

A Novel Control Strategy of UPQC for Power Quality Improvement

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Abstract: *This paper presents a novel control strategy of a three-phase three-wire Unified Power Quality (UPQC) for an improvement in power quality. The UPQC is realized using two back to back connected voltage source inverters (VSIs) to a common dc link capacitor. To extract the fundamental source voltages as reference signals for series APF, a zero crossing detector and the 'sample and hold circuits' are used, while $I \cos\Phi$ theory is used for the control of Shunt APF. The performance of the implemented control algorithm is evaluated in terms of power-factor correction, load balancing and mitigation of voltage and current harmonics for different combinations of linear and non-linear loads. In this control strategy of UPQC, the current/voltage control is applied over the fundamental supply currents/voltages instead of fast changing APFs currents/voltages, there by reducing the computational delay and required sensors. MATLAB/Simulink based simulation results are presented, which support the functionality of the UPQC.*

Keywords: *Power Quality, UPQC, Load Balancing, Power Factor Correction, voltage and current harmonic mitigation.*

1. Introduction

Now a days distribution system are facing poor power quality at the load ends [1]. The main reason behind this is, the increasing use of non-linear and poor power-factor loads such as adjustable speed drives, computer power supplies, furnaces, power converters and traction drives at commercial, domestic and industrial levels. These nonlinear loads draw non-linear current and degrade electric power quality. The quality degradation leads to low power-factor, low

efficiency, overheating of transformers and so on [2]. Apart from this, the over all load on the distribution system is hardly found balanced. In this scenario, it is becoming increasingly difficult for power utility companies to provide their consumers an uninterrupted sinusoidal voltage of constant amplitude. In addition to this, adherence to different power quality standards [3] laid down by different agencies has become a figure of merit for the utilities in deregulate power market.

In past, conventional passive filters have been used to mitigate these identified power quality problems. But passive filters have few limitations such as, fixed compensation, resonance with the source impedance, difficulty in tuning and time dependence of filter parameters [4]. With the use of active and hybrid filters [5]-[6], these problems can be eliminated. Unfortunately, because of severe power quality problems faced by today's power distribution system the utility of these filters become insufficient. Under this circumstance, a new technology called custom power Devices (CPDs) emerged [7-8], which is applicable to distribution systems for enhancing the reliability and quality of the power supply.

The compensating type CPDs mainly covers three devices namely, D-Statcom [9], DVR [10] and UPQC [11-15]. The D-Statcom is a shunt device, which mitigates the current based distortions, while DVR finds its application for the mitigation of voltage based distortions. As the UPQC is a combination of back to back connected series and shunt APFs, hence compensates current and voltage related problems,

simultaneously. The series APF suppresses and isolates voltage-based distortions. The shunt APF cancels current-based distortions. At the same time, it compensates reactive current of the load and improves power factor.

There are many control strategies reported in the literature to control the UPQC for power quality improvements, the most common are the instantaneous active and reactive power theory (the $p-q$ theory) proposed by Akagi [12], symmetrical component transformation [13], synchronous reference frame(SRF) theory [14], and unit vector template(UVT) technique [15] etc. In this paper, a zero crossing detector and the ‘sample and hold circuits’ are used to extract the fundamental source voltages as reference signals for series APF, while $I \cos\Phi$ theory is used for the control of Shunt APF. In this control strategy of UPQC, the current/voltage control is applied over the fundamental supply currents/voltages instead of fast changing APFs currents/voltages, there by reducing the computational delay. The application of $I \cos\Phi$ theory [16-17] has been reported for power-factor correction of active filters in literature.

The UPQC configuration and the load under consideration load are discussed in Section II. The control algorithm for UPQC is discussed in Section III. The SIM POWER SYSTEM (SPS), Matlab/Simulink based simulation results are discussed in Section IV and finally Section V concludes the paper.

2. System Description

The basic block diagram of the UPQC connected on a three-phase three-wire distribution system is shown in Fig.1. The UPQC is connected before the load to make the source currents balanced, sinusoidal and in phase with the supply voltages and at the same time to make the load voltage free from any distortions. Two back to back connected three-leg VSIs are used for the realization of series and shunt APFs. The DC link of both APFs is connected to a common DC link capacitor. The series filter is connected between the supply and load terminals using three single phase transformers with turn’s ratio of 5:1. The primary winding of these transformer are star connected and the secondary windings are connected in series with the three-phase supply. In addition to injecting the required voltage, these transformers are used to filter the switching ripple content in the series active filter.

