle (ωt) waveform for the conventional PLL [22] and the modified PLL algorithms are shown in Fig. 3. The modified PLL has comparatively better performance than that of the conventional PLL. This is because the output (ωt) of the modified PLL has comparitively low oscillations under unbalanced and extremely distorted voltage conditions. Thus the modified PLL circuit is used to calculate the three-phase auxiliary total power by applying three-phase instantaneous source line voltages, i.e., v_{Sab} and v_{Scb} ($v_{Sab} = v_{Sa} - v_{Sb}$; $v_{Scb} = v_{Sc} - v_{Sb}$), in order to determine the transformation angle (ωt) of the system supply voltage. The modified PLL circuit is designed such that it operates properly under unbalanced and extremely distorted voltage conditions. The 3 phase line voltages are measured and used as inputs, and the transformation angle (ωt) is calculated as an output signal of the modified PLL circuit. The line voltages thus measured are multiplied by auxiliary ($i$ax1 and $i$ax2) feedback currents with unity amplitude, in which one of them leads 120° to another to obtain the three-phase auxiliary instantaneous active power (p3ax). To stabilize the output, the fundamental angular reference frequency ($\omega_0 = 2\pi f$) has to be added to that of the output of the proportional–integral (PI) ($P = 0.05; I = 0.01$) controller. Hence by the integration of this calculation, we can obtain the auxiliary transformation angle (ω_t). It is observed that the produced ω_t leads the system fundamental frequency by an angle of 90° therefore, $-\pi/2$ is added to the output of the integrator in order to reach the system fundamental frequency. The a stabile operating point is achieved by the PLL circuit when three phase auxiliary instantaneous active power (p3ax)

becomes zero or when it has a low frequency oscillation. In addition, the transformation angle reaches the fundamental positive-sequence components of the line voltages. Therfore, $\sin(\omega t)$ in the modified PLL output is also in the same phase angle with the fundamental positive sequence components of the measured source voltages (v_{sa}). The modified PLL circuit can be considered to operate satisfactorily under highly distorted and unbalanced system voltages if the PI gains in the PLL algorithm can be tuned accordingly. The proposed modified PLL circuit is used with the proposed SRF-based UPQC control method. It is observed from the performance that it is simple, fast, and robust for utility applications under unbalanced and extremely distorted load and supply voltage conditions. The conventional UPQC and the proposed UPQC control block diagrams are as shown in the Fig. 4. In the conventional control method [6] shown in Fig. 4(a), to compute the reference switching signals in the UPQC. is done by sensing the load current, three-phase source current, three-phase source voltages, dc-link voltage, shunt APF filter current, and series APF injected voltages in transformers.

In the proposed method as shown in the Fig. 4(b), it is observed that sensing the three-phase source current and voltages and load voltages, dc-link voltage are sufficient to compute the required reference switching signals in the UPQC. Generally, in the SRF-based controllers either the source currents (indirect method) or the shunt active filter and the load currents (direct method) are used for generation of the reference-current signal.
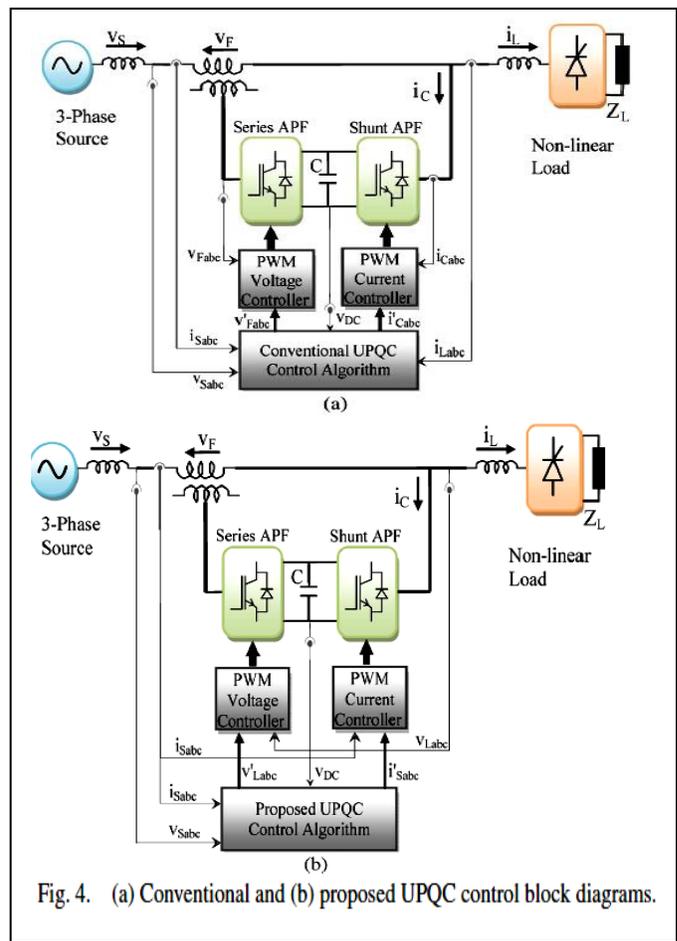

Fig. 4.   (a) Conventional and (b) proposed UPQC control block diagrams.

The SRF-based control method technique proposed presents some advantages, compared with other methods. The overall control system can be easily adopted as it has fewer current

measurements. The proposed method has a better response under the distorted and unbalanced load conditions. The proposed control strategy works good in most of the load-current as well as source-voltage distortions.

