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تحليل أداء جودة مكيف موحد الطاقة تحت تأثير نوعيات طاقة مختلفة باستخدام جهاز التحكم (d–q)

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الخلاصة

في هذه الورقة، تم تطبيق تحكم متزامن مرجعي الإطار (SRF) على جودة القدرة الموحدة المكيفة (UPQC) لتنظيم تحميل التيار الكهربائي وإمدادات التيارات ضد تشويه امدادات التيار الكهربائي، تبلد الجهد / الانتفاخ تحت تأثير أحمال غير الخطية وغير متوازنة. وباستخدام برنامج (Matlab / Simulink) تم استنتاج ثلاث مراحل نظام أربع أسلاك تحت امدادات التيار الكهربائي مشوهة وتبلد الجهد / تضخم وعدم توازن الاحمال غير الخطية. تم أيضا فحص تحليل تدفق الطاقة النشطة وتفاعلها في هذه الدراسة. ويتم حفظ موازنة جهد المكثف باستخدام وحدة تحكم (PI). ويمتد هذا العمل أيضا في ظروف خاطئة وغير طبيعية. تثبت نتائج المحاكاة أنه في ظل ظروف الحمل غير المتوازنة والغير الخطية والظروف غير الطبيعية، فإن جودة القدرة الموحدة المكيفة (UPQC) يعوض بشكل فعال الجهد ومشاكل جودة الطاقة الحالية ذات الصلة، وبالتالي زيادة جودة الطاقة.

Performance analysis of unified power quality conditioner under different power quality issues using d-q based control

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ABSTRACT

Utility has to supply quality power to all consumers. Electrical equipment like compressors and pumps take heavy inrush of current during starting, causing voltage sag/swell. On the other hand, usage of electric drives and switch mode power supplies generate harmonics in the supply system. In this paper, Synchronous Reference Frame (SRF) control applied to Unified Power Quality Conditioner (UPQC) is presented to regulate the load voltage and supply currents against supply voltage distortion, voltage sag/swell under non-linear and unbalanced loads. Using Matlab/Simulink, a three-phase four wire system under distorted voltage supply, voltage sag/swell and unbalanced non-linear load was developed. Active and reactive power flow analysis is also investigated in this study. Capacitor voltage balancing is maintained using PI controller. This work is also extended to the abnormal and fault conditions. Simulation results prove that under nonlinear unbalanced load conditions and abnormal fault conditions, UPQC effectively compensates the voltage and current related power quality problems and thereby increasing power quality.

INTRODUCTION

Utility has to supply quality power to the consumers, failing in which will cause inconvenience of equipment malfunction, underperformance, or even equipment permanent failure. Power electronic supplies, power converter based drives, electric arc furnaces, FACTS controllers, integration of renewable energy systems, and so on produce high harmonics, which affects the grid power quality. Therefore, in modern power systems, the quality of power has gained great importance. By power quality we basically refer to voltage quality, and it is used to supply a pure sinusoidal, constant RMS voltage at a fixed frequency under all loading conditions. Even though a generator may feed constant RMS voltage to the bus bars, starting large loads, which draw high currents, faults in the transmission and distribution lines (like short circuit, L-L-G or L-G faults) cause voltage sags. Due to all these conditions at various levels in power systems, the voltage supplied to the consumer sags resulting in lightning system gets dull, motors operate at low speed, equipment gets over heated, etc. All these leads to underperformance of equipment and lifespan reduction of equipment, nuisance tripping, or unwanted operation of under-voltage relays, process control, motor drive control, or many types of automated machines, which may cause a lot of inconvenience and loss to industries. On utility systems, capacitor switching, lightning on distribution or load end, sudden load shedding, and turning on/off of certain power electronic devices develop transients causing over-voltage (called voltage swell) which can result in adverse conditions like insulation breakdown, short circuits in sensitive equipment and unwanted tripping of overvoltage relay and shutdown of automated devices. The power electronic supplies, power converter based drives and nonlinear loads are causing distortion of voltage and current wave shapes which further lead to overheating in equipment and increased losses.

All these issues posed constant challenges and many questions before electrical engineers. Unified power quality conditioner (UPQC) was proposed (Sabin & Sundaram, 1996; Akagi, 1996), to improve the power system condition and has gone through many modifications to improve the performance. Basically, UPQC has been employed successfully to mitigate or suppress various power quality (PQ) issues like voltage sag/swell, voltage flicker, voltage harmonics, voltage fluctuations, poor power factor, unbalanced voltages and currents, harmonics in load current, reactive current and neutral current (Graovac *et al*., 2007; Kota & Vinnakoti, 2015; Vijji *et al*., 2014; Kesler & Ozdemir, 2011; Khadkikar & Chandra, 2011; Kisck & Kisck, 2007; Zaveri *et al*., 2012). Research on UPQC has increased tremendously over the last decade in areas like the type of the UPQC converter (CSC or VSC), supply system (single-phase and three-phase), and configuration of UPQC topologies (Zaveri & Chudasama, 2012; Ketabi *et al*., 2012; Khadkikar, 2012). Not all the above issues are solved in one configuration of topology, but based on the priority of each issue, thay can be dealt with convincingly.

Synchronous reference frame (SRF) control based on modified-PLL (MPLL) scheme, applied to the right shunt UPQC, is presented in this paper. Mitigation of PQ issues like voltage sag/swell, unbalanced and nonlinear load currents, harmonics in supply voltage, and the ability of the system under faults is investigated with the proposed scheme in Matlab/Simulink software. Total harmonic distortion (%THD) of load voltage and supply current is evaluated for various combinations of supply and load. This study is also expanded to active and reactive power flow analysis. This paper is structured in the following order: power flow analysis of UPQC-SRF based control for shunt and series converter; simulation results and observations.

POWER FLOW ANALYSIS OF UPQC

Unified power quality conditioner (UPQC) is a power conditioner holding the ability to involve many power quality issues relating to voltage and currents, active and reactive power flows, and unbalances in the system. Thus, an UPQC multifunction is used to mitigate the multifunctional conditions in the distribution network, which affect performance of the network.

A UPQC has a couple of voltage source converters (VSC's) with a DC link capacitor as shown in Figure 1. One converter acts as a controlled variable voltage source in series to the line to compensate voltage associated problems like unbalances, sequence components, harmonics, sag, swell, and flicker. The other converter acts as a controlled current source in shunt to the load, which helps compensate current related problems and also reactive power issues along with the DC link voltage regulation when needed. Hence, together they can handle the current together, voltage, and reactive power problems (Karanki *et al*., 2103; Mohammadi *et al*., 2009). The single-phase equivalent circuit of UPQC is shown in Figure 2.

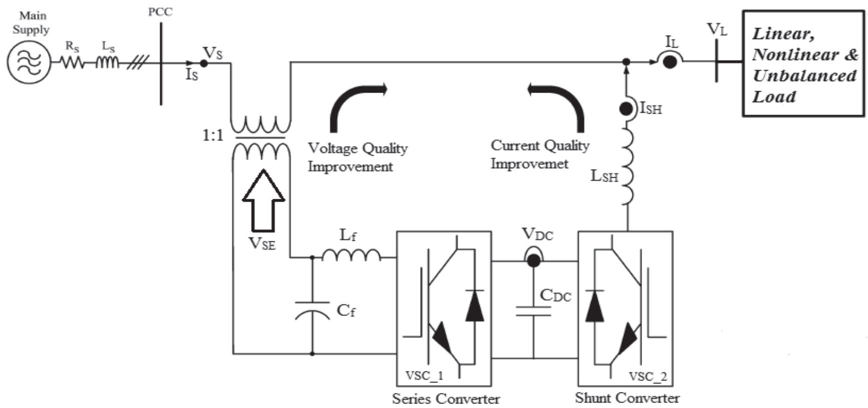


Figure 1. Basic configuration of UPQC.

