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Improved control method under distorted and unbalanced load conditions using generalized UPQC system

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***Abstract*— Power quality has become an important factor in power systems, for consumer and household appliances with proliferation of various electric and electronic equipment and computer systems. The main causes of a poor power quality are harmonic currents, poor power factor, supply-voltage variations, etc. A technique of achieving both active current distortion compensation, power factor correction and also mitigating the supply-voltage variation at the load side, is compensated by unique device of UPQC presented in this paper and this paper presents a modified synchronous-reference frame (SRF)-based control method to Shunt active filter and instantaneous PQ (IPQ) theory based control technique for series active filter to compensate power-quality (PQ) problems through a three-phase four-wire unified PQ conditioner (UPQC) under unbalanced and distorted load conditions. The proposed UPQC system can improve the power quality at the point of common coupling on power distribution systems under unbalanced and distorted load conditions. The simulation results based on Matlab/Simulink are discussed in detail in this paper.**

***Keywords*-Active power filter (APF), harmonics, modified phase locked loop (MPLL), power quality (PQ), synchronous reference frame (SRF), unified power-quality (PQ) conditioner (UPQC).**

I. INTRODUCTION

The unified power quality conditioner (UPQC) is a custom power device, which mitigates voltage and current-related PQ issues in the power distribution systems. In this paper, a UPQC topology for applications with non-stiff source is proposed. The proposed topology enables UPQC to have a reduced dc-link voltage without compromising its compensation capability. This proposed topology also helps to match the dc-link voltage requirement of the shunt and series active filters of the UPQC. The topology uses a capacitor in series with the interfacing inductor of the shunt active filter, and the system neutral is connected to the negative terminal of the dc-link voltage to avoid the requirement of the fourth leg in the voltage source inverter (VSI) of the shunt active filter.

The average switching frequency of the switches in the VSI also reduces; consequently the switching losses in the inverters reduce. The reported topologies of 3P-4W UPQC use active compensation of source neutral current, while the uses of passive elements for the mitigation of source neutral current are advantageous over the active compensation due to ruggedness and less complexity of control. Hence, in this paper a star-delta supported 3P- 4W UPQC is proposed for the mitigation of different PQ problems. The delta connected secondary of a star delta transformer provides a circulating path to the zero sequence current (I_0) in case of unbalanced load and hence the supply neutral current is reduced to zero. Moreover, star-delta supported 3P-4W UPQC may be realized using readily available three-leg VSIs. The deregulated power market, adherence to different power quality standards laid down by different agencies has become a figure of merit for the utilities. On the other hand three-phase four-wire distribution systems are facing severe PQ problems. Some of these are high reactive power burden, voltage and current harmonics, poor power-factor, voltage sag, swells and voltage dip etc. Different devices such as rectifiers, inverters, adjustable speed drives, computer power supplies, furnaces and traction drives lead to non-linear current waveforms and hence degrade the quality of power. The quality degradation leads to low power-factor, low efficiency, overheating of transformers and so on . In addition to this, the load on a 3P-4W distribution system hardly found balanced. Because of this there is an excessive neutral current of fundamental and as well harmonic frequencies in the neutral conductor . For the mitigation of neutral current along with other power quality compensations, different topologies of UPQC reported in literature are three-leg VSI with split capacitor , three-single phase VSI four-leg VSI , current source inverter etc. Out of these proposed topologies, the four-leg VSI topology is most popular, but has the disadvantages of greater number of semiconductor switches, complexity of control, etc. the UPQC, the DC-link voltage requirement for the shunt and series active filters is not the same. Thus, it is challenging task to have a common DC-link of appropriate rating in order to achieve satisfactory shunt and series compensation. The shunt active filter requires higher DC link voltage when compared to the series active filter for proper compensation. In order to have a proper compensation for both series and shunt active filter, the researchers are left with no choice rather than to select common DC-link voltage based on shunt active filter requirement.