B. Reference-Voltage Signal Generation for the Series APF

The SRF-based UPQC control algorithm proposed in this paper can be used to solve the PQ problems that are related to the source-voltage harmonics, unbalanced voltages. It can deal with the voltage sag and swell at the same time. In this method, the series APF controller is used to calculate the reference value that must be injected by the STs, by comparing the load-side line voltages and the positive-sequence component of the source voltage. The reference-voltage signal-generation algorithm for the series APF is as shown in the Fig. 5. In (4), the supply voltages v_{Sabc} are transformed $d-q-0$ by using the transformation matrix **T** given in (2). In addition, the modified PLL conversion is used for the reference voltage calculation.

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \sin(wt) & \sin(wt-2\pi/3) & \sin(wt+2\pi/3) \\ \cos(wt) & \cos(wt-2\pi/3) & \cos(wt+2\pi/3) \end{bmatrix} \quad (2)$$

$$T^{-1} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & \sin(wt) & \cos(wt) \\ 1/\sqrt{2} & \sin(wt-2\pi/3) & \cos(wt-2\pi/3) \\ 1/\sqrt{2} & \sin(wt+2\pi/3) & \cos(wt+2\pi/3) \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} v_{S0} \\ v_{Sd} \\ v_{Sq} \end{bmatrix} = T \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \quad (4)$$

$$v_{Sd} = \bar{v}_{Sd} + \tilde{v}_{Sd}. \quad (5)$$

$$\begin{bmatrix} v'_{La} \\ v'_{Lb} \\ v'_{Lc} \end{bmatrix} = T^{-1} \begin{bmatrix} 0 \\ \bar{v}_{Sd} \\ 0 \end{bmatrix}. \quad (6)$$

The instantaneous source voltages (v_{Sd} and v_{Sq}) have both the oscillating components (v_{Sd} and v_{Sq}) and the average components (v_{Sd} and v_{Sq}) under unbalanced source voltage with harmonics. The oscillating components of v_{Sd} and v_{Sq} consists of the harmonics and the negative-sequence components of the source voltages under the distorted load conditions. The average component of v_{Sd} and v_{Sq} have the positive-sequence components of the voltages. The zero-sequence part (v_{S0}) of the source voltage occurs when the source voltage is very unbalanced. The source voltage in the d-axis (v_{Sd}) is given in (5) consists of the average and oscillating components. The load reference voltages (V_{Labc}) are also calculated as given in (6). The inverse transformation matrix T^{-1} is given in equation (3). It is used for obtaining the

reference load voltages by using the average component of source voltage and ωt produced as per the modified PLL control algorithm. The positive-sequence average value of source-voltage (V_{Sd}) in the d-axis is calculated by the LPF, as shown in the Fig. 5. Zero and negative sequences of source voltage are set to zero to compensate the harmonics, unbalances, and distortions in load voltage as shown in Fig. 5
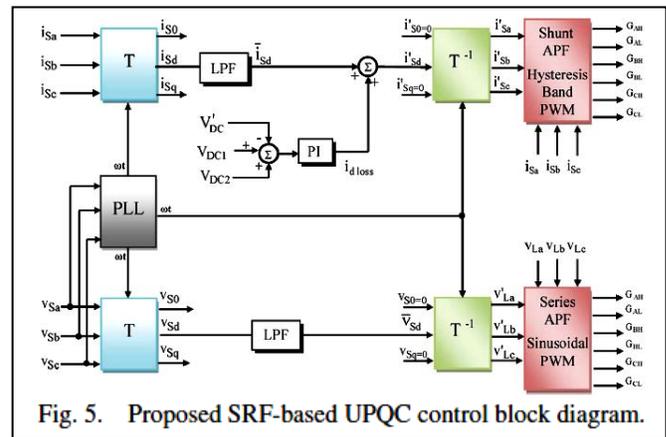

Fig. 5.   Proposed SRF-based UPQC control block diagram.

The load reference voltages (v_{La}, v_{Lb}, and v_{Lc}) and load voltages (v_{La}, v_{Lb}, and v_{Lc}) that are produced are compared in the sinusoidal pulse width modulation (SPWM) controller and the switching signals are produced. They are given to the insulated-gate bipolar transistor (IGBT) to compensate all voltage-related problems at the PCC such as the voltage harmonics, the voltage sag, swell and the voltage unbalances.

C. Reference-Source-Current Signal Generation for Shunt APF

The shunt APF described in this paper can be used to compensate the current harmonics generated in the nonlinear load and thereby the reactive power. The SRF-based shunt APF with the reference source-current signal-generation algorithm proposed uses mainly the source voltages, currents and the dc-link voltages. The source currents are transformed to the $d-q-0$ coordinates, as given in equation(7) using (1) and transformation angle (ωt) generated from the modified PLL. In the 3P4W systems with nonlinear load conditions, the instantaneous source currents (i_{Sd} and i_{Sq}) include both oscillating components (i_{Sd} and i_{Sq}) and the average components (i_{Sd} and i_{Sq}). The oscillating components consist of negative-sequence components and the harmonics of the source currents. The average components consist of the positive-sequence components of current which and correspond to reactive currents. The negative sequence component of the source current (i_{S0}) will come into picture when the load is unbalanced. The SRF-based method employs the positive-sequence average component (i_{Sd}) in the d-axis and the zero- and negative-sequence component (i_{S0} and i_{S0}^1) in the d and q-axes of the source currents, for compensating the harmonics and also the unbalances in the load.