A small capacity rated R-C filter is connected in parallel with the secondary of each series transformer to eliminate the high switching ripple content in the series APF injected voltage. The VSIs for both the series and shunt APFs are implemented with Insulated gate Bipolar Transistors (IGBTs).

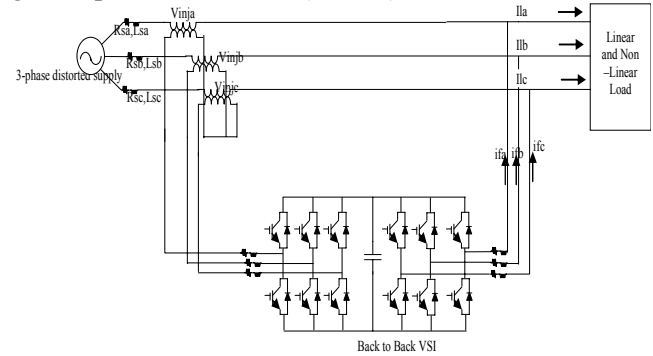


Fig. 1. Basic block diagram of UPQC

In Fig.1 (i_{sa}, i_{sb}, i_{sc}), (i_{la}, i_{lb}, i_{lc}) and (i_{fa}, i_{fb}, i_{fc}) represents the source currents, load currents and shunt APF currents in phase a, b and c respectively. The injected voltages by the series APF in phase a, b and c is represented by v_{inja}, v_{injb} and v_{injc} , respectively. The values of the circuit parameters and the load are given in Appendix.

3. Control Scheme of Series APF

The control scheme for the generation of reference signals for series APF is shown in Fig.2. Since, the supply voltage is distorted, a phase locked loop (PLL) is used to achieve synchronization with the supply voltage [15].

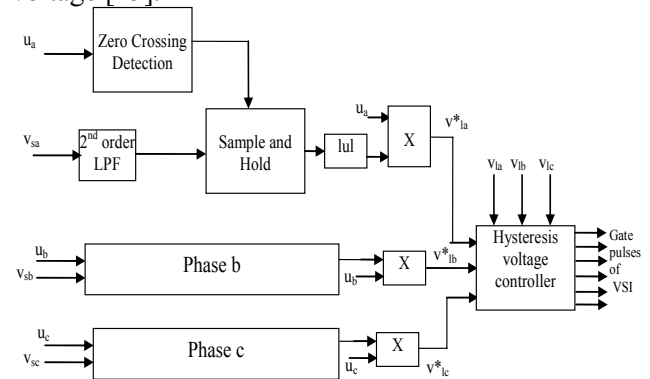


Fig. 2. Control Scheme of Series APF

Three-phase distorted supply voltages are sensed and given to PLL which generates two quadrature unit vectors ($\sin\omega t, \cos\omega t$). The in-phase sine and cosine outputs from the PLL are used to compute the supply

in phase, 120° displaced three unit vectors (u_a, u_b, u_c) using eqn.(1) as:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \sin \theta \\ \cos \theta \end{bmatrix} \quad (1)$$

The amplitude of fundamental source voltage is extracted at zero crossing of the unit template in phase of PCC voltage from the source voltages by shifting the source voltages by $+90^\circ$, using a set of low pass filters. The filters are with 50 Hz cut-off frequency to extract the magnitude of fundamental source voltage. A Zero crossing detector and a “sample and hold” circuit are used to extract the amplitude of fundamental source voltage at zero crossing of corresponding in phase unit template. The amplitude of the fundamental source voltage is then multiplied with the unit vector of the corresponding unit vectors to get the reference load voltages (v_{la}^*, v_{lb}^* and v_{lc}^*) as per eqn.2:

$$\begin{aligned} v_{la}^* &= V_{sa1} * u_a \\ v_{lb}^* &= V_{sb1} * u_b \\ v_{lc}^* &= V_{sc1} * u_c \end{aligned} \quad (2)$$

where, V_{sa1}, V_{sb1} and V_{sc1} are the extracted magnitudes of fundamental source voltages in phase a, b and c respectively. The computed load reference load voltages (v_{la}^*, v_{lb}^* and v_{lc}^*) from eqn. (2) are then given to the hysteresis voltage controller along with the sensed three phase actual load voltages (v_{la}, v_{lb} and v_{lc}). The output of the hysteresis controller is switching signals to the six switches of the VSI of series APF. The hysteresis controller generates the switching signals such that the voltage at PCC becomes the desired sinusoidal reference voltage. Therefore, the injected voltage across the series transformer through the ripple filter cancels out the harmonics present in the supply voltage.

