

# Analysis of UPQC under Unbalanced and Distorted Load Conditions using Synchronous-Reference-Frame Method

K. Rani Hepsiba, S. M. Shariff, P. Saileshbabu

**Abstract**—This paper presents a new synchronous reference-frame (SRF)-based control method to compensate power-quality (PQ) problems through a three-phase four-wire unified PQ conditioner (UPQC) under unbalanced and distorted load conditions. The proposed UPQC system can improve the power quality at the point of common coupling on power distribution systems under unbalanced and distorted load conditions. The simulation results based on Matlab/Simulink are discussed in detail to support the SRF-based control method presented in this paper.

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

## I. INTRODUCTION

UNIFIED POWER-QUALITY (PQ) conditioner (UPQC) systems were widely studied by many researchers as an eventual method to improve the PQ in electrical distribution systems [1]–[11]. The aim of a UPQC is to eliminate the disturbances that affect the performance of the critical load in power systems. The UPQC, therefore, is expected to be one of the most powerful solutions to large-capacity loads sensitive to supply-voltage-imbalance distortions [3]. The UPQC, which has two inverters that share one dc link, can compensate the voltage sag and swell and the harmonic current and voltage, and it can control the power flow and voltage stability. More-over, the UPQC with the combination of a series active power filter (APF) and a shunt APF can also compensate the voltage interruption if it has some energy storage or battery in the dc link [4]. The shunt APF is usually connected across the loads to compensate for all current-related problems, such as the reactive power compensation, power factor improvement, current harmonic compensation, neutral current compensation, dc-link voltage regulation, and load unbalance compensation, whereas the series APF is connected in series with a line through a series transformer (ST).

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It acts as a controlled voltage source and can compensate all voltage-related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc. [2], [3]. In this paper, the proposed synchronous-reference-frame (SRF)-based control method for the UPQC system is optimized without using transformer voltage, load, and filter current measurement, so that the numbers of the current measurements are reduced and the system performance is improved. In the proposed control method, load voltage, source voltage, and source current are measured, evaluated, and tested under un-balanced and distorted load conditions using MATLAB /SIMULINK software

## II. UPQC

The UPQC for harmonic elimination and simultaneous compensation of voltage and current, which improve the PQ, offered for other harmonic sensitive loads at the point of common coupling (PCC). In almost all of the papers on UPQC, it is shown that the UPQC can be utilized to solve PQ problems simultaneously [12]–[15]. Fig. 1 shows a basic system configuration of a general UPQC with series and shunt APFs. The main aim of the series APF is to obtain harmonic isolation between the load and supply. It has the capability of voltage imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer PCC. The shunt APF is used to absorb current harmonics, to compensate for reactive power, and to regulate the dc-link voltage between both APFs.

## III. SRF

The conventional SRF method can be used to extract the harmonics contained in the supply voltages or currents. For current harmonic compensation, the distorted currents are first transferred into two-phase stationary coordinates using  $\alpha$ - $\beta$  transformation (same as in  $p$ - $q$  theory). After that, the stationary frame quantities are transferred into synchronous rotating frames using cosine and sinus functions from the phase-locked loop (PLL). The sinus and cosine functions help to maintain the synchronization with supply voltage and current. Similar to the  $p$ - $q$  theory, using filters, the harmonics and fundamental components are separated easily and transferred back to the  $a$ - $b$ - $c$  frame as reference signals for the filter. The conventional SRF algorithm is also known as  $d$ - $q$  method, and it is based on  $a$ - $b$ - $c$  to  $d$ - $q$ -0 transformation (park transformation), which is proposed for active filter compensation [13].



Several APF and UPQC application works presented in the literature are about

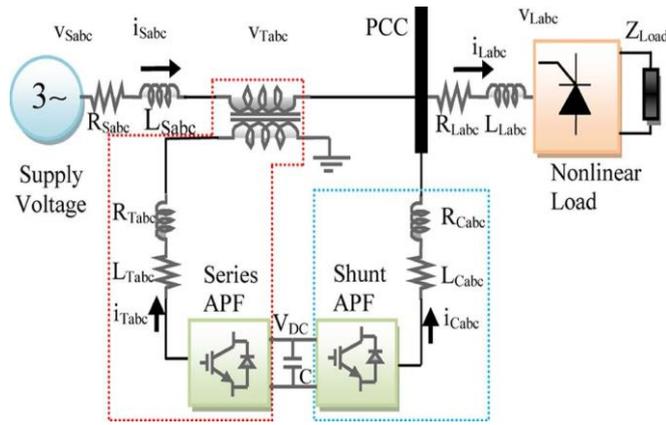


Fig. 1. Basic system configuration of UPQC.

