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A Simplified Control Algorithm for Three-Phase, Four-Wire Unified Power Quality Conditioner

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Abstract

In this paper, a simplified control algorithm for a three-phase, four-wire unified power quality conditioner (UPQC) is presented to compensate for supply voltage distortions/unbalance, supply current harmonics, the supply neutral current, the reactive power and the load unbalance as well as to maintain zero voltage regulation (ZVR) at the point of common coupling (PCC). The UPQC is realized by the integration of series and shunt active filters (AFs) sharing a common dc bus capacitor. The shunt AF is realized using a three-phase, four leg voltage source inverter (VSI) and the series AF is realized using a three-phase, three leg VSI. A dynamic model of the UPQC is developed in the MATLAB/SIMULINK environment and the simulation results demonstrating the power quality improvement in the system are presented for different supply and load conditions.

Key Words: Active Filter, Harmonics, Reactive Power, Unbalance, UPQC, Voltage Regulation

I. Introduction

The main objective of electric utility companies is to supply their customers with uninterrupted sinusoidal voltage of constant magnitude. However this is becoming increasingly difficult to do, because the size and number of non-linear and poor power factor loads such as adjustable speed drives, computer power supplies, furnaces and traction drives are increasing rapidly. Due to their nonlinear nature, these solid state converters cause excessive neutral currents in three phase four wire systems. Moreover, in the case of the distribution system, the overall load on the system is seldom found to be balanced. In the past, the solutions to mitigate these identified power quality problems [1] were through using conventional passive filters. But their limitations such as, fixed compensation, resonance with source impedance and the difficulty in tuning time dependence of filter parameters have ignited the need for active and hybrid filters [2]–[4]. The rating of active filters is reduced through augmenting them with passive filters [5], [6] to form hybrid filters, which reduce overall cost. Also they can provide better compensation than either passive or active filters. If one can afford the cost, then a hybrid of two active filters provides the best solution and thus it is known as a unified power quality conditioner (UPQC) or universal active filter. Therefore, the development of hybrid filter technology has been from a hybrid of passive filters to a hybrid of active filters to provide a cost-effective solution and optimal compensation [7]–[12].

For voltage related power quality problems [3], [4] and for systems supplying diode bridge converters with high dc link capacitive filters, series active or hybrid filter configurations are preferred [5], [6]. However, when using these filters, the dc link voltage and zero voltage regulation (ZVR) are difficult to maintain at the PCC. Series filters can eliminate voltage and current harmonics, but they are not suitable for maintaining zero voltage regulation at the PCC. Moreover for loads such as diode/thyristor bridge converters supplying highly inductive loads and/or unbalanced loads, shunt filters are preferred since they can maintain ZVR and compensate for current harmonics and reactive power [13]. But these filters are not suitable for the elimination of harmonics/unbalance in PCC voltage. In addition, for better rating utilization it is preferable to deal with voltage related problems with a series filter rather than a shunt filter. Therefore to deal with voltage and current related power quality problems, both series and shunt active filters are combined through a common dc link capacitor forming a UPQC. In a UPQC depending upon its application, the arrangement of series and shunt filters are interchangeable. In general when a UPQC is used in a power distribution system [14]–[16], the series filter is installed ahead of the shunt filter. Moreover, in a UPQC installed for voltage flicker/unbalance sensitive loads, the series filter is installed at the load side to effectively meet the requirements of the voltage sensitive load [17]–[20].

This paper presents a 3-phase, 4-wire UPQC configuration suitable for power distribution systems and a simple control algorithm for its control. The series AF is controlled to maintain voltage regulation and to eliminate supply voltage sag/swell, harmonics and unbalance from the load terminal voltage. The shunt AF is controlled to alleviate the supply current from harmonics, negative sequence current, reactive