4. Control Scheme of Shunt APF

The control algorithms for shunt APF consists of the generation of 3-phase reference supply currents (i_{sa}^*, i_{sb}^* and i_{sc}^*). In this proposed control algorithm, the sensed (i_{sa}, i_{sb} and i_{sc}) and reference source currents (i_{sa}^*, i_{sb}^* and i_{sc}^*) are compared in a hysteresis current controller to generate the switching signals to

the switches of the shunt APF. The control algorithm based on the modified ICos Φ algorithm is shown in Fig.3.

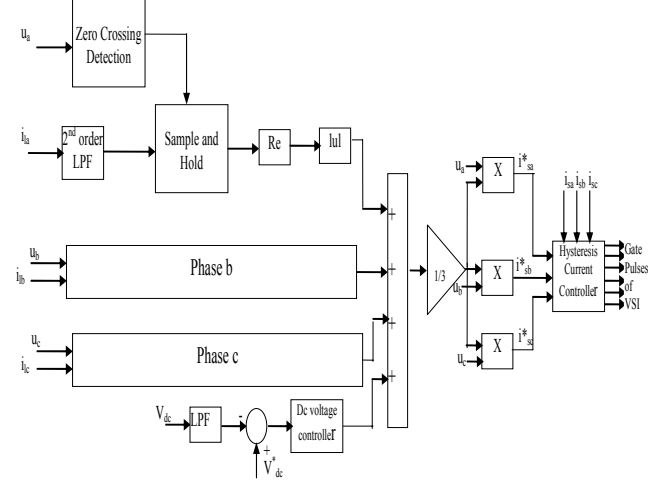


Fig. 3. Control Scheme of Shunt APF using I Cos Φ Theory

The amplitude of active component of fundamental load currents are given as:

$$\begin{aligned} |\text{Re}(I_{La})| &= |I_{La}| \text{Cos} \phi_a; \\ |\text{Re}(I_{Lb})| &= |I_{Lb}| \text{Cos} \phi_b; \\ |\text{Re}(I_{Lc})| &= |I_{Lc}| \text{Cos} \phi_c; \end{aligned} \quad (3)$$

The amplitude of active component (ICos Φ) of fundamental load current is extracted at zero crossing of the unit template in phase of PCC voltage from the load currents by $+90^\circ$, using a set of low pass filters. The filters are with 50 Hz cut-off frequency to extract the fundamental load current. A Zero crossing detector and a “sample and hold” circuit are used to extract the I Cos Φ (amplitude of fundamental load current at zero crossing of corresponding in phase unit template). For balance source currents, the magnitude of active component of reference source currents can be expressed as :

$$I_{sp}^* = (|I_{La}| \text{Cos} \phi_a + |I_{Lb}| \text{Cos} \phi_b + |I_{Lc}| \text{Cos} \phi_c + I_d) / 3 \quad (4)$$

where $|I_{La}| \text{Cos} \phi_a; |I_{Lb}| \text{Cos} \phi_b; |I_{Lc}| \text{Cos} \phi_c$ are the amplitude of the load active currents and I_d is the output of DC bus voltage PI controller for self supporting bus of the UPQC which can be expressed as;

$$I_{(dn)} = I_{d(n-1)} + K_{pd} \{V_{de(n)} - V_{de(n-1)}\} + K_{id} V_{de(n)} \quad (5)$$

where $V_{de(n)} = V_{dcr} - V_{dca(n)}$ denotes the error in V_{dc}

calculated over reference value of V_{dc} . and average value of V_{dc} . K_{pd} and K_{id} are proportional and integral gains of the dc bus voltage PI controller. The three-phase component of source currents can be obtained with in-phase unit templates as:

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = I_{sp}^* \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (6)$$

In this proposed control algorithm, the sensed (i_{sa} , i_{sb} and i_{sc}) and reference source currents (i_{sa}^* , i_{sb}^* and i_{sc}^*) are compared in a hysteresis current controller to generate the switching signals to the switches of the shunt APF which makes the supply currents sinusoidal, balanced in-phase with the voltage at PCC. Hence the supply current contains no harmonics or reactive power component. In addition to this, the current control is applied over the fundamental supply currents instead of the fast changing APF currents, thereby reducing the computational delay and the number of required sensors.