$$\begin{bmatrix} i_{S0} \\ i_{Sd} \\ i_{Sq} \end{bmatrix} = T \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix}. \qquad (7)$$

The active power is fed to the power system by the series APF to compensate for the active power losses of the UPQC power circuit as it causes the reduction in dc-link voltage. A part of the active power must be absorbed from the power system by the shunt APF for the regulation of the dc-link voltage. For this purpose, the dc-link voltage is compared with its reference value (V_{DC}), and the required active current (id_{loss}) is obtained with a PI controller. The fundamental component of source current is calculated by adding it to the required active current and source current average component (i_{Sd}), obtained by an LPF and it is given in (8).

$$i'_{Sd} = i_{dloss} + \bar{i}_{Sd}. \qquad (8)$$

In this method, the negative-sequence and zero sequence components of the source current reference (i_{s0} and i_{Sq}) in the d and q-axes are then set to zero to compensate the unbalance, distortion, harmonics and reactive power in the source current. The source current references are then calculated as given in (9) to compensate for the harmonics, the neutral current, unbalance, and reactive power by regulating the dc-link voltage.

$$\begin{bmatrix} i'_{Sa} \\ i'_{Sb} \\ i'_{Sc} \end{bmatrix} = T^{-1} \begin{bmatrix} 0 \\ i'_{Sd} \\ 0 \end{bmatrix}. \qquad (9)$$

The produced reference-source currents (i_{Sa}, i_{Sb}, and i_{Sc}) and measured source currents (i_{Sa}, i_{Sb}, and i_{Sc}) are to be compared by hysteresis band current controller. The switching signals are produced and given to the IGBT to compensate all the current-related problems, such as the reactive power, current harmonics, neutral current, dc-link voltage regulation, and load-current unbalances. The SRF-based UPQC control method block diagram is as shown in the Fig. 5.

V. SIMULATION RESULTS

In this study, the proposed SRF-based control technique for the UPQC is evaluated by the Matlab/Simulink software under unbalanced as well as the distorted load-current and source-voltage conditions since the unbalanced load currents are very common. But they are an important problem in 3P4W distribution systems [34]. The UPQC system parameters are used in this study and are given in Table I. In the simulation studies done, the results are specified before and after the operation of the proposed UPQC system.

In addition, the dynamic response of the system was tested on the UPQC system was operated and the load was changed. Then, the control method has been examined under the abnormal condition of non-ideal mains voltage and unbalanced load-current conditions in simulation. The passive filters designed with R and C they are used to remove the switching ripples in the voltage and current waveforms. In the proposed UPQC control method, the voltage and current harmonic

compensation capability is as shown in Table II as simulation results and total harmonic distortion (THD) levels. The THD levels that are obtained before and after the filter operation for the conventional and proposed SRF methods. The results show that the proposed control method allows THD levels of 3.0% current and 1.4% voltage by mitigation of all harmonic components.

The proposed control technique is capable of extracting most of the load-current and source-voltage distortions successfully. In the SRF-based control algorithm proposed, the mains currents (i_{Sabc}) and voltages (v_{Sabc}) are measured to calculate the shunt APF reference current, and the mains and load voltages (v_{Labc}) are used in the series APF controller as shown in the Fig. 6. The proposed UPQC control method and the simulation results for the following conditions are examined: 1) distorted and unbalanced mains voltages 2) transformer voltages injected 3) load voltages 4) nonlinear and unbalanced load currents 5) compensator currents injected 6) source currents 7) neutral current of load 8) injected compensator current 9) neutral current of source and 10) reactive power compensation.

The proposed UPQC control algorithm has the ability of compensating both the harmonics and the reactive power of the load, and the neutral current is also eliminated.
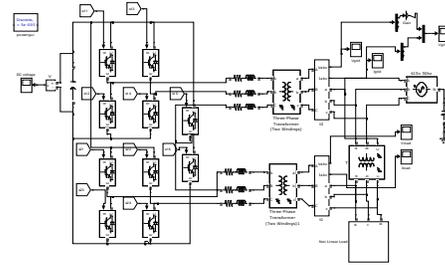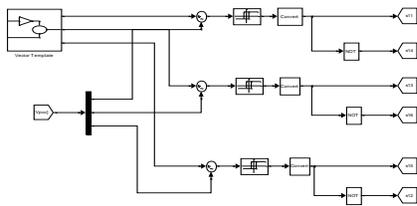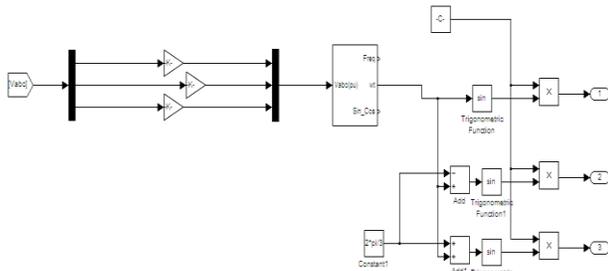
Simulation Models and Results:
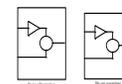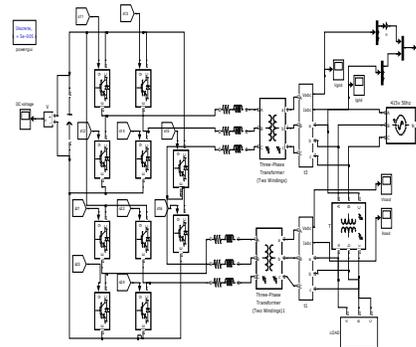
Simulation Model with Proposed ten-switch UPQC topology
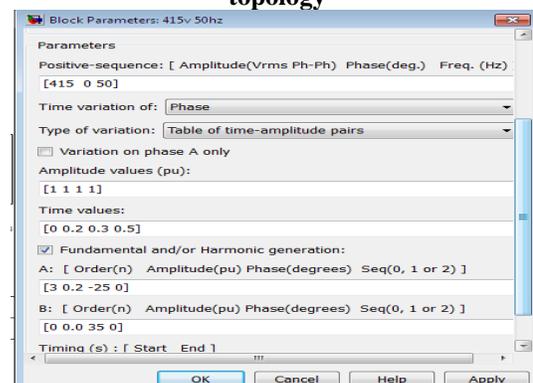
At Normal Condition:

Subsystem of series controller for generating pulses

Subsystem of PLL
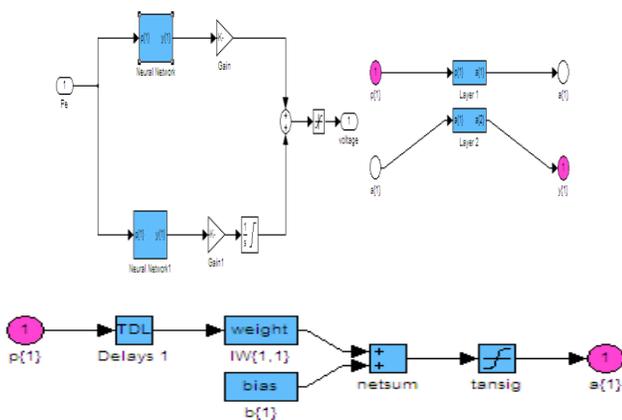
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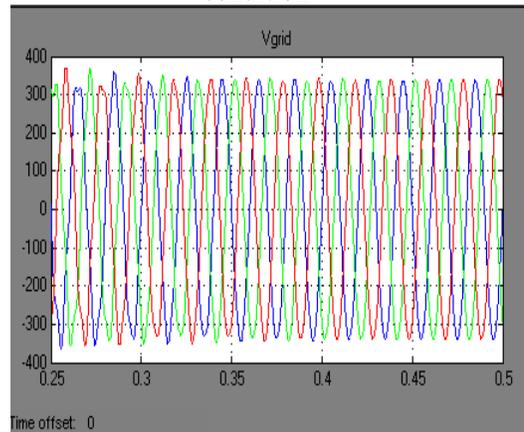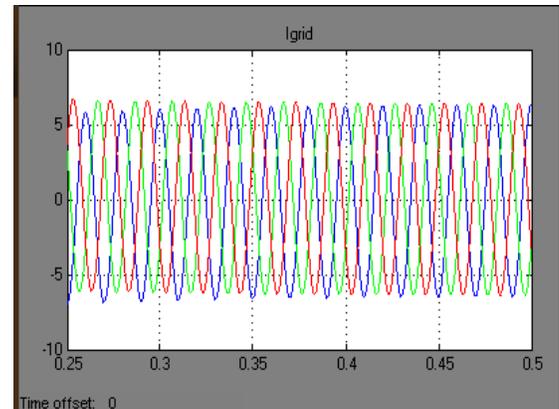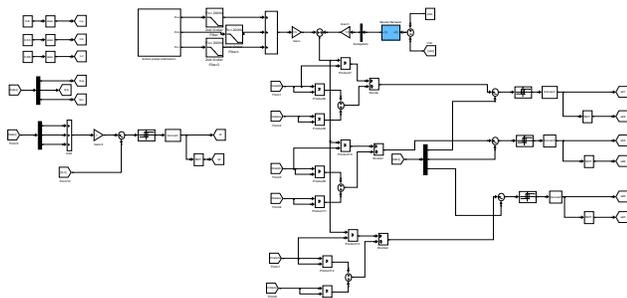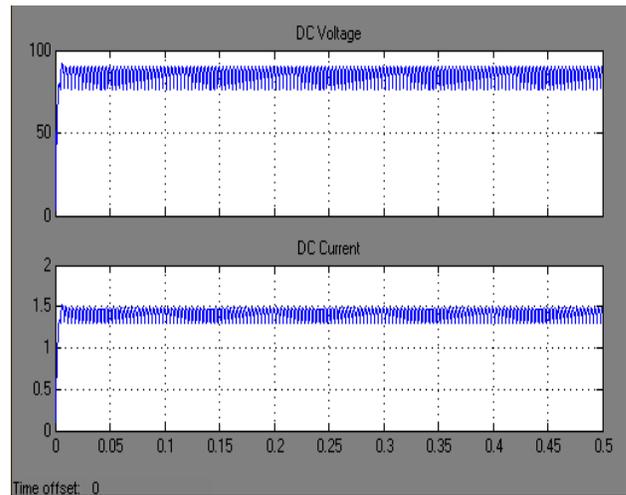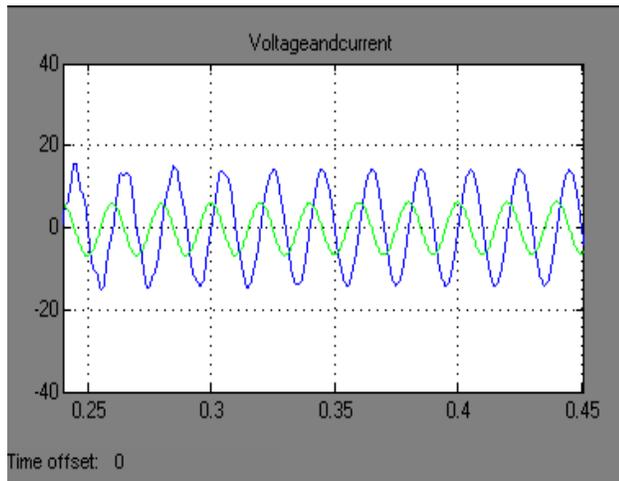
Subsystem of shunt controller for generating pulses (NN Controller)
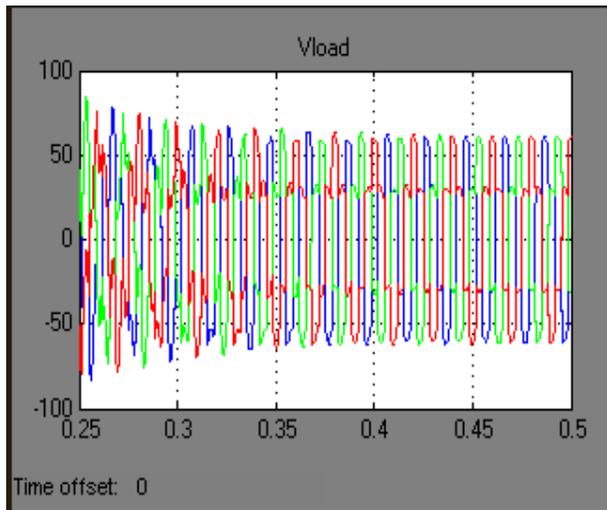
```
1 -    load n
2 -    k1=max(i');
3 -    k2=max(o1');
4 -    P=i'/k1;
5 -    T=o1'/k2;
6 -    n=157128;
7 -    net = newff(minmax(P),[5 1],{'tansig' 'purelin'});
8 -    net.trainParam.epochs = 200;
9 -    net = train(net,P,T);
10 -   Y = sim(net,P);
11 -   plot (P,T,P,Y,'o')
12 -   gensim(net,-1)
13
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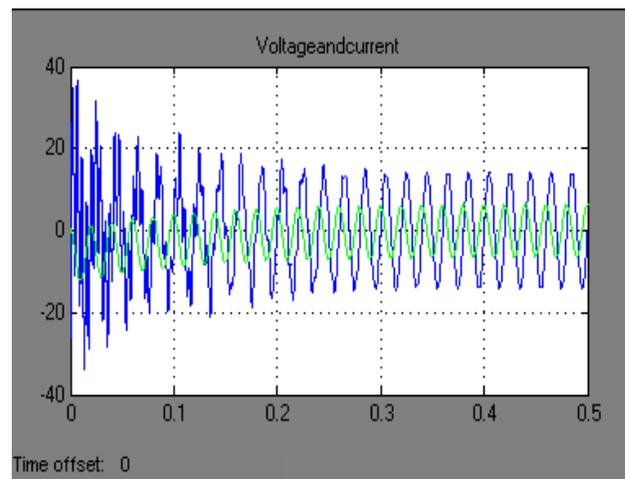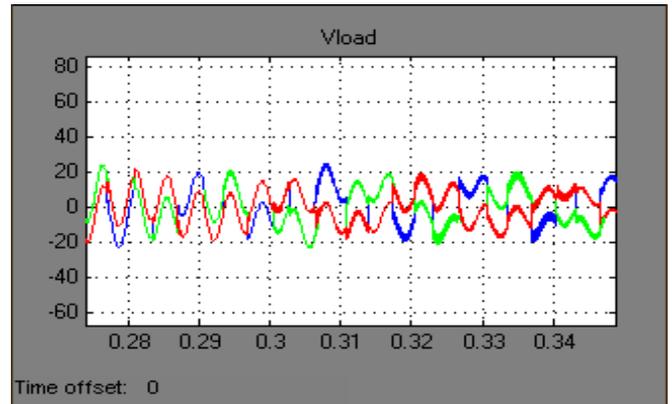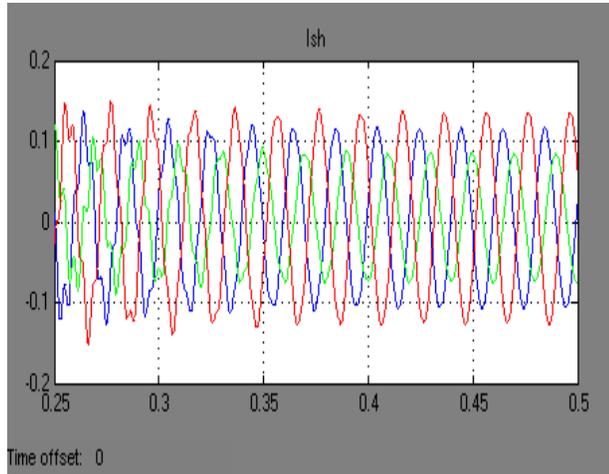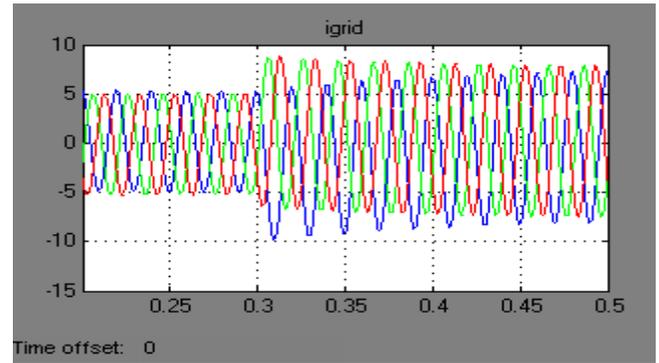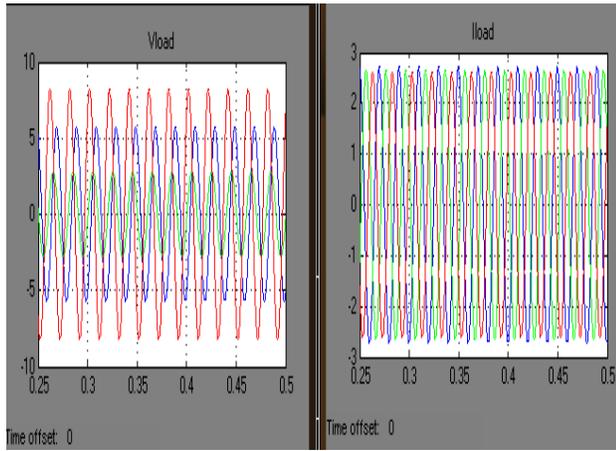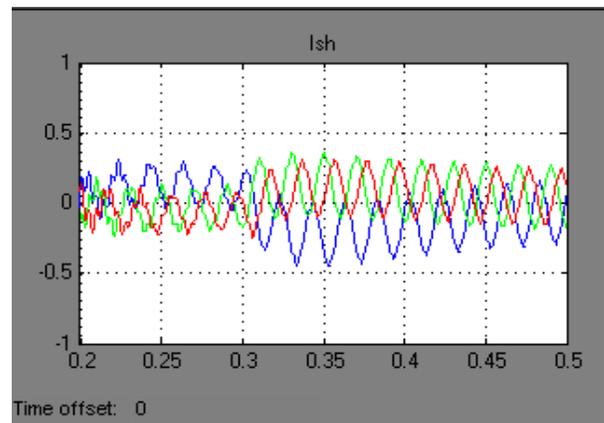
Steady state performance of the proposed ten-switch UPQC system considering a linear RL load (V = 1p.u)