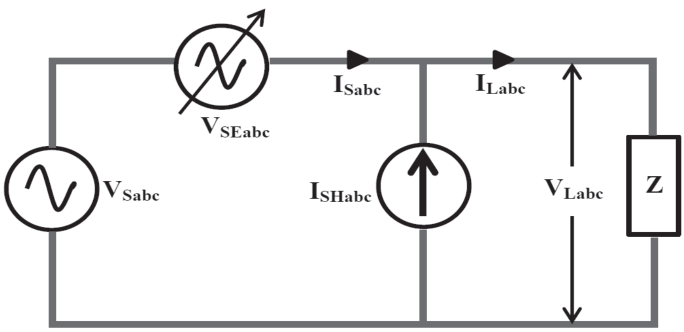


Figure 2. Equivalent circuit of UPQC.

The voltage injected by series converter (V_{SEabc}) is defined as

$$V_{SEabc} = V_{Labc} - V_{Sabc} = -kV_{Labc}\angle 0^0 \quad (1)$$

where V_{Labc}, V_{Sabc}, I_{Sabc}, I_{Labc}, and k are load voltage, supply voltage, supply current, load current, and oscillations in supply voltage, respectively

Mathematically, the active and reactive power flows in the line are analyzed by assuming ideal UPQC. Considering that the active powers at supply (P_{Sabc}) and load terminals (P_{Labc}) are equal, the apparent power at the point of common coupling is given as

$$\left.\begin{aligned} V_{Sabc}I_{Sabc} &= V_{Labc}I_{Labc}\cos(\varphi_n) \\ V_{Labc}(1+k)I_{Sabc} &= V_{Labc}I_{Labc}\cos(\varphi_n) \\ I_{Sabc} &= \frac{I_{Labc}}{1+k}\cos(\varphi_n) \end{aligned}\right\} \quad (2)$$

The apparent power absorbed at series converter (S_{SEabc}) can be expressed as

$$\left.\begin{aligned} S_{SEabc} &= V_{SEabc}I_{Sabc} \\ P_{SEabc} &= V_{SEabc}I_{Sabc}\cos(\varphi_n) = -kV_{Labc}I_{Sabc}\cos(\varphi_n) \\ Q_{SEabc} &= V_{SEabc}I_{Sabc}\sin(\varphi_n) \end{aligned}\right\} \quad (3)$$

After compensation, if the unity power factor ($\cos(\varphi_n)=1$) is considered at supply then

$$\left.\begin{aligned} P_{SEabc} &= V_{SEabc} I_{Sabc} == -kV_{Labc} I_{Sabc} \\ Q_{SEabc} &\cong 0 \end{aligned}\right\} \tag{4}$$

The apparent power at shunt converter (S_{SHabc}) can be expressed as.

$$S_{SHabc} = V_{SHabc} I_{SHabc} \tag{5}$$

where P_{SEabc}, Q_{SEabc}, P_{SHabc}, and Q_{SHabc} are active and reactive powers at series and shunt converters.

Based on this analysis, the operation of UPQC (Fatiha *et al.*, 2011) is explained as follows, When UPQC is not connected, the source supplies require reactive power to the load as shown in Figure 3(a). When UPQC is switched ON, the shunt converter supplies the reactive power required to the load as shown in Figure 3(b), thus relieving the source of burden.

Under voltage sag ($k < 0$, $V_{Sabc} < V_{Labc}$), with voltage at source being reduced, the series converter supplies the active power needed by load. This maintains voltage quality at load. The power to the load supplied by series converter is actually drawn from supply mains via shunt converter as shown in Figure 4. Under voltage swell ($k > 0$, $V_{Sabc} > V_{Labc}$), with more voltage at source, excess real power at source is absorbed by the series converter. This leads the DC link capacitor voltage to rise. To balance the system, the source current drawn is reduced by the shunt converter as shown in Figure 5.

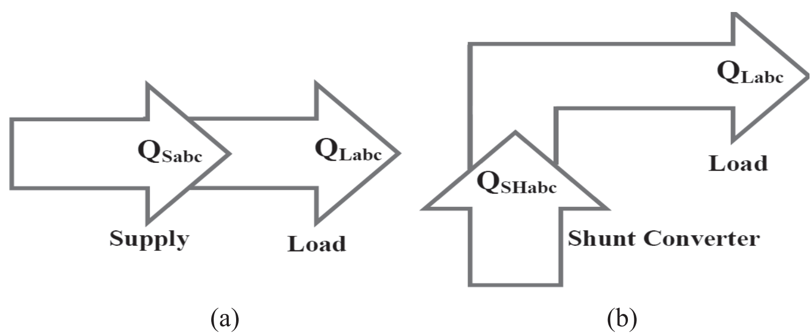


Figure 3. Reactive power flow (a) without UPQC (b) with shunt converter

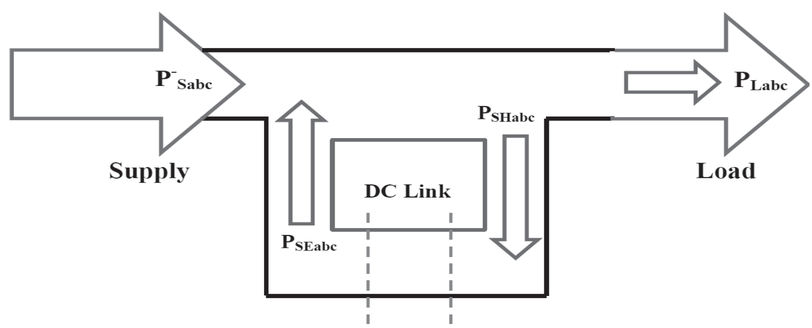


Figure 4. Active power flow during voltage sag conditions

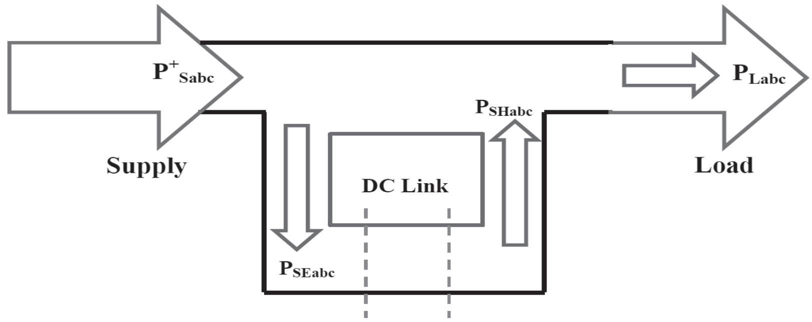


Figure 5. Active power flow during voltage swell conditions

SRF-BASED CONTROL OF UPQC

Supply voltage or load currents with harmonics can be eliminated by SRF method and are often referred to as d-q theory. Here, three-phase to two-phase quantities and their inverse transformation can be done using MPLL, which provides the necessary synchronization with supply.

Series compensation with SRF control

In series compensation, three-phase voltage quantities measured at grid level are transformed into two-phase (dq0) quantities by using MPLL as given in Equation (6). These two-phase quantities are oscillatory in nature as in Equation (7) and (8) due to the presence of the 5th and 7th order harmonics in supply. The harmonics are, thereby, purified by using second-order Butter-worth low pass filter (LPF), resulting only in an averaged component. The cut-off frequency of the filter is chosen as 2 Hz to extract pure DC component from the derived V_{Sd} and V_{Sq}. The frequency of the LPF shall be very low; otherwise, it may permit the oscillation components of the V_{Sd} and V_{Sq} in addition to the DC component which results in harmonic reference voltage for the series converter, and hence, compensation will not be effective.

$$\begin{bmatrix} V_{S0} \\ V_{Sd} \\ V_{Sq} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \sin(wt) & \sin\left(wt - 2\pi/3\right) & \sin\left(wt + 2\pi/3\right) \\ \cos(wt) & \cos\left(wt - 2\pi/3\right) & \cos\left(wt + 2\pi/3\right) \end{bmatrix} \begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix} \tag{6}$$

$$V_{Sd} = \tilde{V}_{Sd} + \overline{V}_{Sd} \tag{7}$$

$$V_{Sq} = \tilde{V}_{Sq} + \overline{V}_{Sq} \tag{8}$$

where $\tilde{V}_{Sd}$ & $\tilde{V}_{Sq}$ represent oscillatory components and $\overline{V}_{Sd}$ & $\overline{V}_{Sq}$ represent averaged components.

