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Design and Simulation of UPQC by Synchronous Reference Frame Theory Considering Loading of Series and Shunt Inverters

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Abstract: In this study, Unified Power Quality Conditioner (UPQC) is designed and simulated by synchronous reference frame theory. The proposed system is comprised of series and shunt inverters which can compensate the sag, swell and unbalance voltage, harmonics and also the reactive power. PI controller is used to stabilize DC link voltage and balance the active power between the shunt and series inverters. The capacity of series and shunt inverters is calculated through loading calculations of these inverters applying phasor diagram to increase the design accuracy. The results of simulation in MATLAB/SIMULINK software show that the system compensates current and voltage distortion correctly.

Key words: Active power filter, power quality, unified power quality conditioner, synchronous reference frame theory, inverter loading

INTRODUCTION

One of the electrical system adapter structures is back to back inverter. According to the controlling structure, back to back inverters might have different operations in compensation. For example, they can operate as shunt and series active filters to simultaneously compensate the load current, harmonics and voltage oscillations. This is called unified power quality conditioner (Akagi *et al.*, 1984; Aredes and Watanabe, 1995).

The duty of UPQC is decreasing the disturbances which effect the operation of the sensitive load. UPQC is able to compensate the swell, sag and unbalanced voltage, current and voltage harmonics and reactive power, through shunt and series voltage source inverters. Voltage source inverter has to generate sinusoidal voltage with the frequency, amplitude and the phase determined by the control system. As shown in Fig. 1, in order to clear the switching oscillation, a passive filter is applied at the output of each inverter. At the output of shunt inverter, high pass second order LC or first order RC filter is allocated and at the output of series inverter, low pass second order LC or resonance filter is allocated.

UPQC controller provides the compensation voltage (v^*_t) through the UPQC series inverter and provides conditioning current (i^*_t) through the shunt inverter by instantaneous sampling of load current and source voltage and current. Resulted reference current are compared with shunt inverter output current

(i_{ra} , i_{rb} and i_{rc}), in a hysteresis type PWM current controller. Then, the required controlling pulses are generated. Required compensation current is generated by inverter applying these signals to the inverter. Resulted reference voltages are compared with a triangular wave form and required controlling pulses are generated to be applied to series voltage source inverter switches.

In this study, a suitable controlling method has been selected to simulation and the rating of series and shunt inverters has been calculated through loading calculations of these inverters applying phasor diagram to increase the design accuracy.

MATERIALS AND METHODS

This study is consisted of three main parts: selecting the controlling method, controller design, series and shunt inverters loading. The controller design section has three subsections: shunt inverter control, DC link control and series inverter control. Theses parts have discussed and finally the simulation results have been introduced.

Selecting the controlling method: UPQC is vastly studied by several researches as an infinite method for power quality conditioning (Akagi and Fujita, 1995; Peng *et al.*, 1998; Fujita and Akagi, 1998; Chen *et al.*, 2000; Hu and Chen, 2000). Different UPQC controlling methods can be classified in three following classes: time-domain controlling method, frequency-domain controlling method and new techniques. Furrier method is one of the methods can be named as frequency-domain methods. The

methods such as P-Q theory, instantaneous reactive power, algorithms based on the synchronous d-q reference frame, instantaneous power balance method, balanced energy method, synchronous detection algorithm, direct detection algorithm and notch filter based controlling method are some can be mentioned for time-domain methods. Dead beat control, space vector modulation and wavelet conversion are some of the new techniques (Mariun *et al.*, 2004).

Three general standards considered to select the controlling method are load characteristics, required accuracy and application facility. All methods end in to similar results when the reference signal is calculated under balanced and sinusoidal conditions where each ends in to different results under unbalanced and non sinusoidal conditions. Dead beat controlling method presents the best operation among the others but more expense should be paid for its calculations.

Among the introduced methods the reference frame methods seem to be more appropriate. The fact is that it needs sinusoidal and balanced voltage and is not sensitive to voltage distortions and is relatively simple. In result, the response time of the control system shortens. So it's prior to utilize the synchronous reference frame theory in UPQC controlling circuit.