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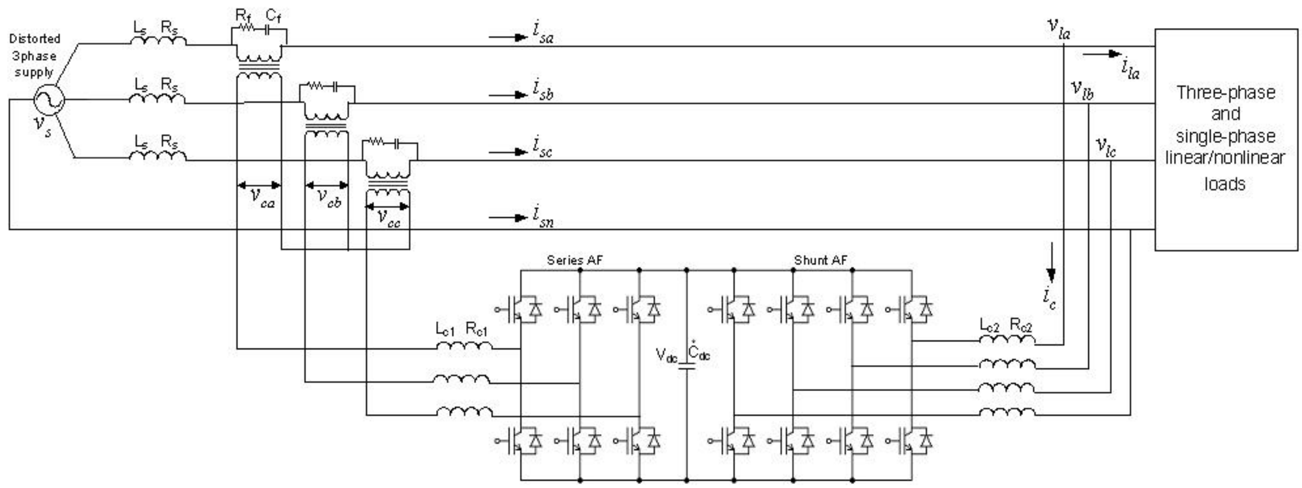

Fig. 1. Detailed configuration of UPQC.

power and neutral current. The dc bus voltage is held constant by the shunt active filter. The performance of the proposed system is demonstrated through simulated waveforms and the harmonic spectra of supply currents and load voltages with and without UPQC.

II. System Configuration

Fig. 1 shows the proposed 3-phase, 4-wire UPQC connected to a power system feeding an unbalanced nonlinear load. It consists of a three leg voltage controlled VSI used as a series active filter and a four leg current controlled VSI used as a shunt active filter. The dc link of both active filters is connected to a common dc capacitor of 1500μF. The series filter is connected between the supply and load terminals using three single phase transformers with turns ratios of 2:1. The primary windings of these transformers are star connected and the secondary windings are connected in series with the three-phase supply. In addition to injecting the voltage, these transformers are used to filter the switching ripple of the series active filter. A small capacity rated RC filter [6] is connected across the secondary of each series transformer to eliminate the high switching ripple content in the series active filter injected voltage. The voltage source inverters for both the active filters are implemented with IGBTs (Insulated Gate Bipolar Transistors). The four leg shunt active filter is connected ahead of a series filter through a small capacity rated inductive filter. This four leg VSI based shunt active filter is capable of suppressing the harmonic currents both in the three phases, and in the neutral conductor of the unbalanced three phase, four wire electrical distribution system. The implemented control algorithm consists mainly of the computation of the three-phase reference voltages at the load terminal ($v_{la}^*, v_{lb}^*, v_{lc}^*$) and the reference supply currents ($i_{sa}^*, i_{sb}^*, i_{sc}^*$). In this control algorithm the shunt and series AF currents/voltages are not sensed. However, in conventional control algorithms, such as using the instantaneous reactive power theory [17] or instantaneous symmetrical components [1], [20], the shunt and series AF currents/voltages are sensed and controlled to match their respective computed reference components there by increasing the number of sensors and computational delays.