Considering the only active component in the two-phase transformation as in Equation (9), reference voltages (V_{La_ref}, V_{Lb_ref}, and V_{Lc_ref}) are generated using Equation (10). From Equations (6) and (10), simulink model of the SRF control scheme for series compensation is designed and is depicted in Figure 6. These generated reference voltages are compared with actual load voltages (V_{La}, V_{Lb}, and V_{Lc}), and their respective error signals are used as reference signals in the SPWM technique.

$$V_{Sd} = \overline{V}_{Sd}; V_{Sq} = 0; V_{S0} = 0 \tag{9}$$

$$\begin{bmatrix} V_{La\_ref} \\ V_{Lb\_ref} \\ V_{Lc\_ref} \end{bmatrix} = \sqrt{2/3} \begin{vmatrix} 1/\sqrt{2} & \sin(wt) & \cos(wt) \\ 1/\sqrt{2} & \sin\left(wt - 2\pi/3\right) & \cos\left(wt - 2\pi/3\right) \\ 1/\sqrt{2} & \sin\left(wt + 2\pi/3\right) & \cos\left(wt + 2\pi/3\right) \end{vmatrix} \begin{bmatrix} V_{S0} \\ V_{Sd} \\ V_{Sq} \end{bmatrix} \tag{10}$$

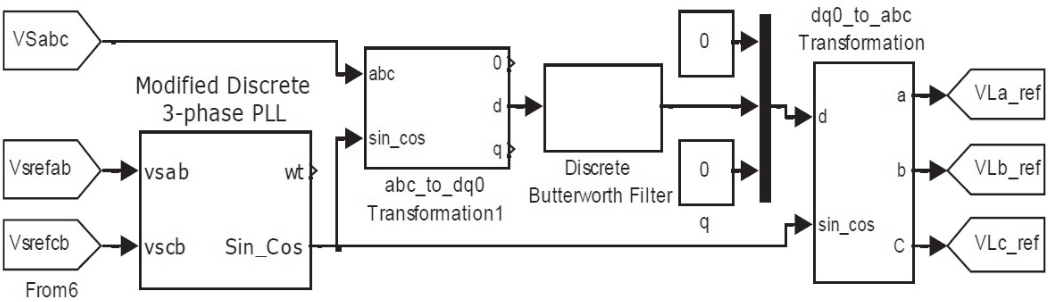


Figure 6. Series controller using SRF.

Shunt compensation with SRF control

In shunt compensation, three-phase current quantities measured at load are transformed into two-phase (dq0) quantities by using MPLL as given in Equation (11). These two-phase quantities are oscillatory in nature due to the presence of 5th and 7th ordered harmonics in supply and nonlinear load. These harmonics are thereby purified by using second-order Butter-worth LPF, resulting only in source current averaged components ($\overline{I}_{Sd}$ and $\overline{I}_{Sq}$). The cut-off frequency of 2 Hz is chosen to extract pure DC components from the derived I_{Sd} and I_{Sq}.

$$\begin{bmatrix} I_{S0} \\ I_{Sd} \\ I_{Sq} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \sin(wt) & \sin\left(wt - 2\pi/3\right) & \sin\left(wt + 2\pi/3\right) \\ \cos(wt) & \cos\left(wt - 2\pi/3\right) & \cos\left(wt + 2\pi/3\right) \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \tag{11}$$

One main tasks of shunt converter is to preserve the desired DC link voltage constant. During voltage sag/swell, series converter absorbs/supplies real power from/to the system. This leads to power imbalance in the network. In order to maintain power balance, DC link voltage is regulated through shunt converter with appropriate controller. The loss component of current (I_{dloss}) due to power imbalance in the system is determined using PI controller. Neglecting $\overline{I}_{Sq}$ and 0 components, source current fundamental reference component is given in Equation (12). Applying inverse transformation to Equation (12), reference currents (I_{Saref}, I_{Sbref}, and I_{Scref}) are generated using Equation (13). From Equation (11) and (13), the Simulink model of the SRF control scheme for shunt compensation is designed and is depicted in Figure 7. Hysteresis current controller is used to drive the shunt converter.

$$I_{Sd}^{*} = I_{dloss} + \bar{I}_{Sd} \tag{12}$$

$$\begin{bmatrix} I_{Saref} \\ I_{Sbref} \\ I_{Scref} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & \sin(wt) & \cos(wt) \\ 1/\sqrt{2} & \sin(wt - 2\pi/3) & \cos(wt - 2\pi/3) \\ 1/\sqrt{2} & \sin(wt + 2\pi/3) & \cos(wt + 2\pi/3) \end{bmatrix} \begin{bmatrix} I_{S0} \\ I_{Sd}^{*} \\ I_{Sq} \end{bmatrix} \tag{13}$$

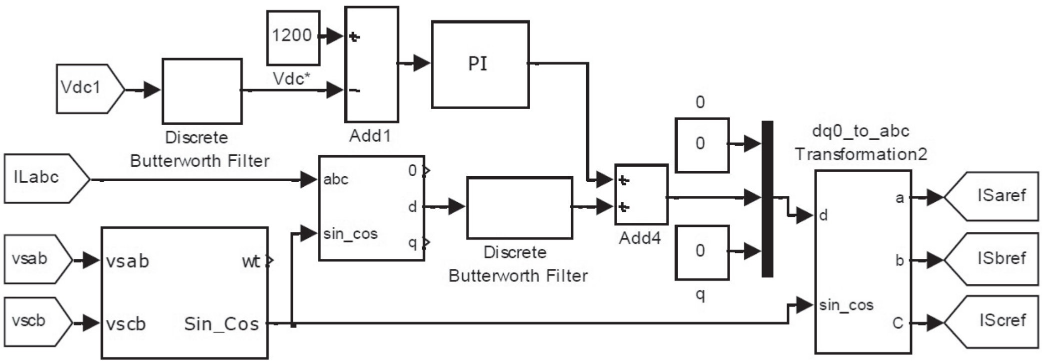


Figure 7. Shunt controller using SRF

SIMULATION RESULTS AND ANALYSIS

The right shunt UPQC (UPQC-R) configuration for a three-phase four-wire system is developed under Matlab/Simulink environment as shown in Figure 8, and its system parameters like supply voltage with frequency, load, DC link capacitor, coupling inductors for series and shunt converters, and rating of series transformer are specified in Table 1.

