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Research Article

Control Strategy for A UPQC System to Compensate Power Quality Problems

P. Suresh[1], G. Vijayakumar[2]

[1]Department of Electrical and Electronics Engineering, Dr. Nagarathinam's College of Engineering, Namakkal, Tamil Nadu, India.
[2]Department of Electrical and Electronics Engineering, Muthayammal Engineering College, Rasipuram, Namakkal, Tamil Nadu, India.

*Corresponding author's e-mail: sureshperiyasamy@gmail.com, vijayakumargovind@yahoo.com

Abstract

This paper presents a novel control strategy for a Unified Power Quality Conditioner (UPQC) system to compensate power quality problems at the point of common coupling (PCC) in a distribution system. The proposed control strategy for shunt active filter uses a simple mathematical concept which reduces the complexity in design. Simulation study shows that an UPQC with proposed control algorithm effectively compensates current harmonics, unbalance and reactive power. The performance of UPQC is verified for a system with voltage distortions, sag /swell using MATLAB/SIMULINK. Based on the simulation results obtained, harmonic and power quality analysis has been done.

Keywords: Power quality; Series active filter; Shunt active filter; Unified Power Quality Conditioner.

Introduction

In the present day scenario, current and voltage based power quality problems have been on the increase due to the extensive use of power electronic controllers and sensitive equipment in the commercial and industrial areas. The alarming rate of increase in controllers using power electronic devices in such industries result in power quality disturbances in the distribution networks. High precision process industries and critical loads such as computers, microprocessor, and medical equipment require uninterrupted and regulated power supply of rated magnitude and frequency. The power quality problems have adverse effect on the industries in terms of equipment failure, data loss, and financial problems and so on [1]. So standards such as IEEE 519-1992 have been developed to maintain the power quality within acceptable limits [2]. A number of mitigation techniques have evolved over the time to maintain the power quality within the standards.

The mitigation techniques include passive filters, active filters, hybrid filters and custom power devices [3-6]. The mitigation of power quality problems with traditional passive filters using passive components provide only fixed compensation. Custom power devices like DVR, STATCOM and UPQC provide high quality power to the customers on demand [7]. The custom power devices overcome power quality disturbances such as voltage sag, swell, transients, voltage and current harmonics, and also provide a solution to reactive power burden. DVR provides a solution to the voltage quality problems while the STATCOM mitigates all the current quality problems [8]. As an optimum solution, UPQC is used to mitigate multiple power quality disturbances of voltage and current simultaneously [9].

The Section 2 of the paper explains the extraction of cosϕ using the proposed algorithm. The section 3 discusses the simulation model on which the proposed algorithm is tested and simulation results verifies the performance of UPQC under different operating conditions. A detailed harmonic and power quality analysis for thyristor converter fed non-linear load at different firing angles is also discussed in this section. Section 4 summarizes the conclusion.

Research methodology

UPQC is a combined operation of series and shunt active power filter with a common dc link capacitor to compensate multiple power quality problems. The shunt active filter provides compensation for the harmonic and reactive components of load current. The series inverter mitigates for voltage harmonics and unbalance,

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sag/swell conditions in the voltage at PCC. The performance of UPQC depends on the control algorithm used to generate reference currents and voltages [10].

The control algorithms of series and shunt active filter in UPQC generate reference signals to provide switching pulses for the PWM inverters. Different control algorithms are available for the control of shunt and series active filter of UPQC such as power balance theory, PI controller based algorithm, Instantaneous symmetrical component theory, synchronous reference frame theory, unit vector template generation, etc [11-15].

In this paper, a control algorithm is proposed for shunt active filter which uses only simple mathematical concepts thereby, simplifying the control circuit design. In this method, the shunt active filter has the ability to maintain the dc link voltage constant and compensates for any unbalance in the load current in addition to compensating for harmonic currents and reactive power. The control of series inverter provides a fast response to the voltage disturbances and makes the voltage at PCC sinusoidal.

Reference current generation strategy

According to the proposed control algorithm, the reactive and harmonic components are to be supplied by the shunt active filter. The three phase distorted load currents are sensed. The distorted nonlinear load currentsconsist of fundamental and harmonics components.The novel current control strategyis based on the extraction of fundamental component of the current from the distorted load current. Figure 1 shows the proposed control strategy to extract cosϕ.