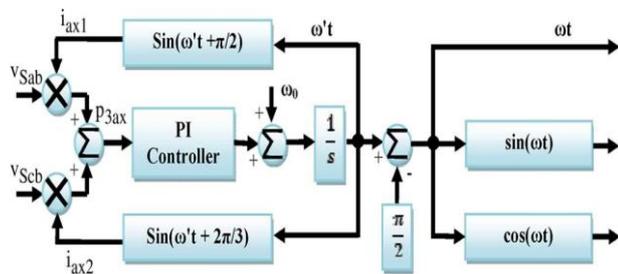


Fig. 2. Modified PLL circuit block diagram.

improving the performance of the compensator [14]–[20], in the SRF-based APF applications in three-phase four-wire (3P4W) systems, voltage and current signals are transformed into the conventional rotating frame (d–q–0). In the SRF method, the transformation angle ( $\omega t$ ) represents the angular position of the reference frame which is rotating at a constant speed in synchronism with the three-phase ac voltage. In nonlinear load conditions, harmonics and reactive currents of the load are determined by PLL algorithms. Then, currents with the same magnitude and reverse phase are produced and injected to the power system in order to compensate neutral current, harmonics, and reactive power. In the stationary reference frame,  $\alpha$ – $\beta$ –0 coordinates are stationary, while in the SRF, d–q–0 coordinates rotate synchronously with supply voltages. Thus, the angular position of the supply voltage vector shows the angular position of the SRF [13]–[20], [31]–[33].

In 3P4W systems, since the  $i_d$  component of the current in the “d” coordinate is in phase with voltage, it corresponds to the positive-sequence current. However, the  $i_q$  component of the current in the “q” coordinate is orthogonal to the  $i_d$  component of the current, and it corresponds to the negative sequence reactive current. The  $i_0$  component of the current, which is orthogonal to  $i_d$  and  $i_q$ , corresponds to the zero sequence component of the current. If the  $i_q$  component of the current is negative, the load has inductive reactive power. If it is positive, the load has capacitive reactive power. In 3P4W nonlinear power systems, the  $i_d$  and  $i_q$  components of the current include both oscillating components ( $i_d$  and  $i_q$ ) and average components ( $\bar{i}_d$  and  $\bar{i}_q$ ), as shown in

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

The oscillating components ( $i_d$  and  $i_q$ ) of the current correspond to harmonic currents, and the average components of the current correspond to the active ( $\bar{i}_d$ ) and reactive ( $\bar{i}_q$ ) currents [13], [14]. In the balanced and linear three-phase systems, the load voltage and current signals generally consist of fundamental positive-sequence components. However, in unbalanced and nonlinear load conditions, they include fundamental positive-, negative-, and zero-sequence components. In APF applications, the fundamental positive-sequence components of the signals should be separated in order to compensate the harmonics.

#### IV. PROPOSED SRF BASED CONTROL ALGORITHM

Among the several APF control methods presented in the literature, the SRF-based control method is one of the most conventional and the most practical methods [11], [12]. The SRF method presents excellent characteristics but it requires decisive PLL techniques. This paper presents a new technique based on the SRF method using the modified PLL algorithm and compares its performances with that of the conventional SRF method under unbalanced and distorted load conditions. The proposed SRF control method uses a–b–c to d–q–0 transformation equations, filters, and the modified PLL algorithm shown in Fig. 2. The sensing of only the source current to realize an SRF-based controller or another type of controller for shunt APF is not new, and this kind of controller can be found in literature [24]–[28]. The proposed SRF-based controller with modified PLL for the UPQC under 3P4W topology and particularly the SRF-based controller for the series APF part is not presented in the literature. The proposed method is simple

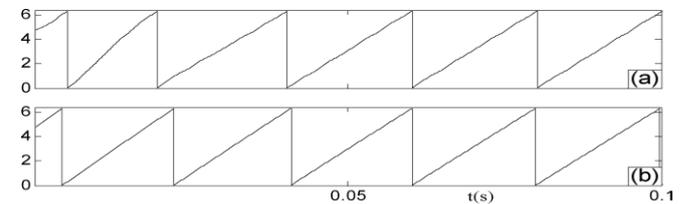


Fig. 3. Transformation angle ( $\omega t$ ) waveforms for the (a) conventional and (b) modified PLL algorithms.

and easy to implement and offers reduced current measurement; therefore, it can be run efficiently in DSP platforms. Hence, the proposed modified PLL algorithm efficiently improves the performance of the UPQC under unbalanced and distorted load conditions.

##### A. Modified PLL

Some PLL algorithms were used with SRF and other control methods in APF applications [13]–[16]. The conventional PLL circuit works properly under distorted and unbalanced system voltages. However, a conventional PLL circuit has low performance for highly distorted and unbalanced system voltages. In this paper, the modified PLL circuit shown in Fig. 2 is employed for the determination of the positive-sequence components of the system voltage signals.