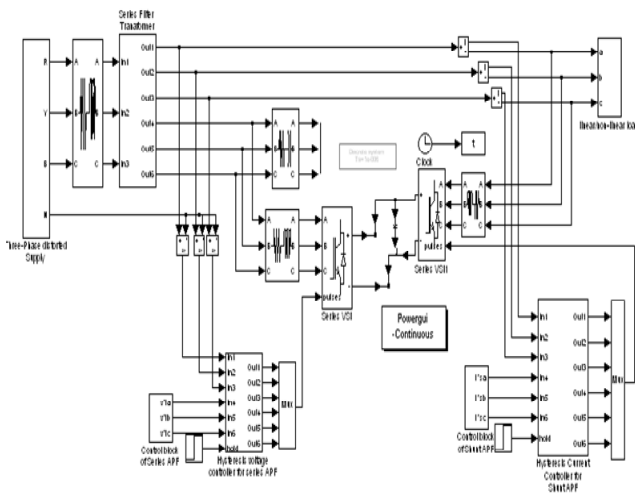


Fig. 4. MATLAB Model of UPQC

5. Results and Discussion

The developed model of UPQC with proposed control scheme using MATLAB/ Simulink and its Sim-Power System toolbox is shown in Fig.4. The performance of UPQC is evaluated in terms of voltage and current harmonics mitigation, load balancing, and power-factor correction under different load conditions. To evaluate the performance of UPQC for voltage harmonic mitigation, the distortion in utility

voltage is introduced intentionally by injecting 5th and 7th order voltage harmonics along with the fundamental.

5.1 Performance of UPQC for load balancing and power-factor correction

Fig. 5 shows the response of UPQC with linear lagging power-factor load for power-factor correction and load balancing. The shunt APF is put into operation at 0.1 sec. Fig.5 (e) shows that after 0.1 sec the source voltage and source current in phase 'a' are exactly in phase. At $t=0.2$ sec the load is changed from three phase to two phase to make the load unbalanced. The shunt APF compensates for the unbalanced load and source currents are still balanced and in phase with the source voltages. It is also observed from Fig.5 (f) that during unbalanced load operation, the dc voltage increases and settles to its previous steady state value, once load is balanced.

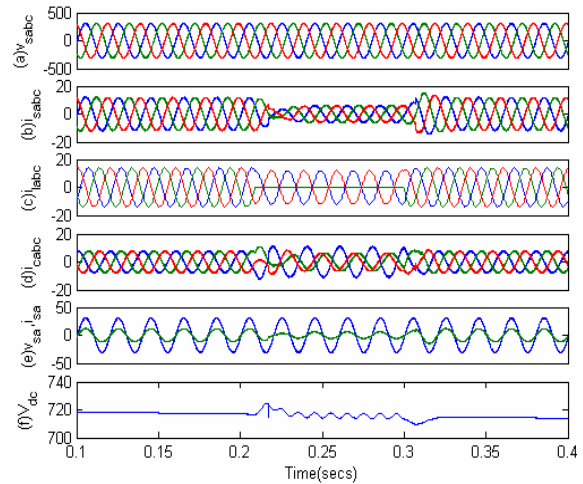


Fig. 5. Performance of UPQC for load balancing and power-factor correction

5.2 Performance of UPQC for load balancing, power-factor correction and current harmonic mitigation

In order to demonstrate the response of UPQC for load balancing, power factor correction and current harmonic mitigation, the load under consideration is a combination of a three-phase diode bridge rectifier with resistive load and unbalanced R-L load in phase 'a' and 'b' only. It is observed that the supply currents are balanced and sinusoidal as is shown in Fig.6 (b).

Fig.6 (e) shows that the supply current is in-phase with the supply voltage.