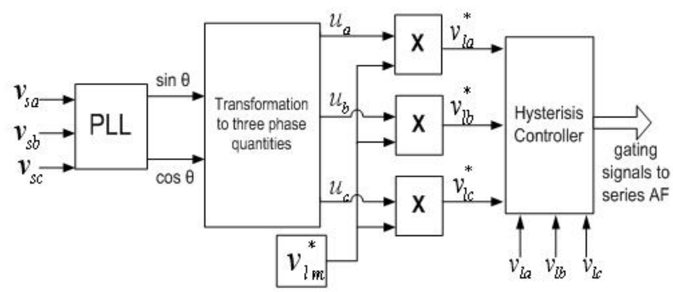

Fig. 2. Control Scheme of Series AF.

III. Control Scheme of Series Filter

A simple algorithm is developed to control the series and shunt filters. The series filter is controlled such that it injects voltages (v_{ca}, v_{cb}, v_{cc}), which cancel out the distortions and/or unbalance present in the supply voltages (v_{sa}, v_{sb}, v_{sc}), thus making the voltages at the PCC (v_{la}, v_{lb}, v_{lc}) perfectly balanced and sinusoidal with the desired amplitude. In other words, the sum of the supply voltage and the injected series filter voltage makes the desired voltage at the load terminals.

The control strategy for the series AF is shown in Fig. 2. Since the supply voltage is unbalanced and or distorted, a phase locked loop (PLL) is used to achieve synchronization with the supply [21]. Three phase distorted/unbalanced supply voltages are sensed and given to the PLL which generates two quadrature unit vectors ($\sin\theta$, $\cos\theta$). The sensed supply voltage is multiplied with a suitable value of gain before being given as an input to the PLL. 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:

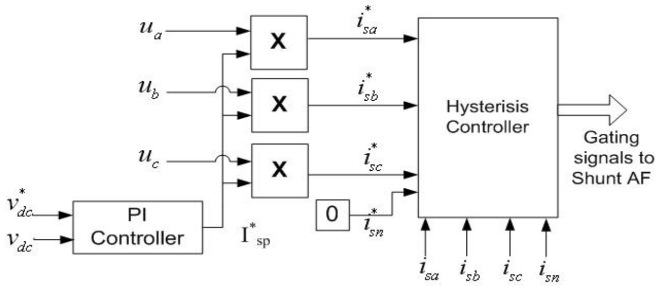

Fig. 3. Control scheme of shunt AF.

$$\begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix} \tag{1}$$

The computed three in-phase unit vectors are then multiplied with the desired peak value of the PCC phase voltage (V^*_{lm}), which becomes the three-phase reference PCC voltages as:

$$\begin{pmatrix} v^*_{la} \\ v^*_{lb} \\ v^*_{lc} \end{pmatrix} = V^*_{lm} \begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} \tag{2}$$

The desired peak value of the PCC phase voltage is considered to be 338V ($= 415\sqrt{2}/\sqrt{3}$V). The computed voltages from eqn. (2) are then given to the hysteresis controller along with the sensed three-phase PCC voltages. The output of the hysteresis controller is switching signals to the six switches of the VSI of the series AF. The hysteresis controller generates the switching signals such that the voltage at the PCC becomes the desired sinusoidal reference voltage. Therefore, the injected voltage across the series transformer through the ripple filter cancels out the harmonics and unbalance present in the supply voltage.

IV. Control Scheme of Shunt Filter

The control algorithm for a shunt AF consists of the generation of 3-phase reference supply currents and it is depicted in Fig. 3. This algorithm uses supply in-phase, $120°$ displaced three unit vectors computed using eqn. (1). The amplitude of the reference supply current (I^*_{sp}) is computed as follows. A comparison of the average and the reference values of the dc bus voltage for the shunt AF results in a voltage error, which is fed to a proportional integral (PI) controller and the output of the PI controller is taken as the reference amplitude of the supply currents. The three in-phase reference supply currents are computed by multiplying their amplitude ($I^*{}_{sp}$) and in-phase unit current vectors as:

$$\begin{pmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \\ i^*_{sn} \end{pmatrix} = I^*_{sp} \begin{pmatrix} u_a \\ u_b \\ u_c \\ 0 \end{pmatrix} \tag{3}$$