This will result in over rating of the series active filter as it requires less DC-link voltage compared to shunt active filter. Due to this criterion, in literature, a higher DC-link voltage based on the UPQC topology has been suggested. With the high value of DC-link capacitor, the Voltage Source Inverters (VSIs) become bulky and the switches used in the VSI also need to be rated for higher value of voltage and current. This in turn increases the entire cost and size of the VSI. To reduce the DC-link voltage storage capacity, few attempts were made in literature. In a hybrid filter has been discussed for motor drive applications.

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II. UPQC

A Unified Power Quality Conditioner (UPQC) is a device that is similar in construction to a Unified Power Flow Conditioner (UPFC). The UPQC, just as in a UPFC, employs two voltage source inverters (VSIs) that connected to a D. C. energy storage capacitor. One of these two VSIs is connected in series with A. C. line while the other is connected in shunt with the A. C. system.

- A UPQC that combines the operations of a Distribution Static Compensator (DSTATCOM) and Dynamic Voltage Regulator (DVR) together.
- One of the serious problems in electrical systems is the increasing number of electronic components of devices that are used by industry as well as residences. These devices, which need high-quality energy to work properly, at the same time, are the most responsible ones for injections of harmonics in the distribution system. Therefore, devices that soften this drawback have been developed. One of them is the unified power quality conditioner (UPQC),
- It consists of a shunt active filter together with a series-active filter. This combination allows a simultaneous compensation of the load currents and the supply voltages, so that compensated current drawn from the network and the compensated supply voltage delivered to the load are sinusoidal, balanced and minimized. The series- and shunt-active filters are connected in a back-to-back configuration, in which the shunt converter is responsible for regulating the common DC-link voltage.
- A UPQC is employed in a power transmission system to perform shunt and series compensation at the same time. A power distribution system may contain unbalance, distortion and even d.c. components. Therefore a UPQC operate, better than a UPFC, with all these aspects in order to provide shunt or series compensation.
- The UPQC is a relatively new device and not much work has yet been reported on it. Sometimes it has been viewed as combination of series and shunt active filters.

The Unified Power Quality Conditioner (UPQC) is one of the best solutions to compensate both current- and voltage-related problems simultaneously. As the UPQC is a combination of series and shunt active power filters (APFs), two APFs have different functions. The series APF filter suppresses and isolates voltage-based distortions, whereas the shunt APF cancels current-based distortions. At the same time, the shunt APF compensates for the reactive current of the load and improves power factor. Many control strategies to determine the reference signals of the voltage and the current of three-phase four wire UPQC are reported in the literature. The most common are the p-q-r theory , modified single-phase p-q theory Synchronous Reference Frame (SRF) theory , symmetrical component transformation , and the Unit Vector Template technique Apart from this, the one-cycle control (without reference calculation) is also used for the control of three-phase, four-wire UPQC. For the mitigation of neutral current, along with other power quality compensation, in the supply currents, different topologies of three-phase four-wire UPQC are reported in the literature. Some of these are three-leg VSI with a split capacitor , three-single phase Voltage Source Inverter (VSI) , four-leg VSI , and Current Source Inverter. As the UPQC is a combination of series and shunt APFs, six single-phase, VSI-based UPQCs require 24 semiconductor devices; hence, they are not attractive. The three-leg VSI with a split capacitor has difficulty in maintaining equal DC voltages of two series-connected capacitors. As such, a four-leg VSI-based UPQC is a better choice in terms of the number of switches, complexity, cost, and so on. In the current paper, the shunt APF of the three-phase, four-wire UPQC is realized using a four-leg VSI and a three-leg VSI is used for series APF.

III. CONTROL STRATEGY OF UPQC

The proposed control strategy aims to generate reference signals for both shunt and series APFs of the UPQC. The proposed control technique is capable of successfully extracting most of the load current and source voltage distortions. The series APF is controlled to eliminate the supply voltage harmonics; whereas the shunt APF is controlled to alleviate the supply current from the harmonics, negative sequence current, reactive power, and load balancing.