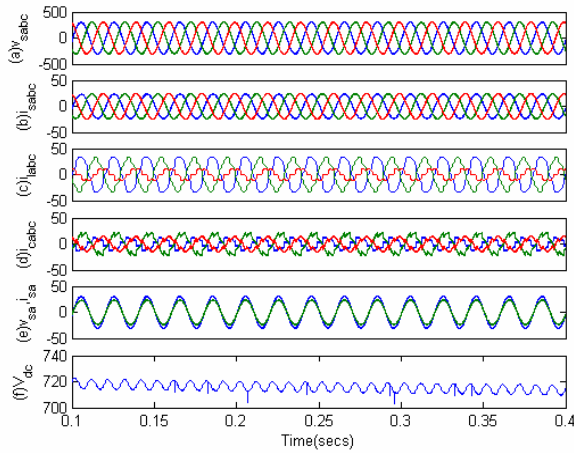


Fig. 6.Performance of UPQC for load balancing, power-factor correction and current harmonic mitigation

5.3 Performance of UPQC for load balancing, power-factor correction, current and voltage harmonic mitigation

In order to verify the effectiveness of control algorithm for voltage harmonic mitigation, the distortion in utility voltage is introduced deliberately by injecting 5th and 7th order voltage harmonics along with the fundamental. Because of this the voltage across the load becomes distorted. Fig.7 shows the response of UPQC for load balancing, power factor correction, voltage harmonic mitigation and current harmonic mitigation. To visualize the shunt APF and series APF performance individually, both APF's are put into operation at different instant of time. At time $t_1=0.1$ sec, shunt APF is put into operation first. It is observed that the supply currents are balanced; sinusoidal and in-phase with the voltages even under non-sinusoidal utility voltage. The source current THD in phase 'c' is improved from 15.56 % to 1.41 %. At time $t_2=0.25$ sec the series APF is put into the operation. The series APF starts compensating voltage harmonics immediately by injecting out of phase harmonic voltage, making the load voltage at load distortion free. The voltage injected by series APF is shown in Fig. 7(c). Here load voltage THD is improved from 5.57 % to 0.53 %. The harmonic spectra of the source current and the load voltage in phase 'c' with compensation and without compensation are shown in Fig. 8.

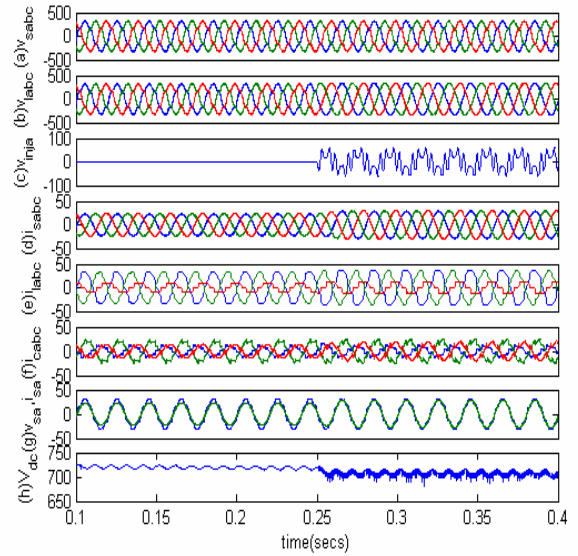


Fig. 7.Performance of UPQC for load balancing, power-factor correction, current and voltage harmonic mitigation