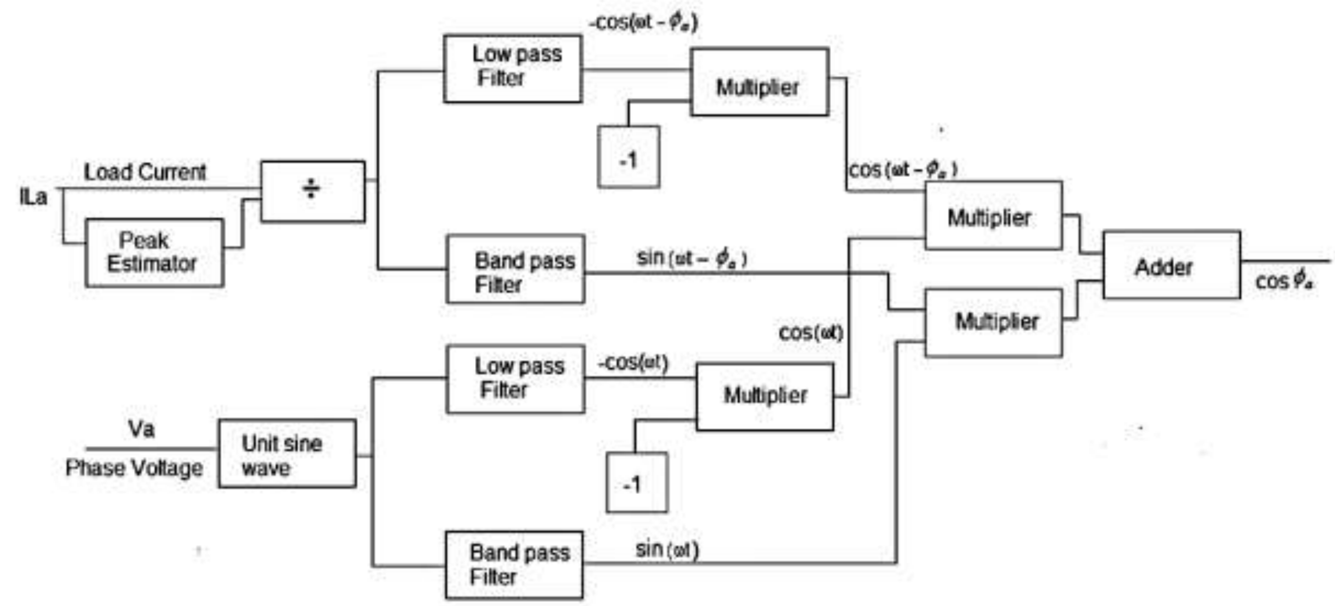

Fig. 1. Schematic of proposed control algorithm for extracting cosϕ for phase a

The real and the reactive parts of the fundamental components are separated by passing through a biquad low pass filter and a band pass filter. The fundamental current obtained from the low pass filter are having an inherent phase delay of 90 degrees and are inverted to obtain the real component of fundamental current as shown in Eq. (1).

$$\begin{aligned} i_{a(lpf)} &= I_{La}\cos(\omega t - \phi_a) \\ i_{b(lpf)} &= I_{Lb}\cos(\omega t - 120^0 - \phi_b) \\ i_{c(lpf)} &= I_{Lc}\cos(\omega t + 120^0 - \phi_c) \end{aligned} \qquad (1)$$

The reactive component is expressed as in Eq. (2).

$$\begin{aligned} i_{a(bpf)} &= I_{La}\sin(\omega t - \phi_a) \\ i_{b(bpf)} &= I_{Lb}\sin(\omega t - 120^0 - \phi_b) \\ i_{c(bpf)} &= I_{Lc}\sin(\omega t + 120^0 - \phi_c) \end{aligned} \qquad (2)$$

The load current is passed through a peak detector to obtain peak value of fundamental load current. The output of low pass filter and band pass filter of each phase are divided by magnitude of fundamental peak load currents to obtain the sine and cosine terms only as in Eq. (3)

$$i_{a(lpf)} = \cos(\omega t - \phi_a)$$
$$i_{b(lpf)} = \cos(\omega t - 120^0 - \phi_b)$$
$$i_{c(lpf)} = \cos(\omega t + 120^0 - \phi_c)$$
$$i_{a(bpf)} = \sin(\omega t - \phi_a) \quad (3)$$
$$i_{b(bpf)} = \sin(\omega t - 120^0 - \phi_b)$$
$$i_{c(bpf)} = \sin(\omega t + 120^0 - \phi_c)$$