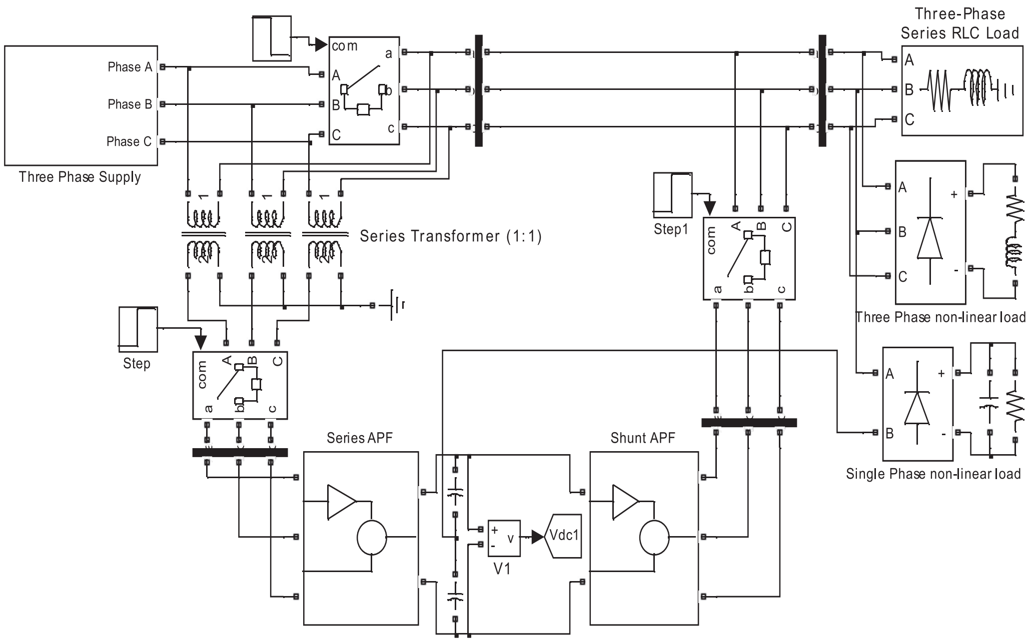


Figure 8. UPQC Matlab/Simulink model of three-phase four-wire system.

Table 1. UPQC system parameters.

	Prameters	Value
Source	Voltage (phase-phase)	415 Vrms
	Frequency	50 Hz
Load	3-Ø linear load	P = 6 kW and Q_L = 0.1 kVAR
	3-Ø nonlinear load	P = 0.2 kW and Q_L = 1.5 kVAR
	1-Ø rectifier with RC load	P = 6 kW and Q_L = 100 VAR
DC-Link	Two series capacitors	C1=C2= 6600µF
Coupling Inductor	Series converter	L_{Tabc} =6mH
	Shunt converter	L_{Cabc} =3 mH
	Three series transformer	5kVA

The proposed system is analyzed in six cases based on different load conditions against supply voltage distortion with 5th order harmonic of 20%, and 7th order harmonic of 10%. Case I: three-phase linear load; Case II: three-phase nonlinear load; Case III: three-phase linear load and three-phase nonlinear load; Case IV: three-phase linear and single-phase nonlinear load; Case V: three-phase nonlinear load and single- phase nonlinear load; Case VI: three-phase linear load, three-phase nonlinear load, and single-phase nonlinear load. The system acts as being uncompensated up to 0.5 sec, and the UPQC is connected at 0.5 sec. The system is assumed to experience 30% of voltage sag/swell from 1 sec to 1.1 sec and 2 sec to 2.1 sec, respectively.

For a given load as mentioned earlier for Case VI, the supply voltage with the fifth and seventh-order harmonics is depicted in Figure 9(a). The series converter compensates these harmonic voltages by injecting the voltage into the phase opposing the harmonic voltage, thereby nullifying the harmonics at load end, which has been observed to be sinusoidal as shown in Figure 9(b). Nonlinear and unbalanced load makes the load currents nonlinear in nature as depicted in Figure 9(c). The shunt converter compensates these nonlinear currents by injecting currents in-to the line, thereby restricting the harmonic currents to load end and making supply currents sinusoidal as depicted in Figure 9(d).

Harmonic spectrum of Figures 9(b) and 9(c) is depicted in Figures 10 and 11, respectively. It is to be observed from Figure 10(a) that the load voltage fundamental component before compensation is 338.3V and its %THD is 22.36%. After compensation, it is 346.7V with %THD of 3.76% as depicted in Figure 10(b). From Figure 11(a), it is observed that the source current fundamental component before compensation is 48.75A with %THD of 44.64%. After compensation, it is increased to 63.04A and its % THD is reduced to 7.08% as shown in Figure 11(b). The fundamental component and %THD of the supply voltage, load voltage, source current, and load current for case VI are tabulated in Table 2. It clearly shows how %THD of source currents and load voltage has greatly reduced from 44.64% to 7.08% and 22.36% to 3.76%. Since load voltages are compensated %THD of load currents is also reduced from 44.64% to 21.67%.

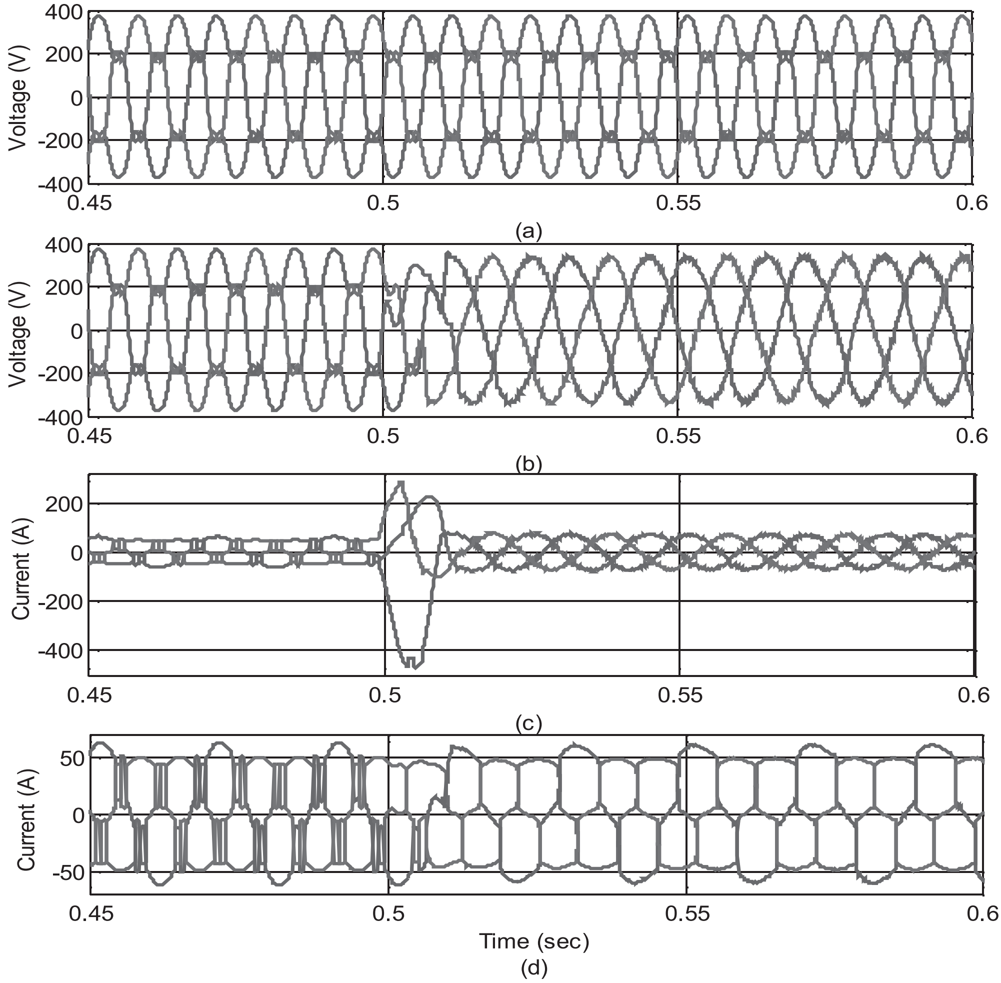
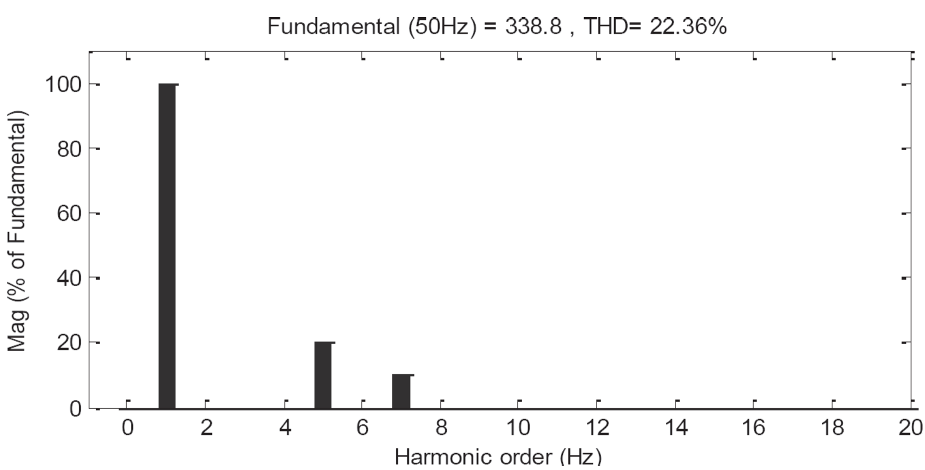
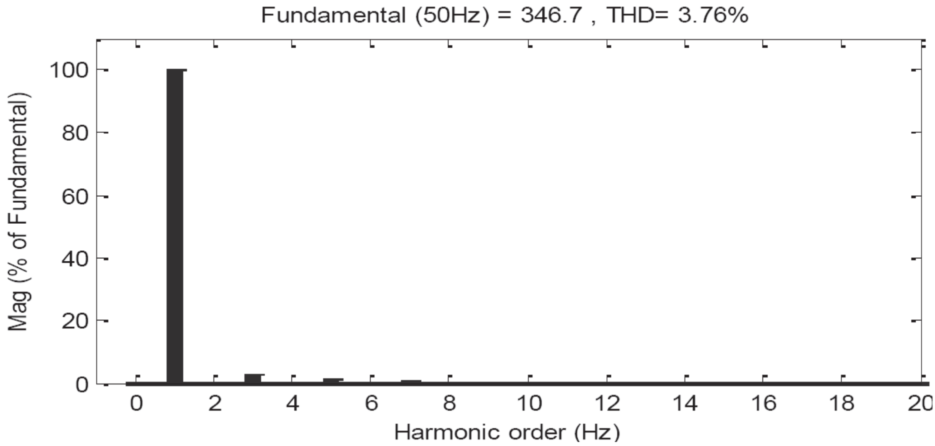