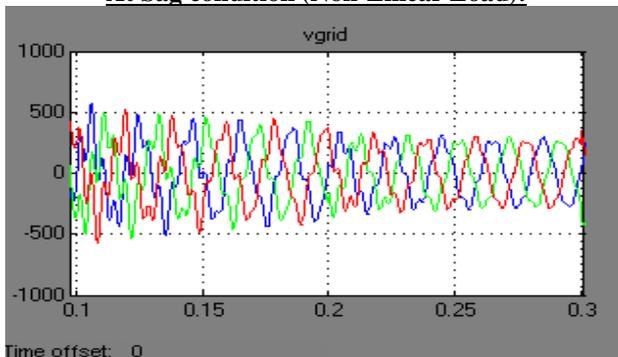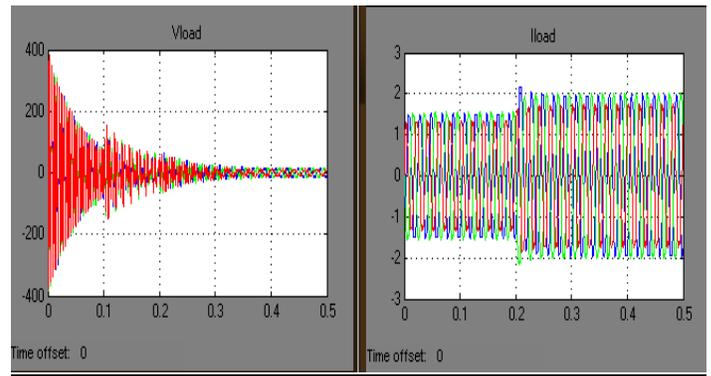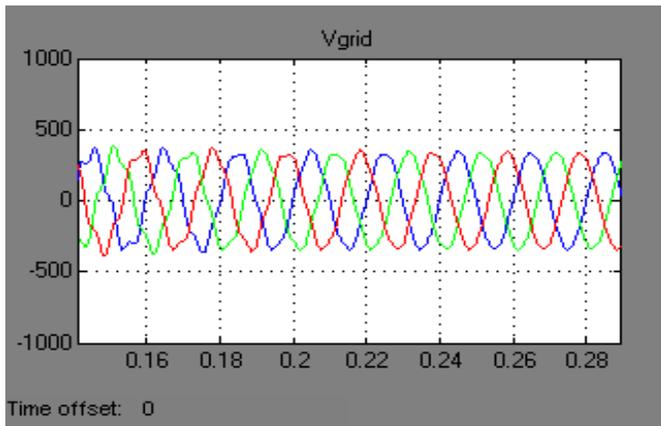
At unbalance voltage sag:
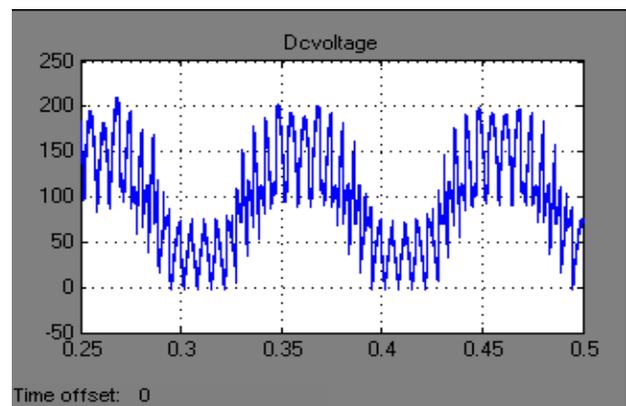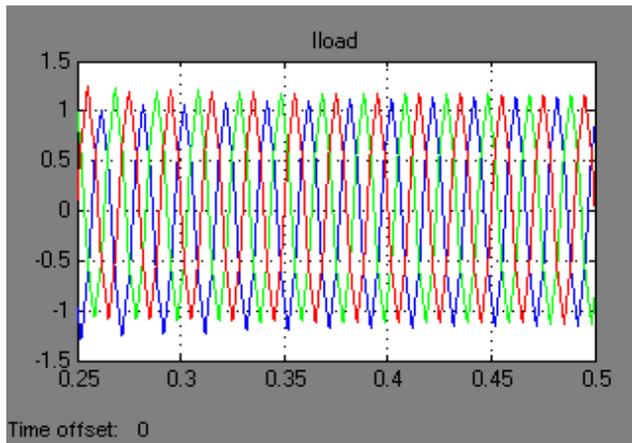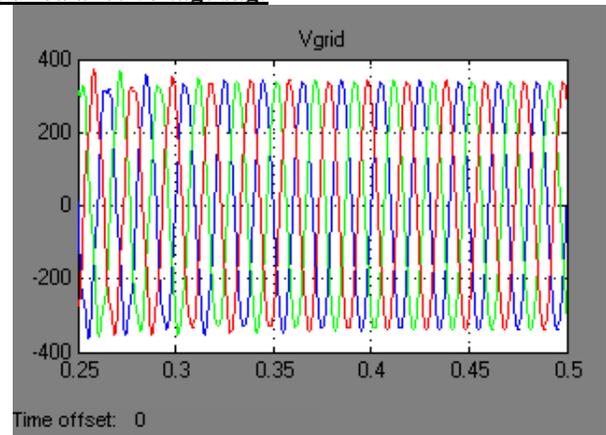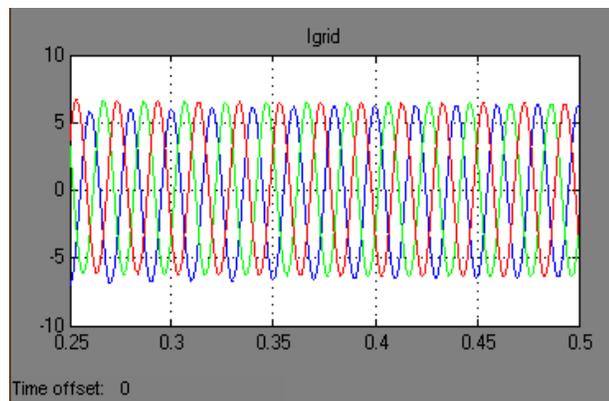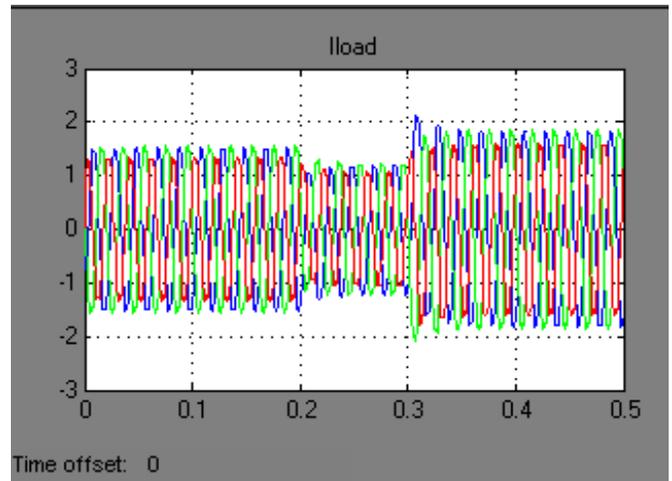
Transition from steady state to unbalanced voltage sag condition (with linear RL load).

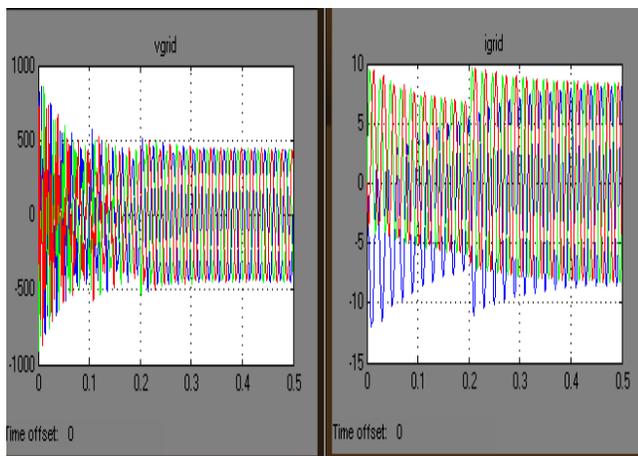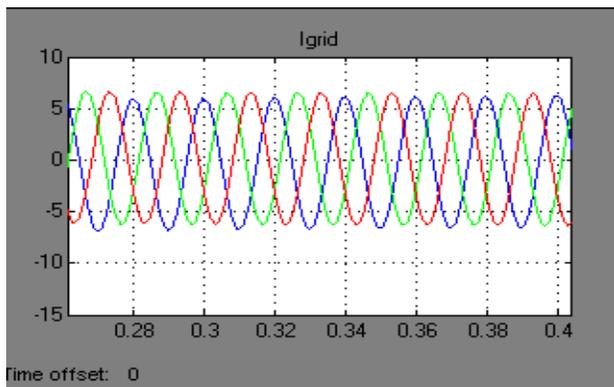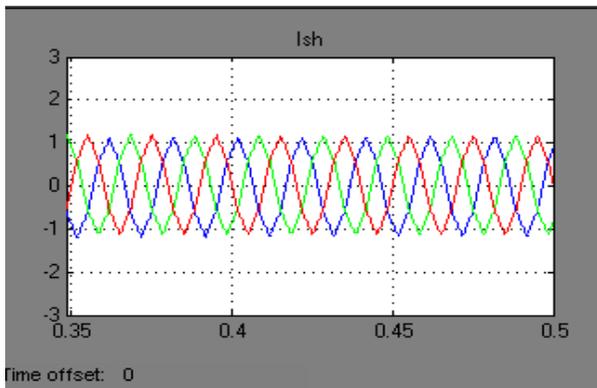**At Sag condition (Non-Linear Load):**

Transition from steady state to balanced voltage sag condition (with non-linear load).

THD Variation

	Without Controller		With PI Controller		With NN Controller	
	Grid Currents(A)	Grid Voltages (V)	Grid Currents(A)	Grid Voltages (V)	Grid Currents(A)	Grid Voltages(V)
Normal Mode	0.2587	0.307	0.2725	0.2865	0.0431	0.03902
Voltage sag condition	0.4231	0.3278	0.1594	0.2000	0.01709	0.01551