A unit template waveform is passed through a low pass filter and bandpass filters. The outputs of low pass filter and band pass filter are as in Eq. (4)

$$U_{a(lpf)} = \cos\omega t; U_{b(lpf)} = \cos(\omega t - 120^0)$$
$$U_{c(lpf)} = \cos(\omega t + 120^0)$$
$$U_{a(bpf)} = \sin\omega t; U_{b(bpf)} = \sin(\omega t - 120^0) \quad (4)$$
$$U_{c(bpf)} = \sin(\omega t + 120^0)$$

On multiplying the filter outputs of each phase in Eq. (4) by filter outputs of each phase in Eq. (3), based on trigonometrical identities, the outputs obtained are shown in Eqs. (5) and (6)

$$U_{a(lpf)}.i_{a(lpf)} = \frac{1}{2}[\cos\phi_a + \cos(2\omega t - \phi_a)]$$
$$U_{b(lpf)}.i_{b(bpf)} = \frac{1}{2}[\cos\phi_b + \cos(2(\omega t - 120^0) - \phi_b)] \quad (5)$$
$$U_{c(lpf)}.i_{c(lpf)} = \frac{1}{2}[\cos\phi_c + \cos(2(\omega t + 120^0) - \phi_c)]$$

$$U_{a(bpf)}.i_{a(bpf)} = \frac{1}{2}[\cos\phi_a - \cos(2\omega t - \phi_a)]$$
$$U_{b(bpf)}.i_{b(bpf)} = \frac{1}{2}[\cos\phi_b - \cos(2(\omega t - 120^0) - \phi_b)] \quad (6)$$
$$U_{c(bpf)}.i_{c(bpf)} = \frac{1}{2}[\cos\phi_c - \cos(2(\omega t + 120^0) - \phi_c)]$$

The displacement power factor of each phase is obtained by adding Eqs. (5) and (6).

$$\cos\phi_a = \frac{1}{2}[\cos\phi_a + \cos(2\omega t - \phi_a)] + \frac{1}{2}[\cos\phi_a - \cos(2\omega t - \phi_a)] \quad (7)$$

To remove unbalance in the source currents, the average of the displacement power factor and load current of each phase is taken as shown in Eq. (8) to obtain the displacement power factor and peak value of reference source currents.`

$$\cos\phi = \frac{\cos\phi_a + \cos\phi_b + \cos\phi_c}{3}$$
$$I_L = \frac{I_{La} + I_{Lb} + I_{Lc}}{3} \quad (8)$$

The magnitude of the desired source current is expressed as

$$|I_{sref}| = I_L \cos\phi \quad (9)$$

The reference source currents for the three phases are obtained by multiplying the desired source current with unit template waveform of the respective phases and is given as

$$I_{a(ref)} = |I_{sref}| U_a$$
$$I_{b(ref)} = |I_{sref}| U_b$$
$$I_{c(ref)} = |I_{sref}| U_c \quad (10)$$

On subtracting the load current from the source reference current, the compensation currents are obtained. The inverter losses are also met with active power drawn from AC mains. The inverter losses are calculated as error signal obtained by comparing the actual capacitor voltage with a reference dc value. The switching pulses for the shunt filter are generated by comparing the reference and actual filter currents in a hysteresis controller.

Reference voltage generation strategy

The series inverter compensates for all the voltage disturbances such as voltage harmonics, sag, and swell at the PCC. The control algorithm of series inverter calculates the reference signals to be injected by the series inverter. The distorted terminal voltages at PCC are sensed and passed through a band pass filter to obtain the fundamental component of voltage as given as

$$v_{La(bpf)} = V_{La}\sin(\omega t)$$
$$v_{Lb(bpf)} = V_{Lb}\sin(\omega t - 120^0)$$
$$v_{Lc(bpf)} = V_{Lc}\sin(\omega t + 120^0) \quad (11)$$

Reference voltages are generated from unit sine wave template and are compared with actual load terminal voltages to generate the switching pulses to series inverter. The operation is indicated as block diagram in Fig. 2.