The reason behind making a modification in conventional PLL is to improve the UPQC filtering performance under highly distorted and unbalanced voltage conditions.

The simulation results according to the transformation angle ( $\omega t$ ) waveform for, first, the conventional PLL and, second, the modified PLL algorithms are shown in Fig. 3. The modified PLL has better performance than that of the conventional PLL, since the output ( $\omega t$ ) of the modified PLL has a low oscillation under highly distorted and unbalanced system voltage conditions.

The modified PLL circuit calculates the three-phase auxiliary total power by applying three-phase instantaneous source line voltages, i.e.,  $V_{sbc}$  ( $V_{sab}=V_{sa}-V_{sb}$ ;  $V_{sbc}=V_{sc}-V_{sb}$ ) in order to determine the transformation angle ( $\omega t$ ) of the system supply voltage.

The modified PLL circuit is designed to operate properly under distorted and unbalanced voltage waveforms. The three-phase line voltages are measured and used as inputs, and the transformation angle ( $\omega t$ ) is calculated as output signal of the modified PLL circuit. The measured line voltages are multiplied by auxiliary ( $i_{ax1}$  and  $i_{ax2}$ ) feedback currents with unity amplitude, and one of them leads  $120^\circ$  to another to obtain three-phase auxiliary instantaneous active power ( $p_{3ax}$ ).

The reference fundamental angular frequency ( $\omega_0 = 2\pi f$ ) is added to the output of the proportional-integral

(PI) ( $P = 0.05$ ;  $I = 0.01$ ) controller to stabilize the output. The auxiliary transformation angle ( $\omega_t$ ) is obtained by the integration of this calculation, but the produced  $\omega_t$  leads  $90^\circ$  to the system fundamental frequency; therefore, the  $-\pi/2$  is added to the output of the integrator in order to reach system fundamental frequency. The PLL circuit arrives at a stable operating point when three-phase auxiliary instantaneous active power ( $p_{3ax}$ ) becomes zero or has low frequency oscillation. In addition, the transformation angle ( $\omega t$ ) which is the output of the modified PLL circuit reaches the fundamental positive-sequence components of the line voltages. Consequently,  $\sin(\omega t)$  in the modified PLL output is in the same phase angle with the fundamental positive-sequence components of the measured source voltages ( $v_{sa}$ ).

The modified PLL circuit can operate satisfactorily under highly distorted and unbalanced system voltages as long as the PI gains in the PLL algorithm are tuned accordingly. The proposed modified PLL circuit has been arranged for use directly in the proposed SRF-based UPQC control method and has been examined as simple, fast, and robust for utility applications with emphasis on operation under unbalanced and distorted load and supply voltage conditions

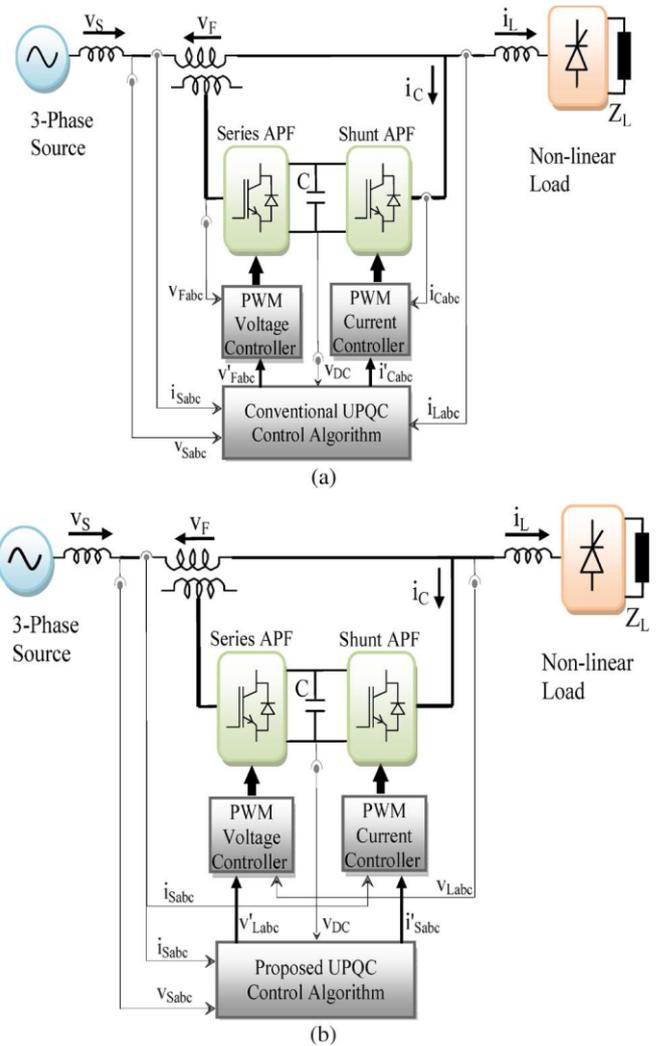


Fig. 4. (a) Conventional and (b) proposed UPQC control block diagrams.