Figure 9. Compensation of (a) supply voltage, (b) load voltage, (c) supply currents, and (d) load current.

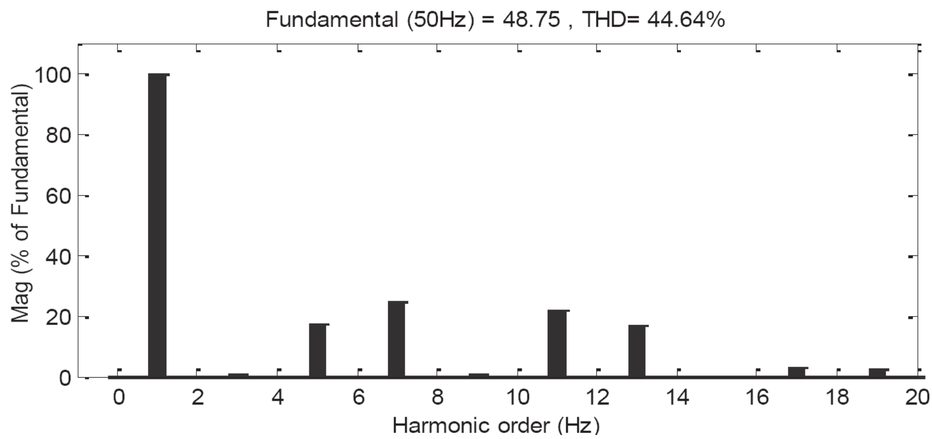


(a)

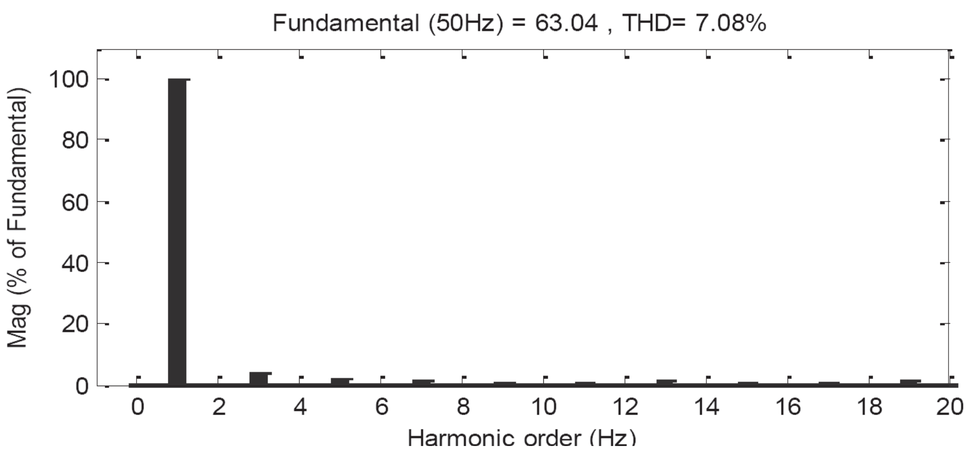


(b)

Figure 10. % THD of load voltage (a) before compensation under (b) normal working conditions.



(a)



(b)

Figure 11. % THD of source current (a) before compensation and (b) after compensation.

Table 2. Fundamental component and %THD

		Fundamental component		%THD	
		Before	After	Before	After
Case VI	V_S	338.8V	338.8V	22.36%	22.36%
	V_L	338.8V	346.7V	22.36%	3.76%
	I_S	48.75A	63.04A	44.64%	7.08%
	I_L	48.75A	54.1A	44.64%	21.67%

The simulation results show good performance under voltage sag and voltage swell. To analyze the performance, 30% of voltage sag/swell is considered in all phases. The supply voltages, compensated load voltages, and supply currents under voltage sag are shown in Figure 12. During this period, the supply voltage reduced from 338.8V to 237.2V, thereby reducing the active power flow from the supply. At this instant, the shunt converter becomes active and draws power from the supply, thereby increasing the supply current. The shunt converter draws 18 kW of active power to supply the series converter through the DC-link capacitor. This causes the supply current to rise from 48.75A to 63.04A. Out of this active power, some active