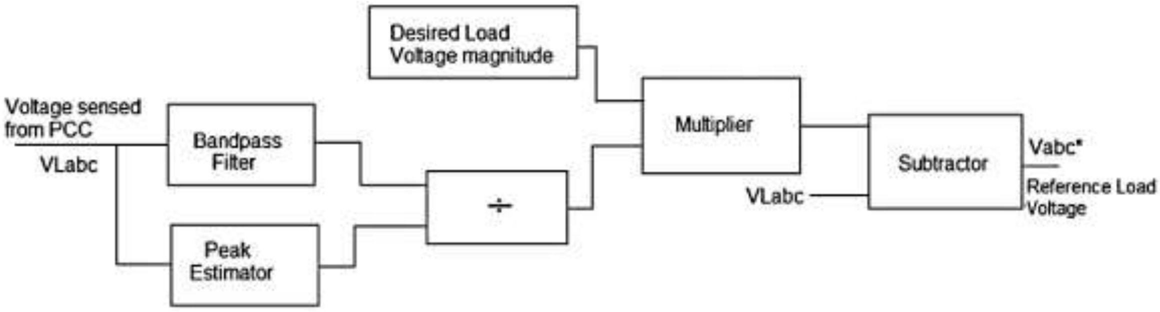

Fig. 2. Block diagram for control of series active filter

Simulation Results

This section verifies the performance of UPQC based on simulation results obtained using MATLAB/Simulink. For simulation analysis, a three- phase thyristor converter load with firing angle control is considered as the harmonic load. A 400V three-phase AC source supplying the thyristor converter feeding a RL load (R=20Ω L=80mH) is selected as the test system. The line impedance is taken as Rs=0.08Ω and Ls=1mH. The shunt active filter of UPQC is controlled by the proposed algorithm to compensate for current harmonics and reactive power. The series active filter of UPQC compensates for sag/swell and distortions in the voltage at the point of common coupling. The system is simulated under different source/load conditions and a harmonic analysis is discussed in detail. The test system with UPQC is shown in Fig. 3.

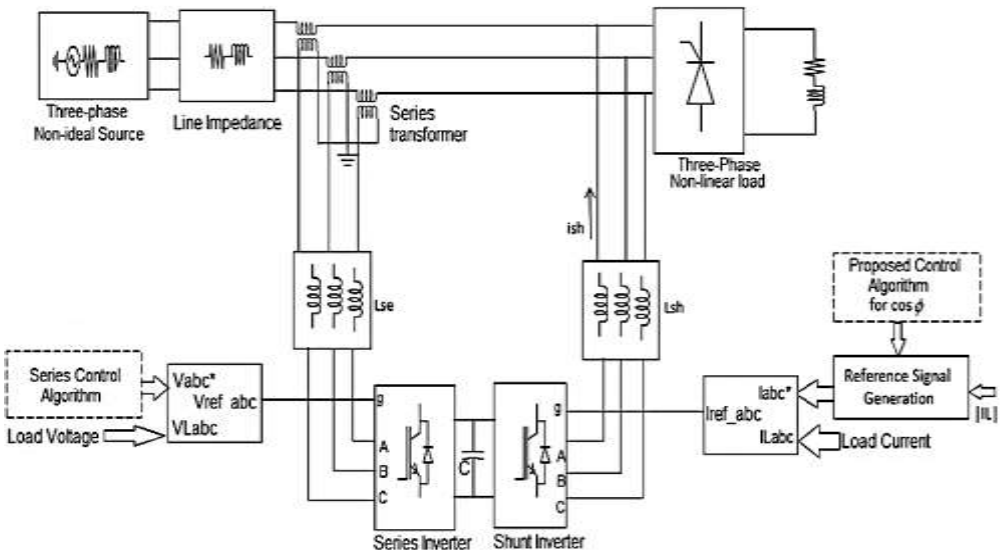

Fig. 3. Simulation model of test system with UPQC

The coupling inductor values, Lsh and Lse for shunt and series inductor values are inductor values are 4mH and 2mH respectively. The PWM inverter is operated at a switching frequency of 10kHz. Table 1 shows the RMS values of the fundamental components of voltage at PCC and source current before and after installation of UPQC. Table 1 shows the THD%, RMS values of the fundamental components of voltage at PCC and source current before and after installation of UPQC.