The conventional and proposed UPQC control block diagrams are shown in Fig. 4. In the conventional control method [6] shown in Fig. 4(a), sensing three-phase source current and voltages, load current, shunt APF filter current, and series APF injected voltages in transformers along with a dc-link voltage are used to compute the reference switching signals in the UPQC. In the proposed method shown in Fig. 4(b), sensing three-phase source current and voltages and load voltages along with a dc-link voltage are adequate to compute the reference switching signals in the UPQC. Generally, for SRF-based controllers, either source currents (indirect method) or shunt active filter and load currents (direct method) are used for reference-current signal generation. The proposed SRF-based control method presents some advantages, compared with other methods. The overall control system can be easily applied since it has less current measurement requirements. The proposed method has an effective response under distorted and unbalanced load conditions. The proposed control strategy is capable of extracting most of the load-current and source-voltage distortions successfully.



$$I_{Sdref} = I_{dloss} + \bar{I}_{Sd} \quad (8)$$

In the proposed method, the zero- and negative-sequence components of the source current reference ( $i_{s0}$  and  $i_{Sq}$ ) in the 0- and q-axes are set to zero in order to compensate the harmonics, unbalance, distortion, and reactive power in the source current. The source current references are calculated as given in (9) to compensate the harmonics, neutral current, unbalance, and reactive power by regulating the dc-link voltage

$$\begin{bmatrix} I_{Saref} \\ I_{Sbref} \\ I_{Scref} \end{bmatrix} = T^{-1} \begin{bmatrix} 0 \\ I_{Sdref} \\ 0 \end{bmatrix} \quad (9)$$

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

### V. SIMULATION RESULTS

The developed model of three-phase four-wire (3P4W) UPQC system in the MATLAB/SIMULINK environment is shown in Figure 5.1. The control algorithm based on SRF theory for both series APF and shunt APF is also modeled in MATLAB. The reference load voltages ( $V_{Laref}$ ,  $V_{Lbref}$ ,  $V_{Lcref}$ ) are desired reference source currents ( $I_{Saref}$ ,  $I_{Sbref}$ ,  $I_{Scref}$ ) based on the SRF Theory are derived from the sensed source currents ( $I_{Sa}$ ,  $I_{Sb}$ ,  $I_{Sc}$ ), sensed source voltages ( $V_{Sa}$ ,  $V_{Sb}$ ,  $V_{Sc}$ ) and DC bus voltage of back to back VSI of UPQC ( $V_{dc}$ ).

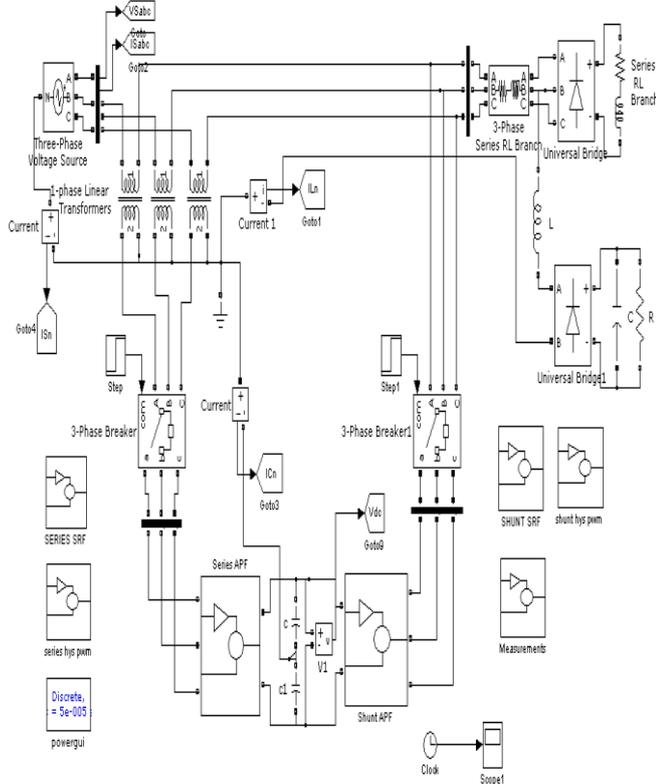


Fig 6.1 MATLAB/SIMULINK model for proposed 3P4W UPQC

Figure 6.2: shown below is series active filter in which six IGBTs are used with corresponding control gate signals