Active filter have been designed, improved, and commercialized in past three decades. They are applicable to compensate current-based distortions such as current harmonics, reactive power and neutral current. They are also used for voltage-based distortion such as voltage harmonics, voltage flickers, voltage sags and swells and voltage imbalances.

They are two categories of active filter such as single-phase and three-phase. Three-phase active filters may be with or without neutral connection and single phase active filters are used to compensate power quality problems caused by single-phase loads such as DC power supplies. Three-phase active filters are used for high power nonlinear loads such as adjustable speed drive (ASD) and AC to DC converters. Based on topologies, they are two kinds of active filter such as current source and voltage source active filters. Current source active filters (CSAF) employ an inductor as the DC energy storage device as shows in Fig. 1. In voltage source active filter (VSAF), a capacitor acts as the storage element as shows in Fig. 2. Between these two topologies, VSAF are inexpensive, lighter, and easier to control compare to CSAF. There are types of connection that can be used for active filter such as shunt active filter, series active filter, parallel active filter, and hybrid active filter.

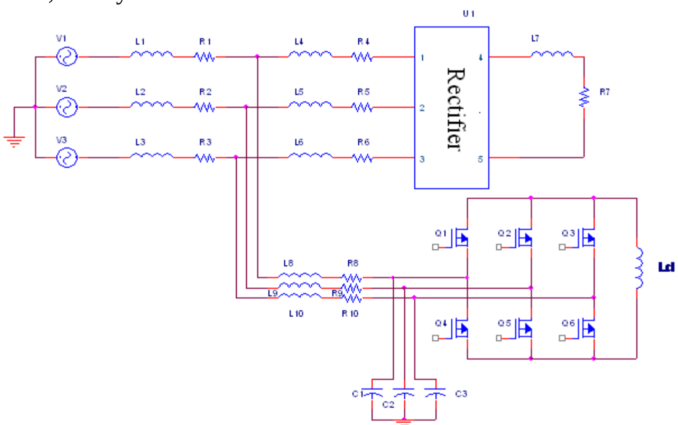

Fig.1 A typical three-phase current source active filter (CSAF)

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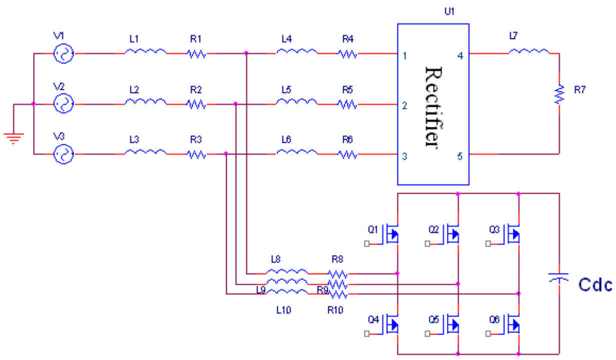

Fig.2 A typical three-phase voltage source active filter (VSAF)