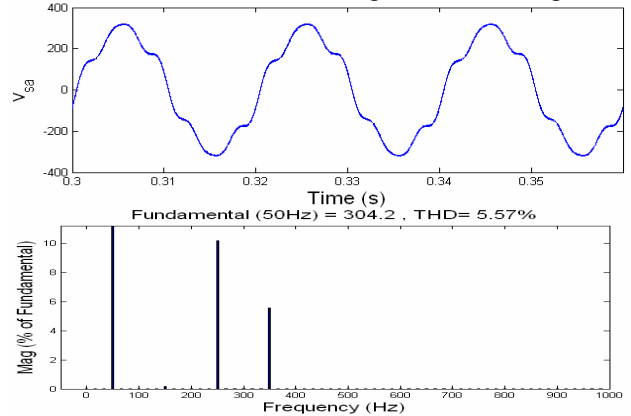


Fig.8 (a) Load voltage and its harmonic spectrum before compensation

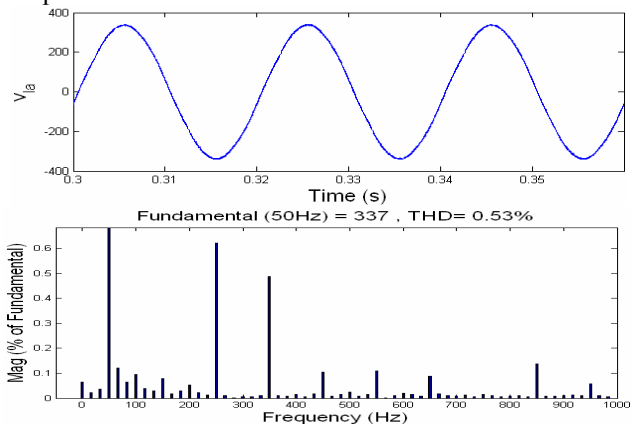


Fig.8 (b) Load voltage and its harmonic spectrum after compensation

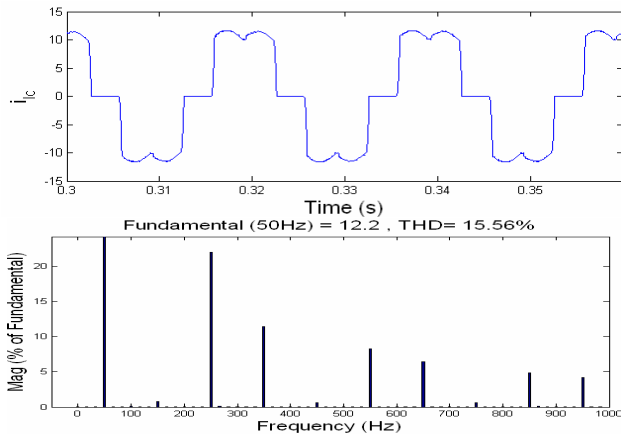


Fig.8 (c) Source current in phase 'c' and its harmonic spectrum before compensation

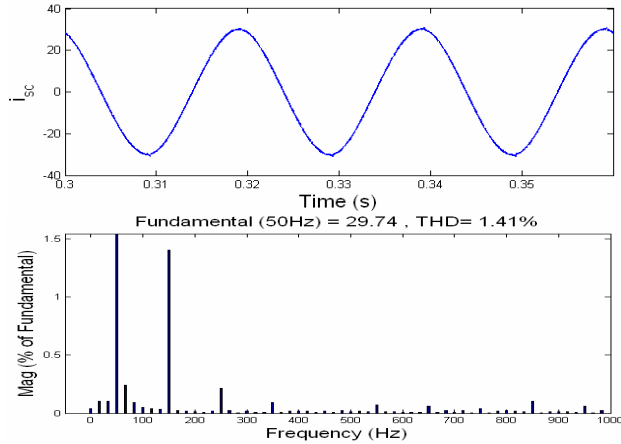


Fig.8 (d) Source current in phase 'c' and its harmonic spectrum after compensation

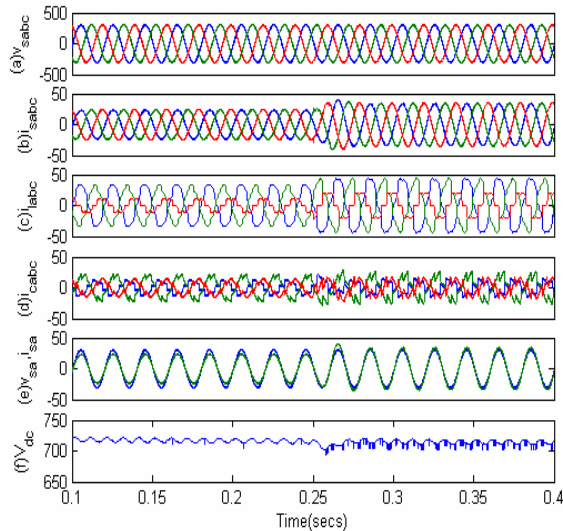


Fig.9 Performance of UPQC for sudden load change

5.4 Performance of UPQC for sudden load change

In order to show the response of UPQC for sudden load change the load across the dc side of the rectifier is increased at $t=0.25$ s. It is observed from Fig.9(b) that in addition to the load balancing, power factor correction and current harmonic mitigation, the UPQC controller acts immediately without any delay in the operation and gain the new steady state. It is also observed from Fig. 9 (f) that there is small dip in dc voltage at $t=0.25$ s, but dc link is able to regulate the dc voltage to its previous value.

5. Conclusion

The proposed control scheme of UPQC has been validated through simulation results using MATLAB software along with simulink and sim-power system toolbox. The proposed control algorithm of UPQC has been observed to be satisfactory for various power quality improvements like load balancing, power-factor correction, voltage harmonics mitigation and current harmonic mitigation. The source current THD is improved from 15.56 % to 1.41 %, while the load voltage THD is improved form 5.57 % to 0.53 %. It is found that supply currents and load voltage harmonic levels are maintained below IEEE-519 standards. In addition to this the performance of UPQC has been found satisfactory during transient conditions.