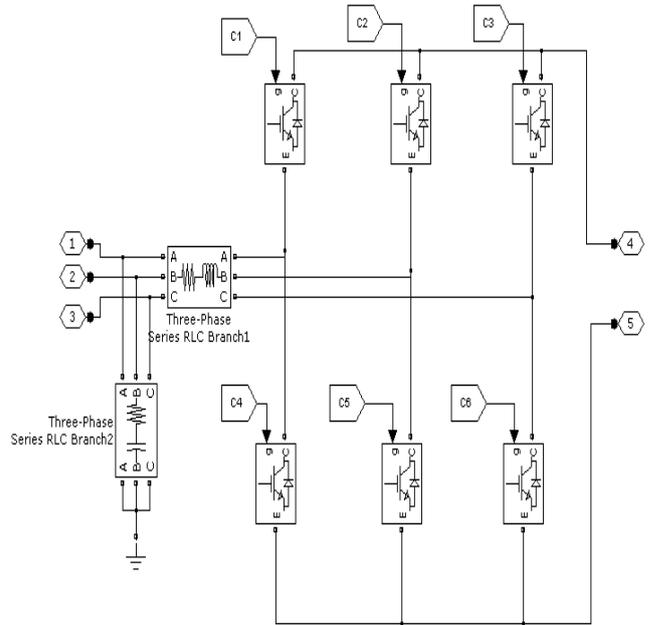


Fig 6.2 Simulation implementation of series Active Power Filter

In place of three single-phase converters, a three leg approach is proposed as shown in the Figure 6.3. The four wire converter can take either of the two forms. The first approach utilizes a standard three-phase converter where the dc-side capacitor is split and the midpoint of the capacitor connection provides the return path for the neutral wire currents. An alternative approach is to use a fourth switching pole are connected to the three phase conductors through a series inductance (also used for filtering) while the fourth switching pole connected (through an optional inductor) to the neutral conductor

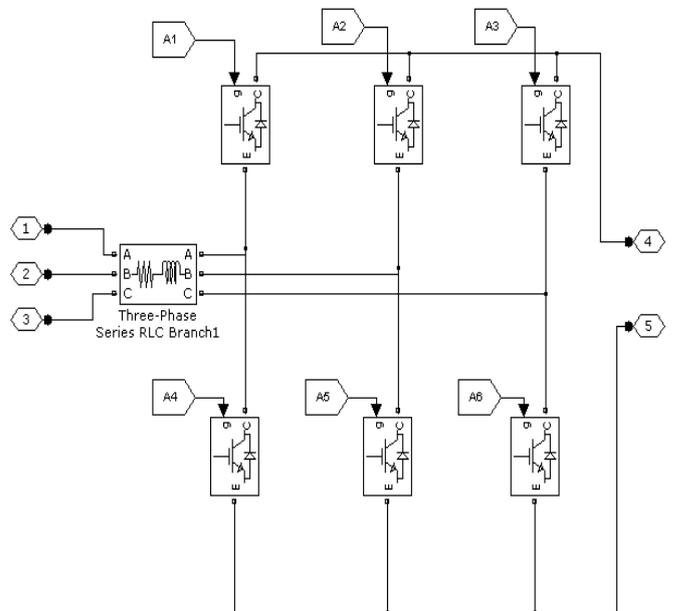


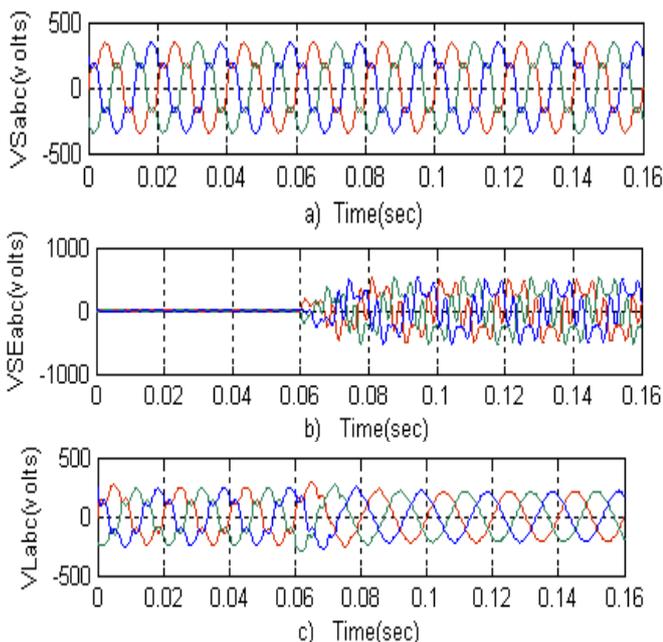
Fig 6.3. Simulation implementation of shunt Active Power Filter