SHUNT APF

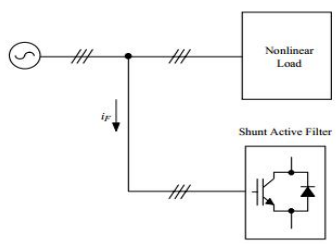

Fig.3 Basic diagram for shunt active power filter stand-alone

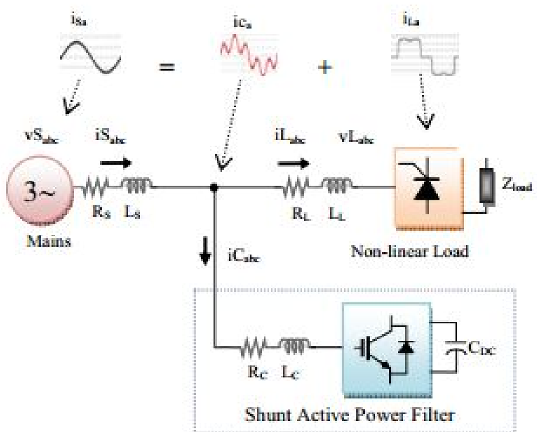

Fig.4. SAPF block diagram

Harmonic current pollution of three-phase electrical power systems is becoming a serious problem due to the wide use of nonlinear loads, such as diode or thyristor rectifiers and a vast variety of power electronics based appliances. Traditionally, passive LC filters have been used to eliminate the current harmonics and to improve the power factor. However, passive LC filters are bulky, load dependent and inflexible. They can also cause resonance problems to the system. In order to solve these problems, APFs have been reported and considered as a possible solution for reducing current harmonics and improving the power factor. Fig. 3.19 shows the basic compensation principle of the three phase shunt APF. It is designed to be connected in parallel with the nonlinear load to detect its harmonic and reactive current and to inject into the system a compensating current. In the conventional p-q theory based control approach for the shunt APF, the compensation current references are generated based on the measurement of load currents. However, the current feedback from the SAPF output is also required and therefore, minimum six CSs are desired in a unbalanced system. In addition, the reference current calculation algorithm are simplified and easily implemented in the experimental prototype. In the reduced current measurement control algorithm, sensing only three-phase voltages, three source currents and a DC-link voltage is adequate to compute reference currents of the three phase SAPF. In this way, the overall system design becomes easier to accomplish and the total implementation cost is reduced.

IV. UPQC CONTROL ALGORITHM

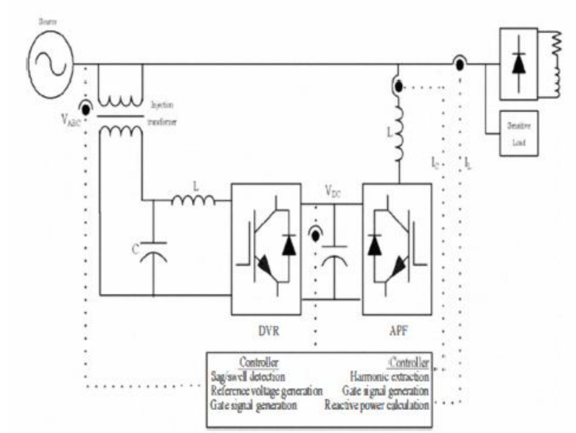

Fig. 5 control Diagram of UPQC system

The UPQC consists of two voltage source inverters Connected back to back with each of them sharing a common dc link. Fig. 5 shows the control diagram of UPQC system. One inverter work as a variable voltage source is called series APF, and the other as a variable current source in called shunt APF. The main aim of the series APF is harmonic isolation between load and Supply; it has the capability of voltage flicker/ imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer PCC. The shunt APF is used to absorb current harmonics, compensate for reactive power and negative-sequence current, and regulate the dc link voltage between both APFs.

Reference Voltage Signal Generation for Series APF

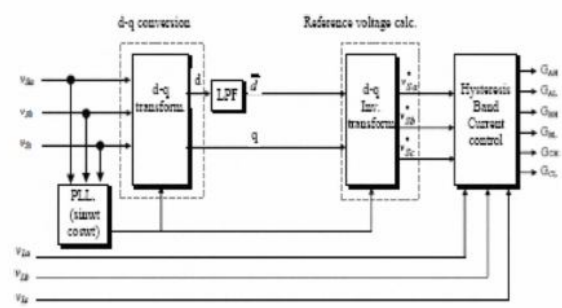

Fig.6 control diagram of Series Active Filter

The series APF control algorithm calculates the reference value to be injected by the series APF transformers, comparing the positive-sequence component with the load

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side line voltages. In equation (1), supply voltages V_{Sabc} are transformed to d-q-O coordinates

$$\begin{bmatrix} V_{s0} \\ V_{sd} \\ V_{sq} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \sin(\omega t) & \sin(\omega t - 2\frac{\pi}{3}) & \sin(\omega t + 2\frac{\pi}{3}) \\ \cos(\omega t) & \cos(\omega t - 2\frac{\pi}{3}) & \cos(\omega t + 2\frac{\pi}{3}) \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}$$