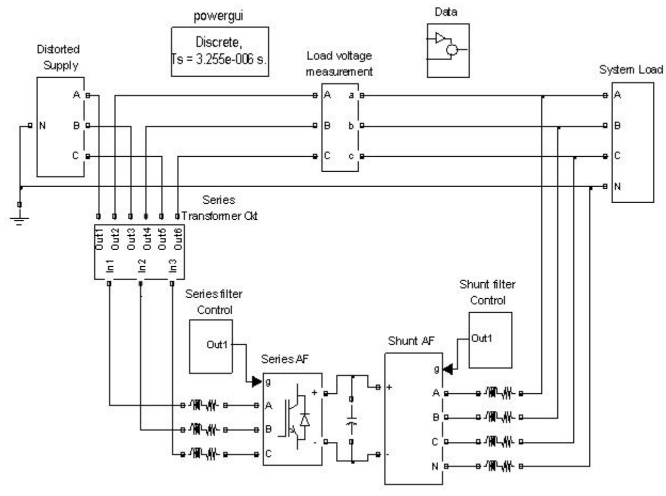

Fig. 4. MATLAB model of the UPQC system.

The computed three-phase supply reference currents are compared with the sensed supply currents and are given to a hysteresis current controller to generate the switching signals to the switches of the shunt AF which makes the supply currents follow its reference values. The source neutral current is controlled to follow a reference signal of zero magnitude by switching the fourth leg of the VSI, through the hysteresis controller. This ensures eliminating the supply neutral current. Hence the supply current contains no harmonics or reactive power components. In this control scheme, the current control is applied over the fundamental supply currents instead of the fast changing AF currents, there by reducing the computational delay and the number of required sensors. Moreover, the load or filter neutral currents are not sensed, further reducing the computational delay.

V. Results and Discussion

The developed model of a UPQC system in the MATLAB/SIMULINK environment is shown in Fig. 4. A 5th harmonic voltage source of 17.5% of the fundamental supply voltage is connected in series with the supply voltage to introduce distortion in the supply voltage. Moreover a 23% unbalance in the supply voltage is considered to verify the effectiveness of the UPQC. The combination of a 15kW nonlinear and a 6kW, 0.8pf linear load is considered as the system load. A diode rectifier drawing constant dc current is considered as the non-linear load. In order to consider the unbalance/neutral current, a 5kW single phase diode rectifier drawing constant dc current is connected between the phase ‘a’ and the neutral wire of the system. The series transformer, ripple filters and active filters are developed using the Power System Blockset toolbox.

Fig. 5 shows the dynamic performance of the proposed UPQC system with the supply voltage unbalance, the distortion and the change in the loads. Initially the sinusoidal and balanced three phase supply is feeding a nonlinear unbalance load up to 0.4sec. Due to the operation of the UPQC, the shunt AF current (i_{ca}) compensates the reactive power and the harmonics of the load, thus the source current follows the