TABLE I. UPQC SIMULATIONPARAMETERS

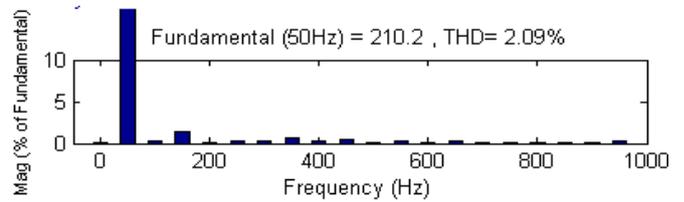
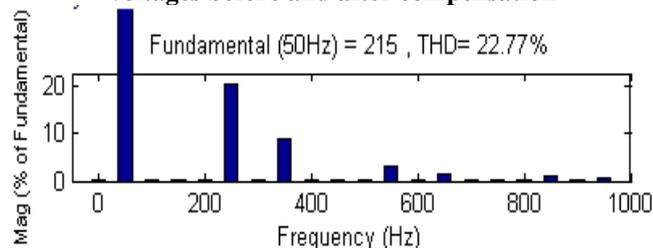
Source	Parameters	Value
	Voltage	$V_{sabc}$ 380 Vrms
	Frequency	$f$ 50Hz
Load	3-Phase ac Line Resistor	$R_{abc}$ 3 $\Omega$
	3-Phase ac Line Inductance	$L_{abc}$ 6mH
	3-Phase dc Inductance	$L_{dc3}$ 11.5mH
	3-Phase dc Resistor	$R_{dc3}$ 30 $\Omega$
	1-Phase dc Resistor, Capacitor	$R_{dc1}$ 100 $\Omega$ , $C_{dc1}$ 75 $\mu$ F
DC Link	1-Phase ac Line Inductance	$L_{La1}$ 5mH
	Voltage	$V'_{dc}$ 700V
	Series dc Capacitor	$C1, C2$ 2200 $\mu$ F
Series APF	ac Line Inductance	$L_{Tabc}$ 10mH
	Filter Resistor	$R_{Tabc}$ 1,2.5 $\Omega$
	Filter Capacitor	$C_{Tabc}$ 36 $\mu$ F
Shunt APF	ac Line Inductance	$L_{Cabc}$ 20.6mH
	Filter Resistor	$R_{Cabc}$ 7.15 $\Omega$

**Results under Non linear Balanced Load condition**

The performance of the UPQC is evaluated in terms of voltage and current harmonics mitigation under balanced and unbalanced load condition. The balanced load is designed using diode bridge rectifier with series R-L(R=30 $\Omega$ , L=11.5mH) load on the dc side and the UPQC is turned on at 0.06 sec. To evaluate the performance of UPQC, the distortion in utility voltage is introduced deliberately by injecting 5<sup>th</sup> (14.15%) and 7<sup>th</sup> (5.52%) order voltage harmonics along with the fundamental. Figure.5.10 shows the distorted mains voltages, voltages injected by the series APF and the load voltages before and after compensation.

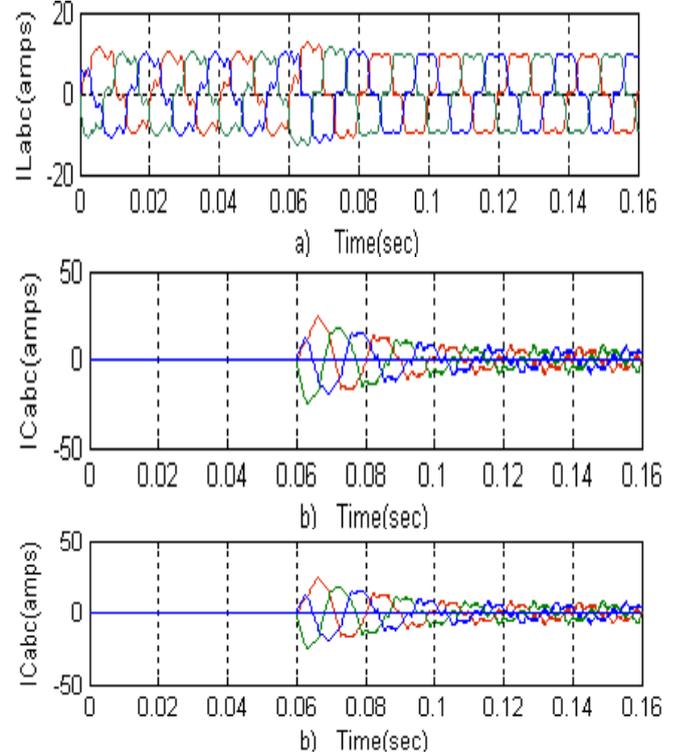


**Fig 7.1 a) Distorted source voltages under balanced load conditions b) Voltages injected by the series c) Load voltages before and after compensation**