The voltage in d axes (V_{Sd}) given in (2) consists of Average and oscillating components of source voltages (V_{Sd} and ~V_{Sd}). The average voltage V_{Sd} is calculated by using second order LPF (low pass filter).

$$V_{sd} = \bar{V}_{sd} + \tilde{V}_{sd}$$

The load side reference voltages are calculated as given in equation (3). The switching signals are assessed by comparing reference voltages and the load voltages (V_{Labc}) via sinusoidal PWM controller.

$$\begin{bmatrix} V^*_{La} \\ V^*_{Lb} \\ V^*_{Lc} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin(\omega t - 2\frac{\pi}{3}) & \cos(\omega t - 2\frac{\pi}{3}) & 1 \\ \sin(\omega t + 2\frac{\pi}{3}) & \cos(\omega t + 2\frac{\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} V_{sd} \\ 0 \\ 0 \end{bmatrix}$$

The three-phase load reference voltages are compared with load line voltages and errors are then processed by sinusoidal PWM controller to generate the required switching signals for series APF switches.

Reference Current Signal Generation for Shunt APF

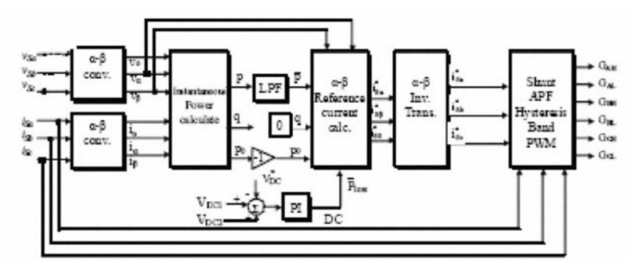

Fig.7 control diagram of Shunt Active Filter

The above figure shows the control diagram of shunt active filter. The shunt active filter compensates the current harmonics and reactive power generated by the nonlinear load. The instantaneous active power (p-q) theory is used to control of shunt APF in real time. In this theory, the instantaneous three-phase currents and voltages are transformed to a-p-O coordinates as shown in below equation

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix}$$

The source side instantaneous real and imaginary power components are calculated by using source currents and phase-neutral voltages. The instantaneous real and imaginary powers include both oscillating and average components as shown. Average components of p and q consist of positive sequence components and of source current. The oscillating components and of p and q include harmonic and negative sequence components of source currents. In order to reduce neutral current, p 0 is calculated by using average and oscillating components of imaginary power and oscillating component of the real power; as given in if both harmonic and reactive power compensation is required. $i_{s\alpha}^*$, $i_{s\beta}^*$, i_{s0}^* are the reference currents of shunt APF in a-p-O coordinates. These currents are transformed to three-phase system.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

$$P_0 = V_0 * i_0 \quad ; \quad p = \bar{p} + \tilde{p}$$

$$\begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} + p_0 + \bar{p}_{loss} \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{s0} \\ i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix}$$

The reference currents are calculated in order to compensate neutral, harmonic and reactive currents in the load. These reference source current signals are then compared with sensed three-phase source currents, and the errors are processed by hysteresis band PWM controller to generate the required switching signals for the shunt APF Switches.

V. RESULTS

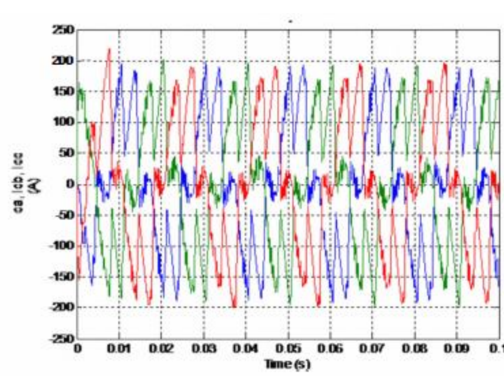

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Fig.8 Three phase compensating current