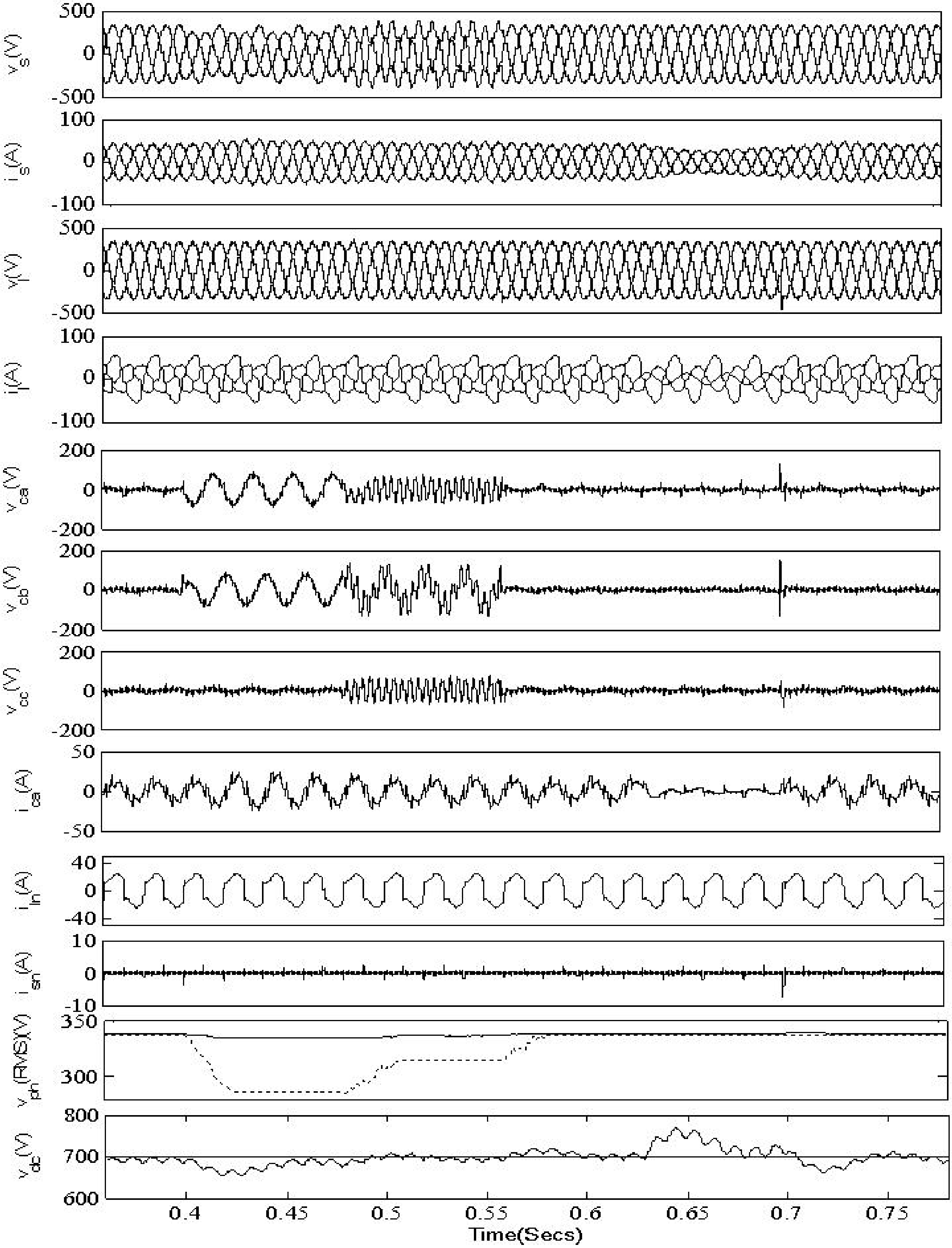

Fig. 5. Dynamic response of UPQC for unbalanced supply from t=0.4 to 0.48sec, distorted and unbalanced supply from t=0.48 to 0.56sec, and for load change at t=0.64 and 0.7sec.

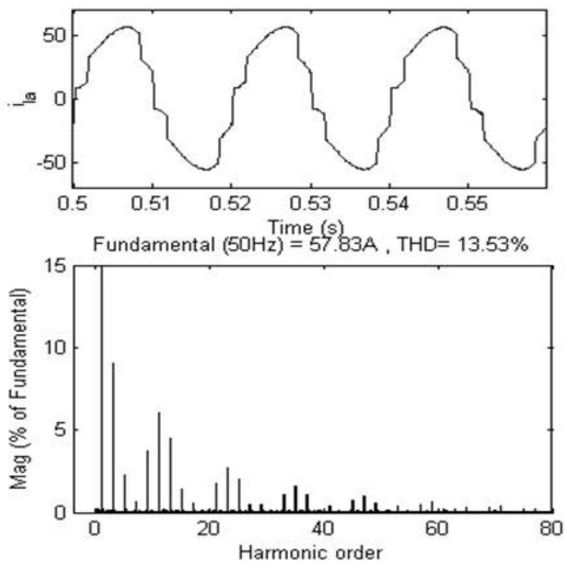

Fig. 6. Load current and its harmonic spectrum.