Distorted source voltage and balanced non-linear load

The test system is simulated with distortions introduced in the supply voltage at time 0.1s. The distorted voltage profile is as shown in Fig. 4(a). The distorted voltage contains 20% of 5th order and 5% of 7th order harmonics of the fundamental voltage. The THD of the voltage waveform is 20.62% which may affect the working of sensitive loads connected to the PCC. Also, the non-linear load connected to the system is drawing distorted current. The three phase source currents are distorted in equal amount and the THD is 26.34%. From the simulation results as shown in Fig. 4, it is found that the voltage and source current harmonics have greatly reduced with the implementation of UPQC. The results displayed in Table 1 shows that THD% of voltage at PCC and source current is within the IEEE limits. The source current is almost in phase with the source voltage, thus making the power factor unity.

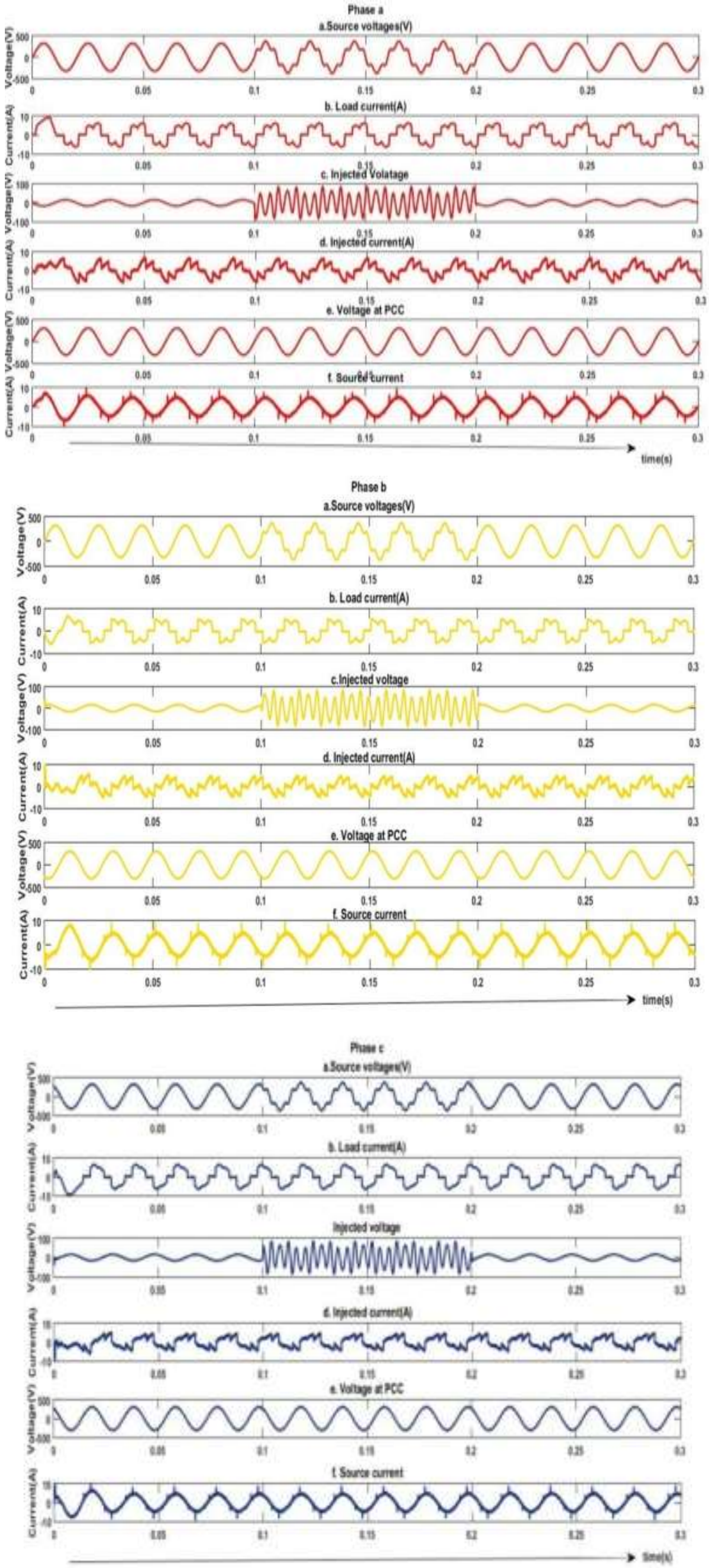

Fig. 4. Simulation results of (a) source voltage,(b) load current,(c) series injected voltage,(d) shunt injected,e) voltage with UPQC at PCC, (f) source current for a thyristor converter feeding a RL load with distorted supply and balanced load condition

Voltage sag /swell and balanced non-linear load

The simulation results of the test system shows the transient performance of UPQC under voltage sag and swell are shown in Fig. 5. Voltage Sag of 25% is introduced between 0.2s and 0.3s. Later on, at time of 0.5s, suddenly a 30% swell is introduced in the system.