CONTROLLER DESIGN

The control system of proposed system is shown in Fig. 1 which is comprised of three following parts:

- Shunt inverter control
- DC link voltage control
- Series inverter control

Shunt inverter control: Figure 2 shows the UPQC shunt inverter controlling block diagram using synchronous reference frame theory where the sensitive load currents are i_{ia} , i_{ib} and i_{ic} .

The measured currents of load are transferred into dq0 frame using sinusoidal functions through dq0 synchronous reference frame conversion. The sinusoidal functions are obtained through the grid voltage using PLL. Here, the currents are divided into AC and DC components.

$$i_{id} = \bar{i}_d + \tilde{i}_d, \quad i_{iq} = \bar{i}_q + \tilde{i}_q \quad (1)$$

The active part of current is i_d and i_q is the reactive one. AC and DC elements can be derived by a low pass filter. Controlling algorithm corrects the system's power

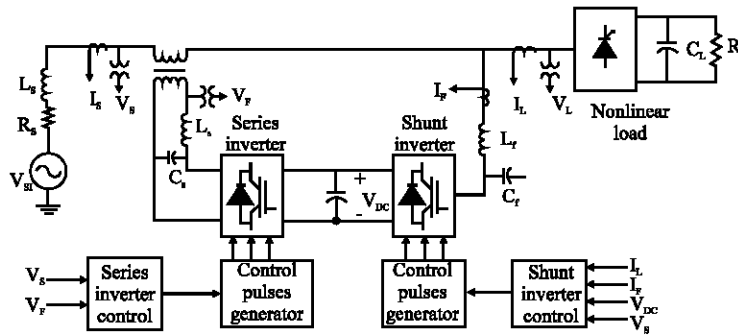


Fig. 1: Overall configuration and control of proposed system

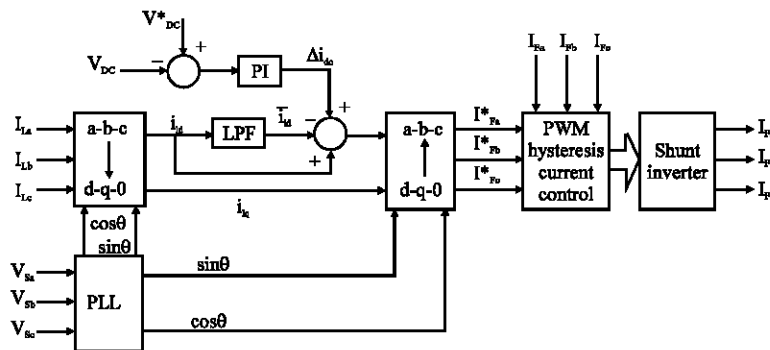


Fig. 2: Shunt inverter control block diagram

factor and compensates the all current harmonic components by generating the reference current as Eq. 2:

$$i_{rd}^* = \bar{i}_{id}, i_{rq}^* = i_{iq} \quad (2)$$

Here, system's current are:

$$i_{sd} = \bar{i}_{iq}, i_{sq} = 0 \quad (3)$$

Switching losses and the power received from the DC link capacitors through the series inverter can decrease the average value of DC bus voltage. Other distortions such as unbalance conditions and sudden changes in load current can result in oscillations in DC bus voltage.

In order to track the error between the measured and desired capacitor voltage values, a PI controller is applied. The resulted controlling signal is applied to current control system in shunt voltage source inverter which stabilizes the DC capacitor voltage by receiving required power from the grid. Δi_{dc} , the output of PI controller is added to the q component of reference current and so the reference current would be as Eq. 4:

$$i_{rd}^* = \bar{i}_{id} + \Delta i_{dc}, i_{rq}^* = i_{iq} \quad (4)$$

As shown in Fig. 4, the reference current is transferred into abc frame through reverse conversion of synchronous reference frame. Resulted reference current (i_{ra}^* , i_{rb}^* and i_{rc}^*) are compared with the output current of shunt inverter (i_{sa} , i_{sb} and i_{sc}) in PWM. Now, the current controller and the required controlling pulses are generated. Required compensation current is generated by inverter applying these signals to shunt inverter's power switch gates.

DC link voltage control: A PI controller is used to track the error exists between the measured and desired values of capacitor voltage in order to control the DC link voltage as Fig. 3 (Ghosh and Ledwich, 2001).