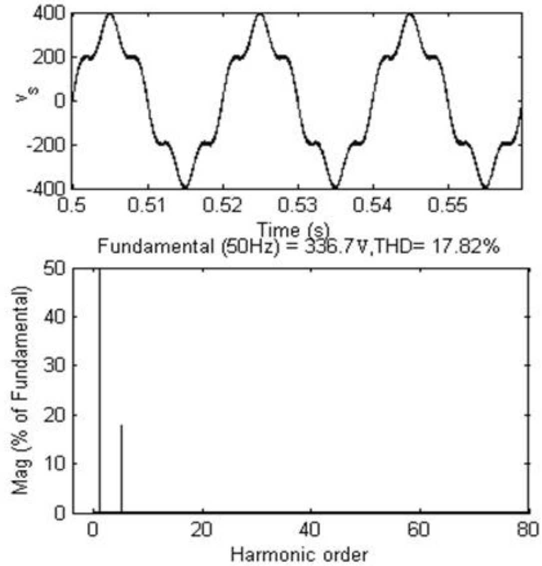

Fig. 8. Supply voltage and its harmonic spectrum.

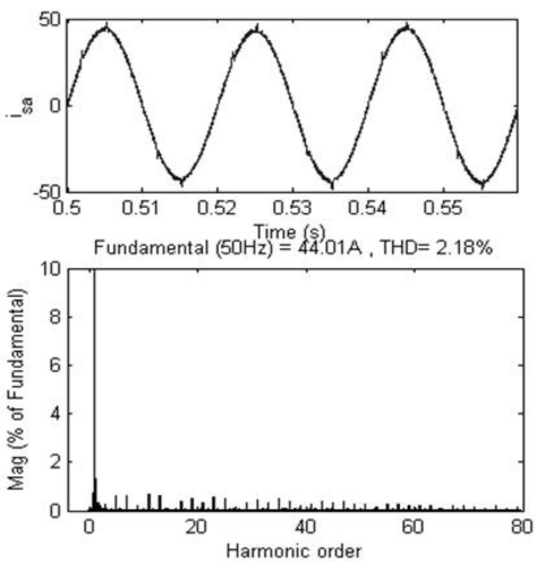

Fig. 7. Supply current and its harmonic spectrum.

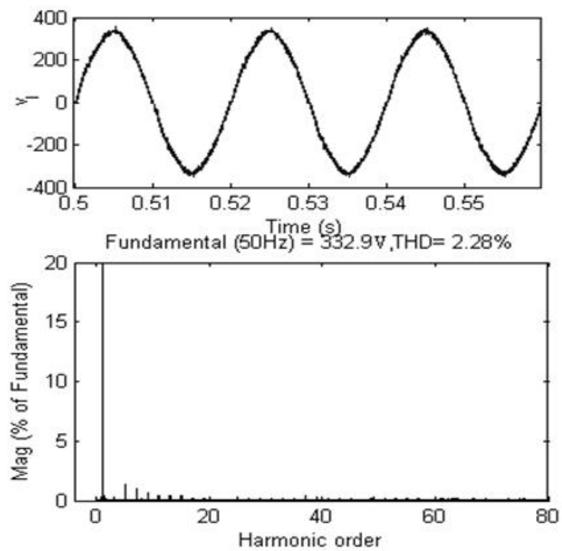

Fig. 9. PCC voltage and its harmonic spectrum.

sinusoidal reference currents. The THD of the supply current is 2.18%, while the load current THD is 13.53% as shown in Fig. 6 and Fig. 7 respectively. Moreover, the peak value of the supply current after compensation is less than the peak value of the load current, thereby increasing the loading capability of the AC mains. The RMS value of the phase 'a' supply current after compensation is reduced to 28.33A and before compensation its value is 41.44A as given in Table 1. The UPQC effectively maintains the sinusoidal supply currents and a constant DC bus voltage when the load is reduced at 0.62sec and increased at 0.7sec as shown in Fig. 5. Due to the connection of a single phase diode rectifier, a current (i_{ln}) of 18.6A flows in the load neutral conductor. This current is compensated for by the fourth leg of the shunt AF, thus reducing the supply neutral current (i_{sn}) to zero.