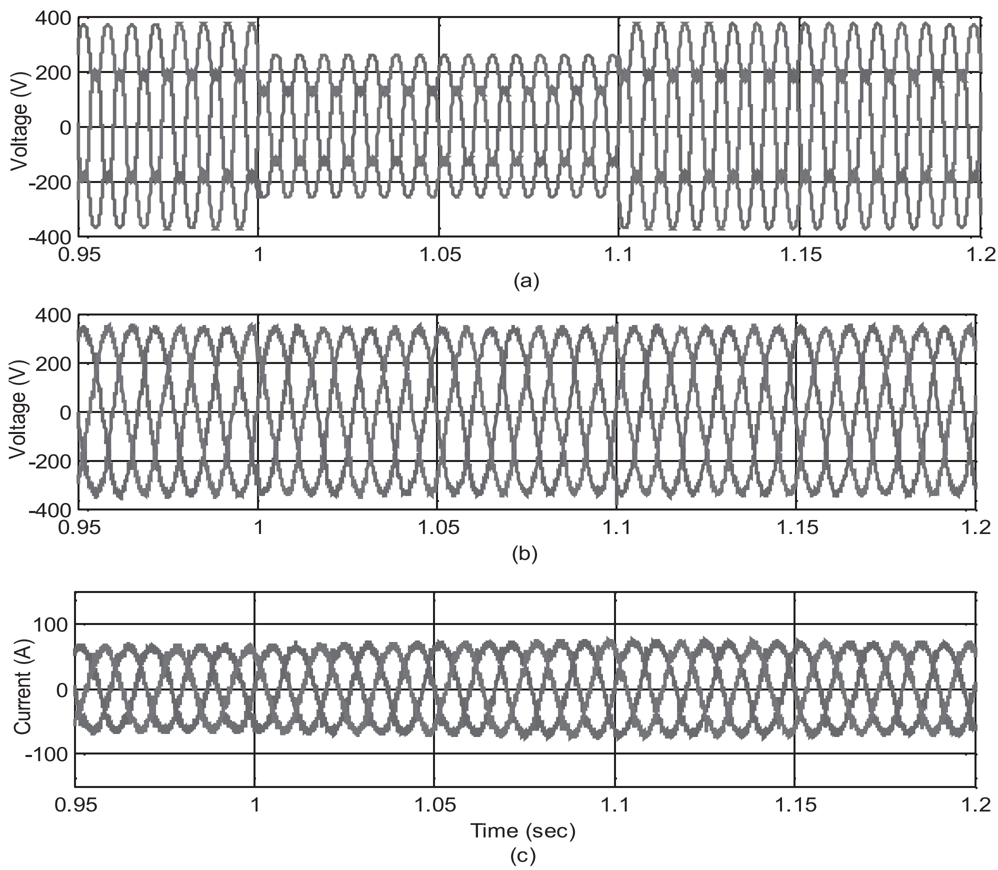


Figure 12. Compensation during voltage sag (a) supply voltage (b) load voltage and (c) supply currents.

power around (0.5 kW) is used to maintain the capacitor voltage and to overcome the losses in the converter, filters, transformers, and so on. The remaining active power of 17.5 kW is supplied by the series converter to compensate the sagged voltage and maintain constant load voltage. Here, it can be observed that the series converter effectively supplies the required active power to the load by maintaining constant load voltage. During sag, the entire reactive power of 2.2 kVAR is supplied by the shunt converter alone to the load which relieves the supply from providing reactive power, as it can be observed that the reactive power delivered by the source after compensation is zero.

During voltage swell, the supply voltage is increased from 338.8V to 440.5V as depicted in Figure 13. This increases the active power to 10 kW. Now, the series converter becomes active and draws voltage from the supply to maintain the voltage across DC-link capacitor constant. The series converter draws 2.8 kW of active power and supply to the shunt converter through the DC-link.

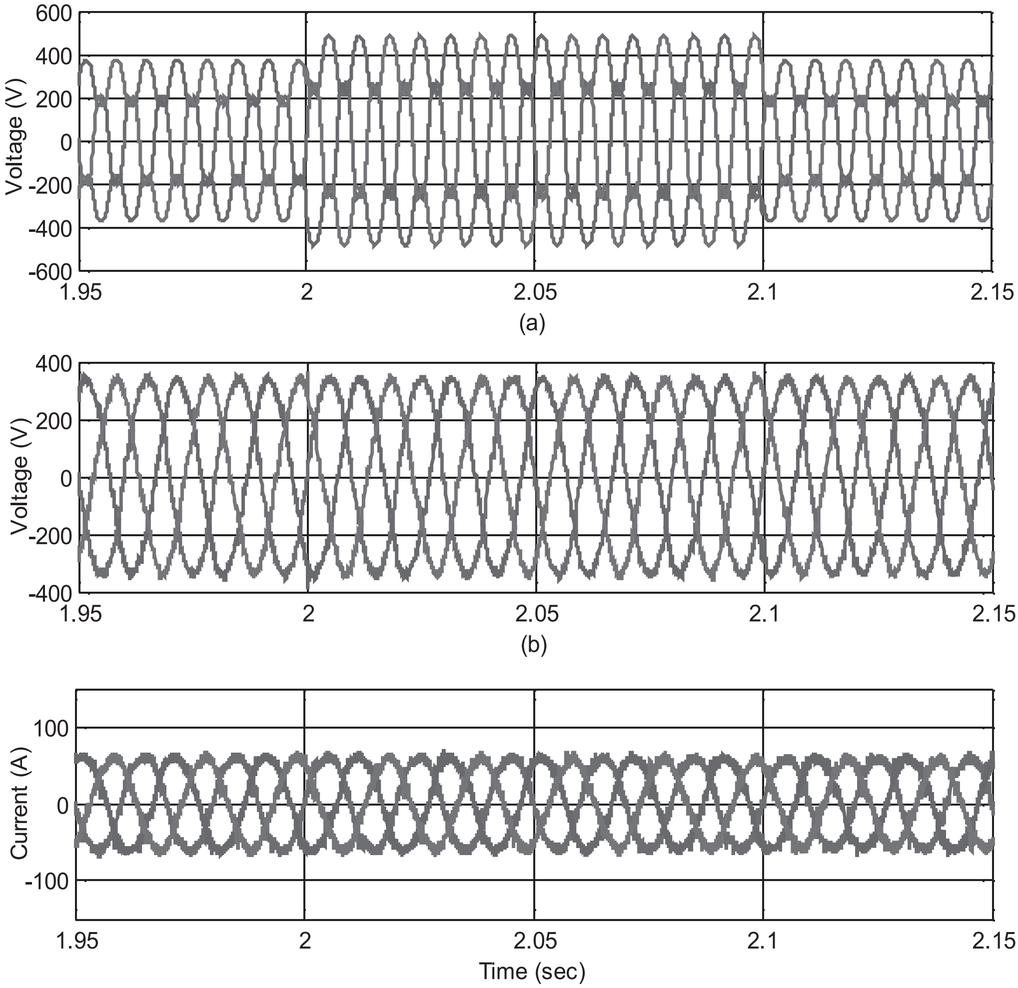


Figure 13. Compensation during voltage swells (a) supply voltage (b) load voltage and (c) supply currents.

capacitor. 2.3 kW active power is supplied by the shunt converter to compensate the swelled voltage and maintain constant load voltage. This decreases the supply current from 63.08A to 61.91A.Here, it is to be observed that the series converter effectively suppresses the excess active power from the supply and maintains constant load voltage. It is also observed that, during swell, the entire reactive power of 1000 VAR is supplied by the shunt converter alone to the load, relieving the supply. Therefore, the power supplied by the source after compensation is zero.

In this work, capacitor voltage balancing is also achieved by adding a loss component derived from PI controller to the source current fundamental reference component. Figure 14(a) shows the capacitor voltage during normal working conditions. Here, it is observed from Figure 14(b) that, after voltage sag/swell, the capacitor voltage regains its original state using PI controller.

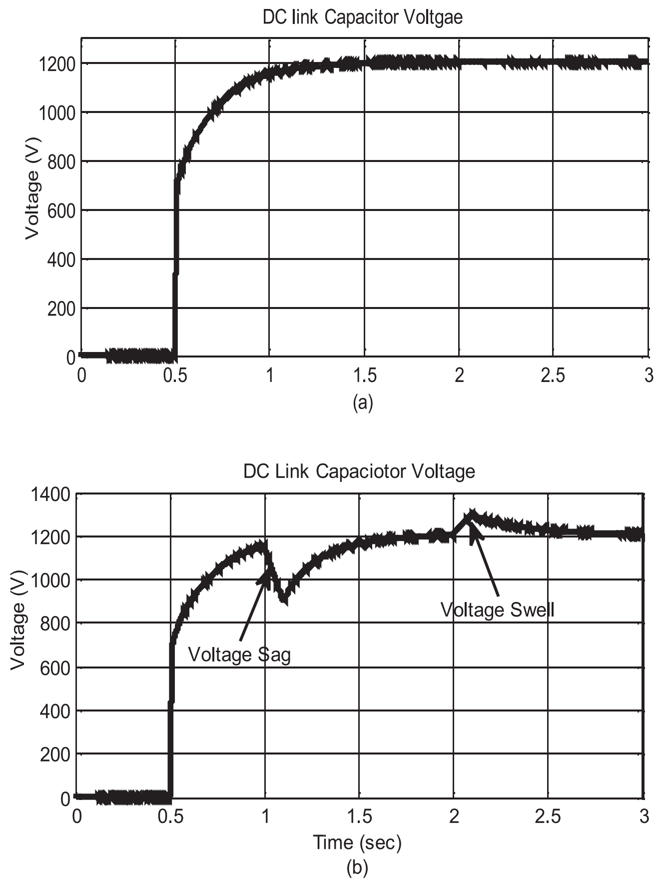


Figure 14. Capacitor voltage during (a) normal conditions and (b) voltage sag/swell.