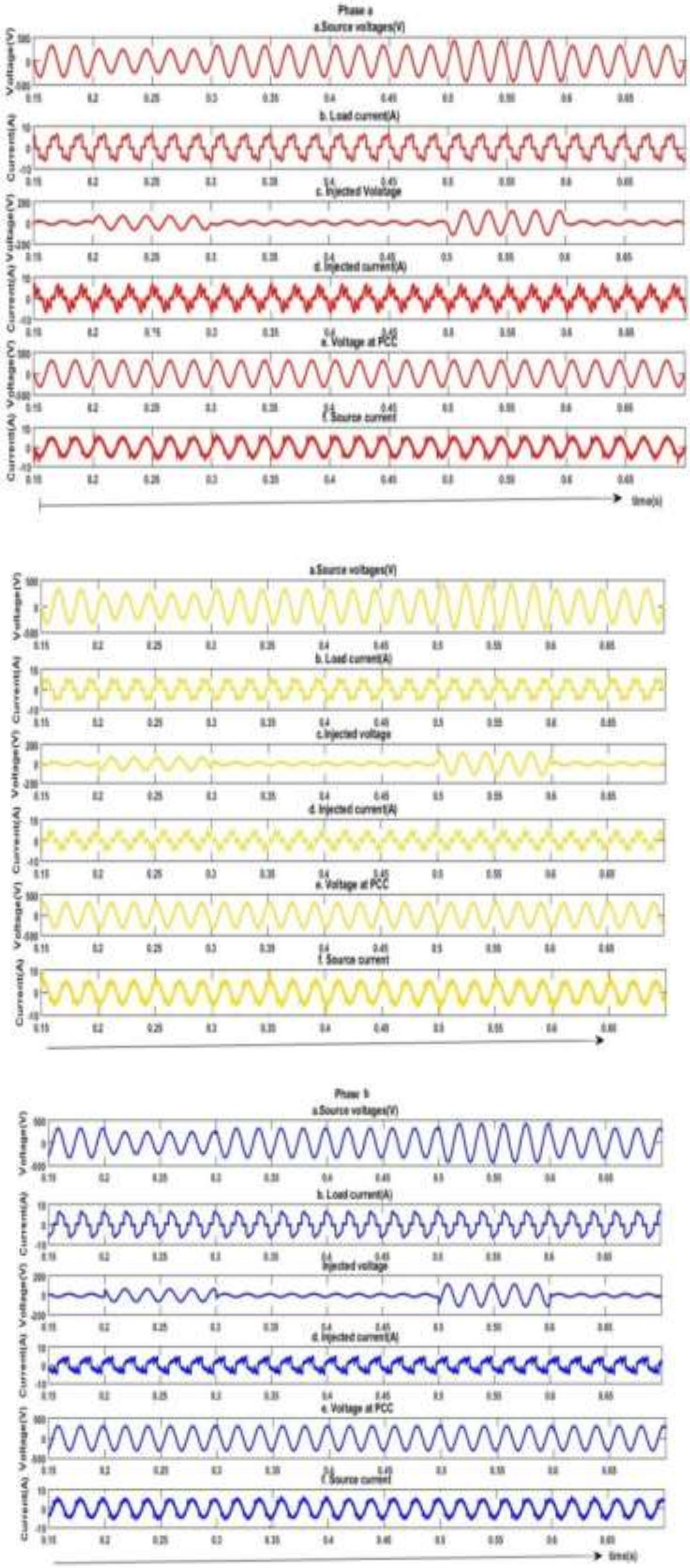

Fig. 5. Simulation results of (a) source voltage, (b) load current, (c) series injected voltage, (d) shunt injected, e) voltage with UPQC at PCC, (f) source current for a thyristor converter feeding a RL load for supply with sag/swelland unbalanced load condition