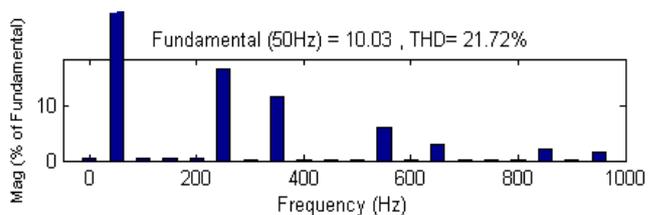


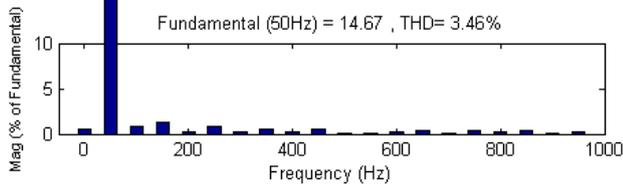
**Fig:7.2 :THD in load voltage under balanced load condition a) Before compensation b) After compensation**

The Total Harmonic Distortion (THD) in the load voltages before and after compensation by UPQC under balanced load condition is as shown in Figure 7.2 (a &b) From these figures, it can be observed that the THD before compensation in mains voltage is 22.77% and after switching on of UPQC, the THD is reduced to 2.09%. To visualize the effective controlling of shunt APF, the load currents before and after compensation, the compensated currents and the source currents are shown in fig 7.3 Initially load and source currents are same. Whenever shunt APF is switched on at t=0.06 sec which is connected across the load i.e at PCC (Point of Common Coupling), the source currents become distortion free which are shown in Figure 7.3 c). The compensated currents are injected by the shunt APF as shown in Figure 7.3: b).



**Fig7.3. a) Load currents under balanced load condition b) Injected currents with shunt APF c) Source currents before and after compensation**



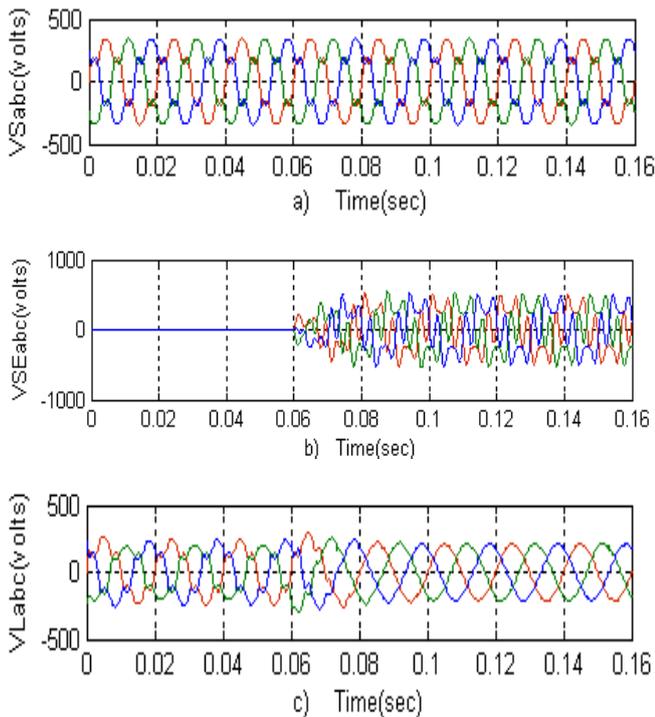


**Fig 7.4: THD in source currents under balanced load condition a) Before compensation b) After compensation**

The THD in source currents before and after compensation are shown in Fig. 7.4 (a&b) . The THD in source currents is found as 21.72% before compensation and is reduced to 3.46% after the compensation. This shows that the UPQC works efficiently and effectively minimizes the THD in load voltages and source currents under balanced

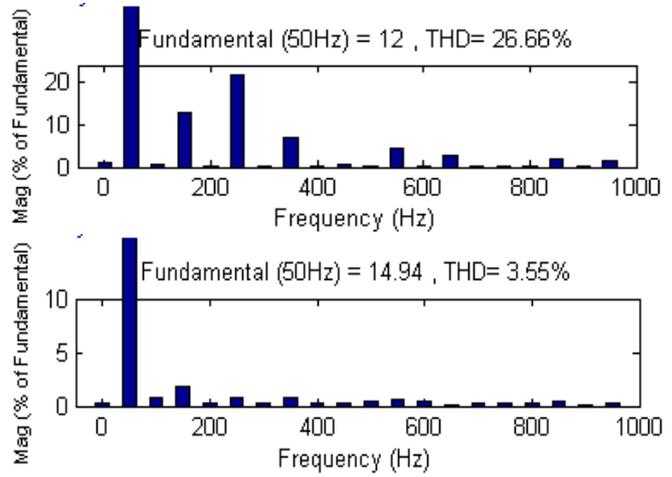
**Results under Non linear Un-balanced Load condition**

The Unbalanced load is created by using three phase diode bridge rectifier with series R-L (R=30Ω, L=11.5mH) load is connected on the dc side and one single phase diode rectifier with parallel R-C (R=100Ω, C=75μF) is connected on dc side. The distortion in source voltage is obtained by injecting 5<sup>th</sup> and 7<sup>th</sup> harmonic components of fundamental voltages. Figure.7.5 : a) represents the distorted source voltages under unbalanced load conditions. The series APF compensating the voltage harmonics immediately by injecting the phase harmonic voltage as shown in Figure.7.5: b), making the load voltage distortion-free which is shown in Figure.7.5: c).