Analysis: From the simulation results, it is observed that the THD effect for Non-linear load is high and checked for different conditions like normal condition, balanced linear RL load and unbalanced Non-linear load. It is observed that for NN controller the THD values are reduced in grid voltages and currents, when compared to PI controller and No controller. The control method proposed has been evaluated and tested under various dynamical and steady-state load conditions. Simulation results under the load changing conditions are as shown in the Fig. 7. In this case, the UPQC system is operated within 0.15 s and the load-current amplitudes are increased approximately by 100% in 0.2 s. The output voltage shows almost invisible transient during 100% step load change in the proposed control method. A better dynamic performance can be clearly observed from Fig. 7 under load changing. The current and voltage with the distortions is compensated to create the sinusoidal waveforms at the PCC. Before the compensation, the THD levels of the load voltage in the phase A was 20.2% and the source current is 31.2%. After the compensation, the THD level of the load voltage is approximately 1.4% and the source current is approximately 3.0%. The harmonics and the unbalanced components are very well compensated in case of the unbalanced and distorted current and voltage at the PCC. The simulation results show that the proposed control strategy can compensate the harmonic components as well as most of the other unbalanced load current distortions. It is shown that the UPQC can compensate the voltage and current problems simultaneously and it has excellent compensating characteristics even under the unbalanced components that occur in electric power systems with 3P4W. The obtained simulation results with the proposed UPQC control technique with the modified PLL circuit show that it yields better compensation performance than the conventional PLL.

VII. FUTURE SCOPE OF WORK

The proposed paper can be extended by using a super capacitor at the DC link capacitance to improve the rate of discharge at UPQC. The energy density of the super capacitor is high hence the discharge rate is fast. The super capacitor can be used in series with a DC\DC converter to improve the voltage level before the DC link capacitance and to reduce the number of super capacitors used to serve the purpose. The extension work is shown in the form of a block diagram below.
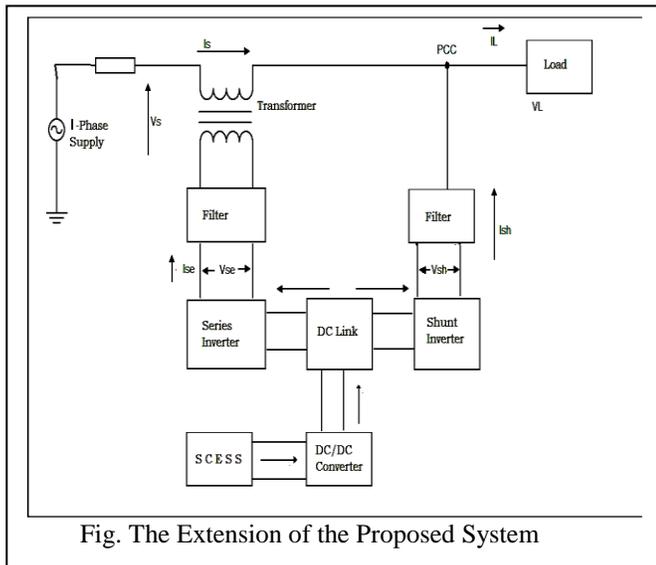

Fig. The Extension of the Proposed System

VIII. CONCLUSION

The proposed system is used for compensating the voltage sag and swells with the improved power factor. This paper proposed a new configuration of UPQC that consists of UPQC with SRF control to compensate the voltage interruption. The UPQC method proposed is used to compensate the reactive power, harmonic current, voltage sag and swell, voltage unbalance, and also the voltage interruption. The control strategy for the proposed UPQC was derived based on the Synchronous reference frame method. The operation of proposed system was verified through the simulations with the MATLAB/SIMULINK software. The UPQC method proposed has the best capability of improving the power quality at the installation point in the distribution system. The proposed system can replace the UPS, which is very much effective for the long duration of voltage interruption. Even when the long duration of voltage interruption is very rare in the present power system. This paper is used to estimate and can be further extended with the super capacitor for better results.

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