Along with this study, simulations were also carried out for various load conditions, and their respective %THD's are given in Table 3. Active and reactive power flows in a line during voltage sag/swell are already discussed in this paper. In addition to that, active and reactive power flows under steady-state conditions are also analyzed with various loads as mentioned earlier and are tabulated in Table 4.

Table 3. Fundamental component and %THD.

		Fundamental component		%THD	
		Before	**After**	**Before**	**After**
Case I	V_S	338.8V	338.8V	22.36%	22.36%
	V_L	338.8V	347.1V	22.36%	3.86%
	I_S	11.81A	15.99A	22.27%	2.88%
	I_L	11.81A	12.1A	22.27%	3.64%
Case II	V_S	338.8V	338.8V	22.36%	22.36%
	V_L	338.8V	346.8V	22.36%	3.66%
	I_S	36.95A	47.05A	54.95%	7.89%
	I_L	36.95A	41.88A	54.95%	27.34%
Case III	V_S	338.8V	338.8V	22.36%	22.36%
	V_L	338.8V	346.8V	22.36%	3.69%
	I_S	48.75A	58.98A	44.64%	7.37%
	I_L	48.75A	54.04A	44.64%	21.60%
Case IV	V_S	338.8V	338.8V	22.36%	22.36%
	V_L	338.8V	347.1V	22.36%	3.28%
	I_S	11.81A	20.12A	22.27	2.75%
	I_L	11.81A	12.09A	22.27	3.27%
Case V	V_S	338.8V	338.8V	22.36%	22.36%
	V_L	338.8V	347.3V	22.36%	3.87%
	I_S	36.95A	50.08A	54.95%	8.10%
	I_L	36.95A	42.07A	54.95%	27.68%
Case VI	V_S	338.8V	338.8V	22.36%	22.36%
	V_L	338.8V	346.7V	22.36%	3.76%
	I_S	48.75A	63.04A	44.64%	7.08%
	I_L	48.75A	54.1A	44.64%	21.67%

Table 4. Active and reactive power flows.

		Active Power (kW)		Reactive Power (kVAR)	
		Before	**After**	**Before**	**After**
Case I	Supply side	6.3	7.9	0.087	0
	Load side	6.3	6	0.087	0.1
	Shunt Converter	0	1.9	0	-0.1
Case II	Supply side	19.8	23.2	0	0
	Load side	19.8	20.8	0	1.25
	Shunt Converter	0	2.4	0	-1.25
Case III	Supply side	26.1	29.1	0.1	0
	Load side	26.1	26.8	0.1	1.2
	Shunt Converter	0	2.3	0	-1.2
Case IV	Supply side	8.4	10.1	0.06	0
	Load side	8.4	8	0.06	0.2
	Shunt Converter	0	2.1	0	-0.2
Case V	Supply side	21.9	25.2	-0.06	0
	Load side	21.9	22.9	-0.06	1.25
	Shunt Converter	0	2.3	0	-1.25
Case VI	Supply side	28.2	31.2	0.056	0
	Load side	28.2	28.9	0.056	1.4
	Shunt Converter	0	2.3	0	-1.4

This work is also extended towards the abnormal and fault conditions like line to ground fault (L-G) and three-phase to earth fault (L-L-L-G). The simulation results due to L-G fault are depicted in Figure 15.

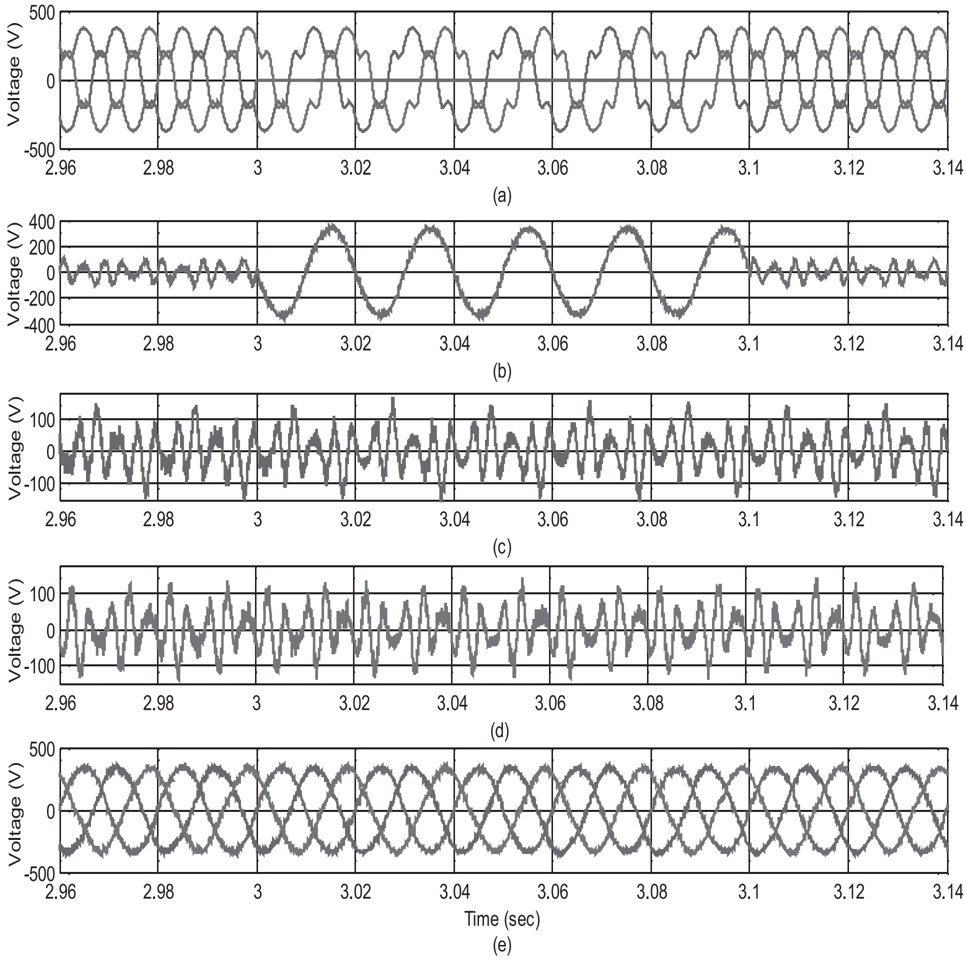


Figure 15. (a) Supply voltage (b) injected voltage in phase A (c) injected voltage in phase B (d) injected voltage in phase C and (e) load voltage.

Fault line in phase A and healthy lines in phases B and C can be clearly observed from Figure 15(a) during 3 sec to 3.1 sec. It is observed from Figures 15(b),15(c), and 15(d) that the voltages injected by the series converter before and after L-G fault are the same. During the period of L-G fault, phase A of the series converter injects the total load voltage as required by the load, and the deviated fundamental component will be injected in phases B and C. This maintains sinusoidal load voltage with constant magnitude in all the phases as shown in Figure 15(e).

The performance of the UPQC under L-L-L-G fault or short interruptions is also analyzed. The simulation results under L-L-L-G faults or voltage interruptions are depicted in Figure 16. The voltage interruption can be clearly observed from Figure 16(a) during 3 sec to 3.1 sec.