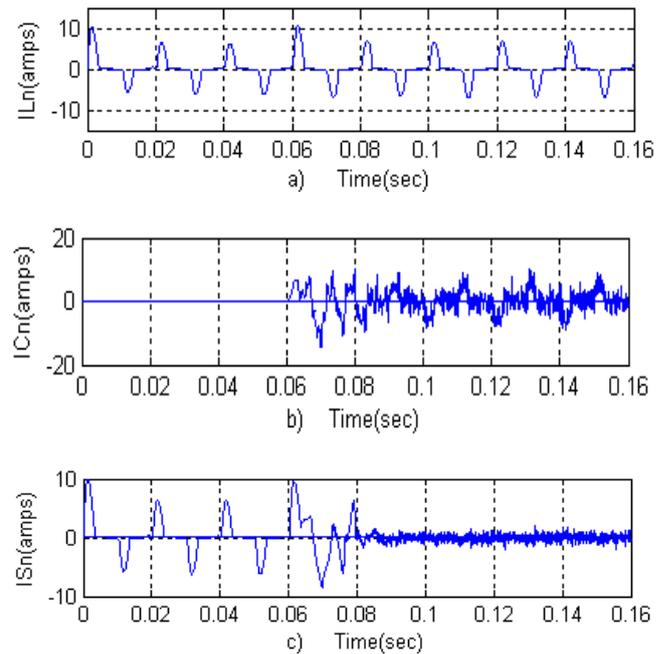
**Figure 7.5: a) Distorted source voltages under unbalanced load condition b) Voltages injected by the series APF c) Compensated load voltages**

The THD in source currents before and after compensation are shown in Figure 7.6. The THD in source currents is found as 26.66% before compensation and is reduced to 3.55% after the compensation. This shows that the UPQC works efficiently and effectively minimizes the THD in load voltages and source currents under un-balanced load condition.



**Figure 7.6: THD in source currents under unbalanced load conditions a) Before compensation b) After compensation**

Under unbalanced condition, load neutral current ( $I_{Ln}$ ) comes in to picture as shown in Figure.7.7, initially source neutral current ( $I_{Sn}$ ) is same as load neutral current ( $I_{Ln}$ ) and is compensated after 0.06 sec with the turn-on of UPQC. The source neutral current is compensated by injecting equal magnitude, opposite phase compensator current to that of load neutral current through the split phase capacitor topology. The Figure.7.7: a) shows the load neutral current, Figure.7.7: b) represents the injected compensator current and Figure.7.7: c) depicts the source neutral current.



**Figure 7.7 : a) load neutral current under unbalanced load conditions b) Injected compensator current c) Source neutral current**

The performance of the SRF-based control for the UPQC with modified PLL control is compared with the conventional PLL control and the observations are listed in the Table 1. From Table 1, it can be noticed that the modified PLL control gives better performance compared to conventional PLL control.

**Table 2: Comparing conventional and proposed PLL Control methods for UPQC**

System Voltage Condition	Before UPQC			After UPQC			
	Phases	Current (Amps)	Voltage (Volts)	Conventional PLL		Proposed PLL	
				Current (Amps)	Voltage (Volts)	Current (Amps)	Voltage (Volts)
Balanced with Distorted THD (%)	A	21.53	22.96	4.10	2.45	3.57	1.93
	B	21.72	22.77	3.61	2.67	3.46	2.09
	C	21.51	22.97	3.93	3.43	3.48	2.72
Unbalanced with Distorted THD (%)	A	22.41	22.90	3.75	3.12	3.61	1.75
	B	26.66	22.40	3.68	3.89	3.55	2.42
	C	22.06	22.87	3.72	3.07	3.49	2.32

**VI. CONCLUSION**

This paper describes a new SRF-based control strategy used in the UPQC, which mainly compensates the reactive power along with voltage and current harmonics under non ideal mains voltage and unbalanced load-current conditions. The proposed control strategy uses only loads and mains voltage measurements for the series APF, based on the SRF theory. The conventional methods require the measurements of load, source, and filter currents for the shunt APF and source and injection transformer voltage for the series APF. The simulation results show that, when under unbalanced and nonlinear load-current conditions, the aforementioned control algorithm eliminates the impact of distortion and unbalance of load current on the power line, making the power factor unity. Meanwhile, the series APF isolates the loads and source voltage in unbalanced and distorted load conditions, and the shunt APF compensates reactive power, neutral current, and harmonics and provides three-phase balanced and rated currents for the mains

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