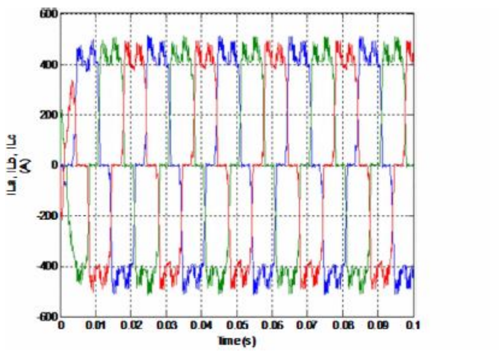

Fig. 9 Three phase load current

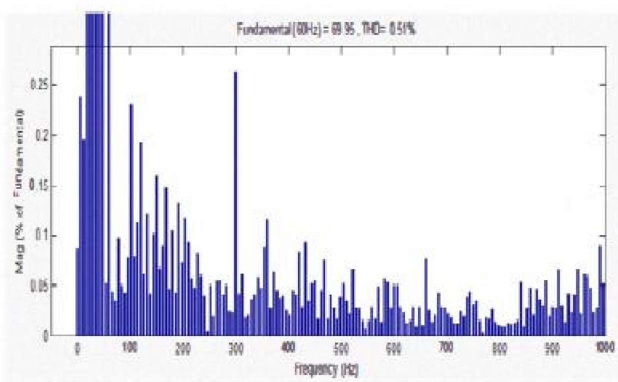

Fig. 10 THD of the source current

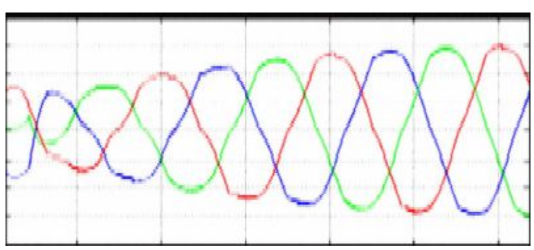

Fig. 11 Three phase source current before Compensation

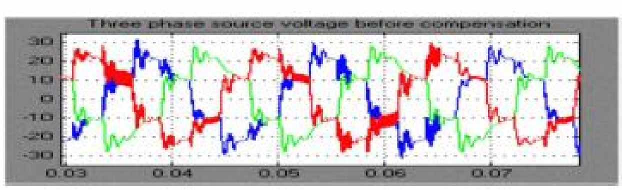

Fig. 12 Three phase source voltage before compensation

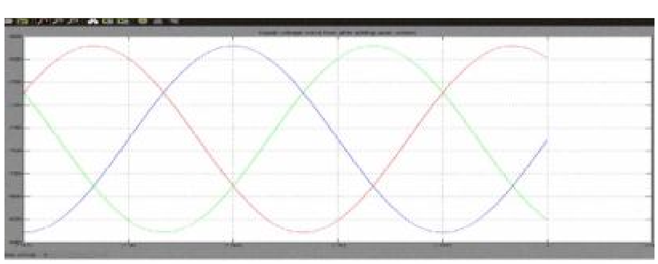

Fig. 13 Supply voltage after adding UPQC system

Fig. 14 .Supply current after adding UPQC system

VI. CONCLUSION

The proposed control strategy use only minimum measurement like loads and mains voltage measurements for series APF based on the modified PLL with synchronous reference frame theory. The instantaneous reactive power theory is used for shunt APF control algorithm by measuring mains voltage, currents and capacitor voltage. But the conventional methods require measurements of the load, source and filter voltages and currents. The simulation results show that, when unbalanced and Nonlinear load current or unbalanced and distorted mains voltage conditions, the above control algorithms eliminate the impact of distortion and unbalance of load current on the power line, making the power factor unity. Meanwhile, the Series APF isolates the loads voltages and source voltage, the shunt APF provides three-phase balanced and rated currents for the loads.

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