The supply voltage (v_s) unbalance is considered by reducing the voltage magnitude in phases 'a' and 'b' by 23% from time 0.4 to 0.48 sec as shown in Fig. 5. By a suitable series filter injection voltage (v_{ca} & v_{cb}), the load voltage (v_l) is maintained at the desired value. The amplitude of the load phase voltage (v_{ph}) without compensation is shown in dotted lines. It is maintained within $\pm$2V of its reference value after employing the UPQC, thus maintaining the reference voltage at the load terminals. In addition, a distortion of 17.82% is considered in the supply voltage along with an unbalance in phase 'b' from 0.48 to 0.56sec. The harmonic spectrum of the supply voltage is shown in Fig. 8.

In this case also, the series AF is able to maintain the desired reference voltage at the PCC with a reduced THD of 2.28% as shown in Fig. 9. A load change is considered by opening phase 'b' of the three phase diode bridge rectifier from t=0.64sec to 0.7sec. In all the dynamic conditions, the dc link voltage is effectively maintained at its reference value of 700V by the shunt AF. The effectiveness of the UPQC in reducing the supply current and load voltage harmonics for unbalanced supply and load conditions is represented in Table 1.

TABLE I
RMS VALUES AND PERCENTAGE THD OF LOAD CURRENT AND SUPPLY CURRENT AND PERCENTAGE THD OF SUPPLY VOLTAGE AND PCC VOLTAGE WITH UPQC FOR UNBALANCED SUPPLY AND LOAD CONDITIONS

	Load Current		Supply Current		Supply Voltage	PCC Voltage
	RMS (A)	THD (%)	RM (A)	THD (%)	THD (%)	THD (%)
Phase-a	41.44	13.53	28.33	2.18	17.82	2.28
Phase-b	23.64	18.55	28.43	1.99	23.19	1.24
Phase-c	23.72	17.85	28.50	2.11	17.82	2.99

VI. CONCLUSIONS

The effectiveness of the UPQC has been demonstrated in maintaining three-phase balanced sinusoidal constant load voltages, harmonic elimination, power factor correction, load balancing and supply neutral current compensation. Supply currents and load voltage harmonic levels are maintained below IEEE-519 standards under all conditions. Moreover, the supply neutral current is also eliminated, without sensing the AF or the load neutral current. The computational delay and the number of sensors are reduced by indirectly controlling the three phase supply currents.

APPENDIX

Supply voltage: 415V (L-L) RMS, 50Hz.
5th harmonic supply voltage considered to create distortion in supply voltage: 60V/ph.
Supply impedance: 0.5mH, 0.1Ω.
DC link voltage: 700V.
DC link capacitance value: 1500μF
Ripple filter parameters: 3.35mH, 0.1Ω; 6.0μF, 6.0Ω.
Dc link voltage PI controller parameters:
K_p = 0.35, K_i=2.