To maintain the voltage at PCC at rated value, the series transformer injects an in phase voltage. Thus the UPQC maintains the load voltage at the desired level during the sag and swell duration. An unbalance in load is introduced by connecting additional star connected loadto the three phases on the AC side of the non-linear load. The source current is same as load current without the UPQC. Table 1 compares the %THD values of the main current without and with UPQC when shunt compensation is provided by new control strategy. Here also, the proposed control algorithm made the source currents to be balanced, sinusoidal and unity power factor currents. The source current THD% has been brought down which is within the levels set by IEEE standards

Table 1. Simulation Analysis of Different Operating Condition for a 3-Phase Thyrsistor Converter Load

SOURCE/LOAD	PHASE	WITHOUT UPQC				WITH UPQC			
		V_{RMS}AT PCC(V)	THD%	I_{RMS} (A)	THD%	V_{RMS}AT PCC(V)	THD%	I_{RMS} (A)	THD%
Distorted Source Voltage and Balanced Non-linear Load	a	230.9	20.62	17.16	12.28	230.9	0.18	8.34	3.94
	b	230.9	20.62	17.16	12.28	230.9	0.18	8.35	3.36
	c	230.9	20.62	17.16	12.28	230.9	0.18	8.34	4.04
Voltage Sag and Unbalanced Non-linear Load	a	173.2	0	3.94	34.07	230.9	0	3.32	3.66
	b	173.2	0	3.36	35.72	230.9	0	3.29	3.63
	c	173.2	0	4.04	28.89	230.9	0	3.28	3.67
Voltage Swell and Unbalanced Non-linear Load	a	300.2	0	3.96	34.08	230.9	0	3.26	3.64
	b	00.2	0	3.36	35.74	230.9	0	3.23	3.63
	c	300.2	0	4.05	28.04	230.9	0	3.19	3.67

Performance of UPQC – A harmonic analysis

A detailed analysis of various power quality indices are done based on the simulation results. Tables 2 and 3 shows power quality analysis of a system under distorted voltage and load current condition. The power quality indices are compared for a thyristor converter fed RL load at different firing angles.

Table 2. Harmonic Analysis without and with UPQC for various firing angles

α, (in Degrees)	Without UPQC				With UPQC			
	V_{rms}at PCC (V)	THD %	I_{RMS} (A)	THD %	V_{rms}at PCC (V)	THD%	I_{RMS} (A)	THD %
0	230.9	20.62	17.16	15.95	230.9	0.13	16.5	0.68
30	230.9	20.62	15.0	22.70	230.9	0.20	12.6	1.53
45	230.9	20.62	12.28	26.34	230.9	0.03	8.34	2.26
60	230.9	20.62	8.71	29.64	230.9	0.18	4.45	3.85

Table 3. Power Parameters without and with UPQC for various firing angles

α (in Degrees)	*P* (kW)	*Q* (kVAR)	*S* (kVA)	*D* (kVAD)	Disp. Power factor	Distortion power factor	Power factor
	Without UPQC						
0	10.57	5.43	12.29	3.13	0.889	0.967	0.859
30	7.97	6.66	10.87	3.20	0.767	0.955	0.732
45	5.46	6.51	8.98	2.90	0.642	0.947	0.607
60	2.81	5.33	6.42	2.21	0.466	0.939	0.437
	With UPQC						
0	11.43	0	11.41	0	0.999	0.999	0.998
30	8.73	0	8.72	0	0.999	0.999	0.998
45	5.77	0	5.77	0	1	0.999	0.999
60	3.08	0	3.08	0	1	0.999	0.999

The current drawn from the source have only fundamental component and is reduced as firing angle increases. The shunt active filter of UPQC compensates for the reactive power and distortions effectively at all load conditions. The series active filter of UPQC compensates for voltage distortions at PCC. The power factor becomes almost unity with UPQC, THD% of voltage and source current are within the permissible IEEE limits at all firing angles. During the various operations of the system at all firing angles, the distortion power has reduced to zero, the displacement and distortion power factor has become close to unity. Thus, an overall improvement in all the parameters is seen as a result of the implementation of UPQC.

Conclusions

A novel control algorithm for shunt active filter of UPQC based on simple mathematical concepts is proposed in this paper. The new control algorithm is verified to generate balanced reference current in distorted as well as unbalanced condition. From the MATLAB/Simulink based simulation studies, the UPQC is verified to operate satisfactorily by simultaneously compensating voltage and current disturbances in different operating conditions. The detailed analysis on the power quality indices shows that the UPQC improves the THD, makes the power factor unity and compensates the reactive power.

Conflicts of Interest

Authors declare no conflict of interest.

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