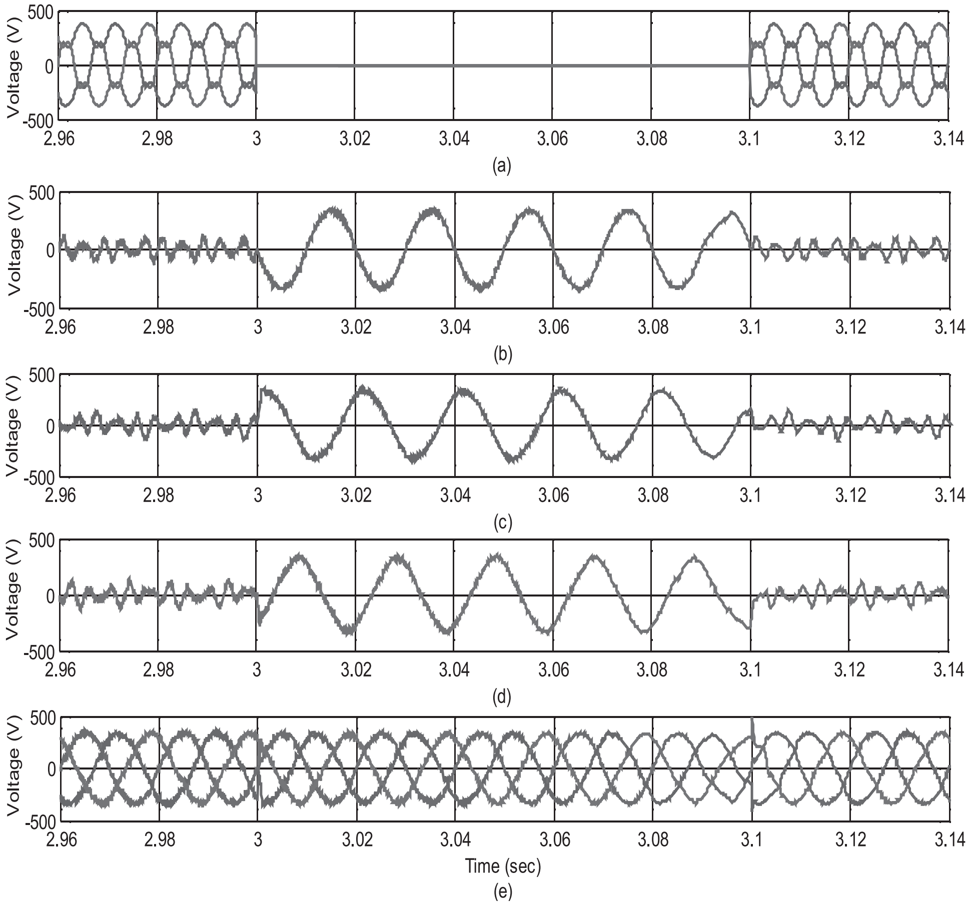


Figure 16. (a) Supply voltage (b) injected voltage in phase A (c) injected voltage in phase B (d) injected voltage in phase C and (e) load voltage.

During this period, the series converter injects the required amount of voltage to maintain the constant sinusoidal magnitude in load voltage. This can be done with the help of the DC-link capacitor, which discharges through the series converter, thereby suppling the required active power to the load voltage. The injected voltage in phases A, B, and C can be clearly observed from Figures 16(b), 16(c), and 16(d), respectively. It can also be observed that, before and after the voltage interruption period, the series converter injects only the deviated fundamental component, whereas, during voltage interruption period, it injects the total load voltage as required by the load to maintain the sinusoidal voltage with constant magnitude throughout the simulation run time. The same can be observed from Figure 16(e).

CONCLUSION

An SRF based control scheme with modified PLL is used to control UPQC in this paper. In SRF based control, three-phase sinusoidal quantities are transformed into constant quantities (d-q-0) and hence the harmonics can be filtered more easily and effectively compared to conventional schemes like PQ theory based control, unit vector based control, improved active and reactive current component theory and so on. Hysteresis current control and SPWM control are used for shunt and series converters. The performance of the proposed control scheme for UPQC is analyzed with a 415V supply having 5^{th} order harmonic of 20% and 7^{th} order harmonic of 10% in six different cases based on various load conditions. Simulations are carried out in Matlab/Simulink. The results show effective compensation of voltage and current harmonics in all six cases. In this work, the Dc-link capacitor voltage is also maintained constant using a PI controller. The active and reactive power flows are also analyzed in this paper. From the results, it is also observed that the utility is free from supplying reactive power, thereby improving the power factor at supply side. This work is also extended to abnormal and fault conditions. The results demonstrate the ability of the proposed scheme to compensate power quality issues under abnormal and faulty conditions also. Finally, it is concluded that UPQC with the proposed SRF based control with MPLL scheme effectively mitigates supply voltage harmonics and load current harmonics, and compensates voltage related problems like voltage sag, voltage swell and short interruptions, and so on.

REFERENCES

Sabin, D.D. & Sundaram, A. 1996. Quality enhances reliability. IEEE Spectrum, **33**(2):34- 41.

Akagi, H. 1996. New trends in active filters for power conditioning. IEEE Trans. Ind. Applicat., **32**(6):1312-1322.

Graovac, D. Katic, V.A. & Rufer, A. 2007. Power quality problems compensation with universal power quality conditioning system. IEEE Trans. Power Del., **22**(2):968-976.

Kota, V.R. & Vinnakoti, S. 2015. SRF-based control of unified power quality conditioner for power quality enhancement. IEEE Conf., Electrical, Electronics, Signals, Communication and Optimization (EESCO), 1-6.

Vijji, A.J. & Victoire, T.A.A. 2014. Enhanced PLL based SRF control method for UPQC with fault protection under unbalanced load conditions. Elsevier, Int.J. Electrical Power and Energy Systems, 58:319-328.

Kesler, M. & Ozdemir, E. 2011. Synchronous-reference-frame-based control method for UPQC under unbalanced and distorted load conditions. IEEE Trans. Ind. Electronics, **58**(9):3967-3975.

Khadkikar, V. & Chandra, A. 2011. UPQC-S: A novel concept of simultaneous voltage sag/swell and load reactive power compensations utilizing series inverter of UPQC. IEEE Trans. Power Electronics, **26**(9):2415-2425.

Kisck, D.O. & Kisck, M. 2007. Single-phase unified power quality conditioner with optimum voltage angle injection for minimum VA requirement. IEEE Conf., Power Electronics Specialists Conference (PESC), 574-579.

Zaveri, T., Bhalja, B.R. & Zaveri, N. 2012. Load compensation using DSTATCOM in three-phase, three-wire distribution system under various source voltage and delta connected load conditions. Elsevier, Int.J. Electrical Power and Energy Systems, **41**(1): 34-43.

Zaveri, N. & Chudasama, A. 2012. Control strategies for harmonic mitigation and power factor correction using shunt active filter under various source voltage conditions. Elsevier, Int.J. Electrical Power and Energy Systems, **42**(1):661-671.

Ketabi, A., Farshadnia, M., Malekpour, M. & Feuillet, R. 2012. A new control strategy for active power line conditioner (APLC) using adaptive notch filter. Elsevier, Int.J. Electrical Power and Energy Systems, 47:31-40.

Khadkikar, V. 2012. Enhancing electric power quality using UPQC: A comprehensive overview. IEEE Trans. Power Electronics, **27**(5):2484-2497.

Karanki, S.B., Geddada, N., Mishra, M.K. & Kumar, B.K. 2013. A modified three-phase four wire UPQC topology with reduced DC-link voltage rating. IEEE Trans. Ind. Electronics, **60**(9):3555-3566.

Mohammadi, H.R., Varjani, A.Y. & Mokhtari, H. 2009. Multiconverter unified power-quality conditioning system: MC-UPQC. IEEE Trans. Power Delivery, **24**(3):1679-1686.

Fatiha, M., Farshadnia, M.M. & Nadia, A.-A. 2011. New hysteresis control band of an unified power quality conditioner. Elsevier, Int.J. Electric Power Systems Research, **81**(9):1743-1753.

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