REFERENCES

[1] A. Ghosh and G. Ledwich, *Power Quality Enhancement using Custom Power Devices, London*, Kluwer Academic Publishers, 2002.
[2] B. Singh, A. Chandra and K. Al-Haddad, “A review of active filters for power quality improvement,” *IEEE Trans. Industrial Electronics*, Vol. 46, No. 5, pp.960-971, Oct. 1999.
[3] H. Akagi, “New trends in active filters for power conditioning,” *IEEE Trans. Industry Applications*, Vol. 32, pp.1312-1322, Nov.-Dec.96.
[4] B. Singh, V. Verma, A. Chandra and K. Al-Haddad, “Hybrid filters for power quality improvement,” *IEE Proc. Generation, Transmission and Distribution*, Vol.152, pp. 365–378, May 2005.
[5] H. Fujita and H. Akagi, “A practical approach to harmonic compensation in power systems-series connection of passive and active filters,” *IEEE Trans. Industry Applications*, Vol. 27, No.6, pp.1020-1025, Nov-Dec 1991.
[6] L. Moran, I. Pastorini, J. Dixon and R. Wallace, “Series active power filter compensates current harmonics and voltage unbalance simultaneously,” *Proc.IEE Gener., Trans. and Distrib.*, Vol. 147, No.1, pp.31–36, Jan. 2000.
[7] A. Chandra, B. Singh, B. N. Singh and K. Al-Haddad, “An improved control algorithm of shunt active filter for voltage regulation, harmonic elimination, power-factor correction, and balancing of nonlinear loads,” *IEEE Trans. Power Electronics*, Vol.15, no.3, pp.495-507, May 2000.
[8] F. Barrero, S. Martinez, F. Yeves, F. Mur, and P.M. Martinez, “Universal and reconfigurable to UPS active power filter for line conditioning,” *IEEE Trans. Power Delivery*, Vol. 18, No. 1, pp. 283 –290, Jan. 2003.
[9] A. Elnady, W. El-Khattam, and M.M.A. Salama, “Mitigation of AC arc furnace voltage flicker using the unified power quality conditioner,” *in Proc. IEEE PES Winter Meeting’02*, pp. 735-739, 2002.
[10] R. Faranda, R. and I. Valade, “UPQC compensation strategy and design aimed at reducing losses,” *in Proc. IEEE-ISIE’02*, pp. 1264 -1270, 2002.
[11] S.J. Chiang, W.J. Ai, and F.J. Lin, “Parallel operation of capacity-limited three-phase four-wire active power filters,” *IEE Proc. Electric Power Applications*, Vol.149, No. 5, pp. 329 –336, Sept. 2002.
[12] S.J. Chiang, “A three-phase four-wire power conditioner with load-dependent voltage regulation for energy saving,” *in Proc. IEEE APEC’03, 2003*, pp. 159 –164.
[13] Amit Kumar Jindal, Arindam Ghosh and Avinash Joshi, “The protection of sensitive loads from interharmonic currents using shunt/series active filters,” *J. Electric Power Syst. Res.*, Vol. 73, pp. 187-196, Feb. 2005.
[14] M. A. Hannan and A. Mohamed, “PSCAD/EMTDC simulation of unified series-shunt compensator for power quality improvement,” *IEEE Trans. Power Delivery*, Vol. 20, pp. 1650–1656, Apr. 2005.
[15] S.A.O. da Silva, P.F. Donoso-Garcia, P.C. Cortizo, P.F. Seixas, “A comparative analysis of control algorithms for three-phase line-interactive UPS systems with series-parallel active power-line conditioning using SRF method,” *in Proc. IEEE PESC’00*, pp. 1023 -1028, 2000.
[16] C. Zhan, V.K. Ramachandaramurthy, A. Arulampalam, C. Fitzer, M. Barnes and N. Jenkins, “Universal custom power conditioner (UCPC) with integrated control,” *in Proc. IEEE PES Winter Meeting’01*, pp.1039 -1044, 2001,
[17] H. Fujita and H. Akagi, “The unified power quality conditioner: The integration of series active filters and shunt active filters,” *IEEE Trans. Power Electronics*, Vol. 13, pp.315-322, Mar. 1998.
[18] A. Elnady, and M.M.A. Salama, “New functionalities of the unified power quality conditioner,” in Proc. IEEE-PES T&D Conf.’01, 2001, pp. 415 -420.
[19] A. Elnady, and M.M.A. Salama, “New functionalities of an adaptive unified power quality conditioner,” *in Proc. IEEE-PES Winter Meeting’01*, pp. 295 -300, 2001.
[20] A. Ghosh and G. Ledwich, “A unified power quality conditioner (UPQC) for simultaneous voltage and current compensation,” *Journal of Electric Power Systems Research*, Vol. 59, pp. 55-63, Aug. 2001.
[21] V. Khadkikar, P. Agarwal, A. Chandra, A. O. Barry and T. D. Nguyen, “A simple new control technique for unified power quality conditioner (UPQC),” *in Proc.11th Int.Conf. on Harmonics and Quality of Power*, pp. 289 - 293, Sep. 2004.

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