Appendix

The system parameters used are as follows:
 Supply voltage and line impedance: 415 V L-L, $f=50$ Hz, $R_s=0.1$ ohm, $L_s=1.5$ mH
 Filter: $R=7\Omega$, $C=5\mu$ F
 DC bus capacitance: $C_{dc}=3000\mu$ F
 $K_p=2$, $K_i=2$
 Transformer: 250MVA, 58KV/12KV
 Loads: Three-Phase Rectifier Load $R=50 \Omega$ and $R_a=R_b=10 \Omega$, $L_a=5$ mH, $L_b=20$ mH, $R_c=L_c=0$.

References

1. Baggini, A.: *Hand Book on power quality*. In: John Wiley & Sons, New Jersey, USA, 2008.

2. Gunther, E.W., Mehta, H.: *A survey of distribution system power quality*. In: IEEE Trans. on Power Delivery, vol.10 (1995), No.1, Jan.1995, pp.322-329.
3. *IEEE recommended Practices and Recommendations for harmonics Control in Electric Power Systems*. In: IEEE std.519, 1992.
4. Das, J. C.: Passive filters - potentialities and limitations. In: *IEEE Trans. Ind. Applicat.*, vol.40(2004), pp.232-241.
5. Singh, B., Haddad, AL.K. Chandra, A.: *A review of active filters for power quality improvement*. In: IEEE Trans. on Ind. Electron, vol.46 (1999), pp. 960–971.
6. Singh, B., Verma, V., Chandra, A., Al-Haddad, and K.: *Hybrid filters for power quality improvement*. In: Proc. IEE on Generation, Transmission and Distribution, vol.152 (2005), May2005, pp.365-378.
7. Ghosh, A., Ledwich, G.: *Power Quality Enhancement Using Custom Power Devices*” Kulwer International Series in Engineering and Computer Science, 2002.
8. Hingorani, N. G.: Introducing custom power. In: Proc. IEEE Spectrum, vol.32 (1995), June1995, pp.41-48.
9. Sahay, K., Dwivedi, B.: *Super capacitor Energy Storage Based Dstatcom Modeling and Simulation for Distribution System*. In: JEE, Vol.10 (2010), Edition-4.
10. Praveen, J., Muni, B.P., Venkateshwarlu, S., Makthal, H.V.: *Review of dynamic voltage restorer for power quality Improvement*. In: Proc. IEEE IECON2004, Vol.1 (2004), Nov.2004, pp.749-754.
11. Han, B., Bae, B., Kim, H., Baek, S.: Combined operation of unified power-quality conditioner with distributed generation. In: *IEEE Trans. Power Del.*, vol. 21(2006), no. 1, Jan. 2006, pp. 330–338.
12. Akagi, H., Kanazawa, Y., Nabae, A.: Instantaneous reactive power compensator comprising switching device without energy store Components. In: IEEE Trans. on Industry Applications, vol.1 (1984) A-20, No.3, pp.625-630.
13. Ghosh, A., Joshi, A.:A new algorithm for the generation of reference voltages of a DVR using the method of instantaneous symmetrical components. In: Proc. IEEE on Power Engineering Review, vol.22 (2002), pp.63-65.
14. Pengcheng, Z., Xun, L., Kang, Y., Jian, C.: A novel control scheme in 2-phaseSFR for unified power quality conditioner. In:Proc. IEEE on IECON’03, , vol.2(2003), pp.1617-1622.
15. Khadkikar, V., Agarwal, P., Chandra, A., Barry, A.O., Nguyen, T.D.:A simple new control technique for unified power quality conditioner (UPQC).In: Proc. on. Harmonics and Quality of Power, Sept.2004, pp.289-293.
16. Bhuvaneswari, G.,Nair, M.G., Kumar Reddy, S.:Comparison of Synchronous detection and ICos Φ Shunt Active Filtering Algorithm. In: Conf. IEEE PEDES’06, Dec.2006, pp.1-5.
17. Bhuvaneswari, G., Nair, M. G.: Design, Simulation and analog Circuit Implementation of a Three-Phase Shunt Active Filter Using the ICos Φ Algorithm. In: IEEE Trans. on Power Delivery, vol.23 (2008), pp.1222-1235.