This signal is applied to current control system in shunt voltage source inverter in a way that the DC capacitor voltage is stabilized by receiving the required active power from the grid. Correct regulation of proportional controller's parameter plays an important role in DC voltage control system's response. Too much increase in proportional gain leads to instability in control system and too much reduction decreases the responding speed of control system. Integral gain of controller corrects the steady state error of the voltage control system.

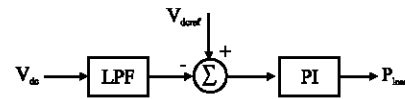


Fig. 3: DC link voltage control block diagram

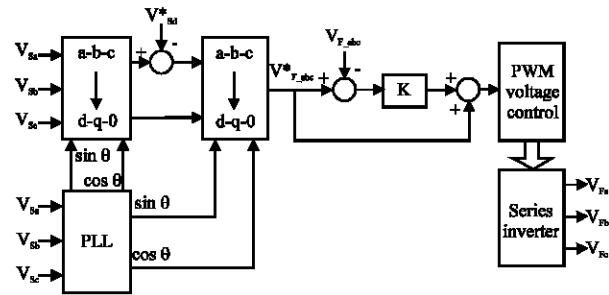


Fig. 4: Series inverter control block diagram

If this gain value is selected large, the resulted error in steady state is corrected faster and too much increase in its value ends in overshoot in system response.

Series inverter control: Sinusoidal voltage controlling strategy of load is generally proposed to control the series part of UPQC. Here, the series part of UPQC is controlled in a way that it compensates the whole voltage distortions and maintains load voltage 3-phase balanced sinusoidal. In order to reach this, the synchronous reference frame theory is applied (Hu and Chen, 2000).

In this method the desired value of load phase voltage in d axis and q axis is compared with the load voltage and the result is considered as the reference signal.

The controlling circuit of series inverter is shown in Fig. 4. SPWM method is used to optimize the response of series inverter.

SERIES AND SHUNT INVERTERS LOADING

Generally, the injected voltage has the same phase with the source voltage when there is balanced voltage source. So, series inverter usually consumes active power. If there is (same phase) injection, UPQC is compensated with the least voltage (Basu *et al.*, 2007). Following figures explain the UPQC operation in system's main frequency.

The index 1 presents the variable related to the situation faced before the voltage drop occurrence and index 2 presents the situation faced after the voltage drop occurrence. V_L is the voltage of load and V_o is the load nominal value in pu V_s is the source voltage and I_s is the source current. I_L presents the load current which has the

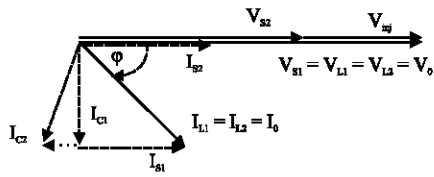


Fig. 5: Phasor diagram of shunt and series inverters loading

power factor of $\cos\phi$. I_o is the nominal value of load current in p.u and I_c is the current injected by shunt inverter.

When the voltage and current of the system have the same phases, the transferring power of series inverter is completely active because of the operation of shunt inverter (Basu *et al.*, 2007). As it is obvious in Fig. 5, shunt inverter current increases by voltage drop occurrence. The reason is the consumption of active power by series inverter through shunt inverter. When the voltage drops in grid, the series inverter should compensate voltage drop to maintain the voltage in desired value. This injected voltage and source current have the same phases. So, the series inverter just transfers the active power.

As it's obvious in Fig. 5, the shunt inverter receives active power from the grid in addition to reactive power injection, as voltage drops. This power is the one that series inverter requires to inject to the grid in order to compensate voltage drop and it is obtained from the shunt inverter through the DC link.

According to the vector diagrams of Fig. 5 following term can be mentioned for each phase:

$$V_{L1} = V_{L2} = V_{S1} = V_o \text{ p.u} \quad (5)$$

For load current it can be mentioned that:

$$I_L = I_{L1} = I_{L2} = I_o \text{ p.u} \quad (6)$$

Assuming that, the UPQC has no losses it can be noted that the electrical power of load side would not change passing the UPQC and will have the same value in the source side.

$$V_S I_S = V_L I_L \cos\phi \quad (7)$$

As voltage drops V_{s2} is less than V_{s1} ($V_{s2} < V_{s1}$). If x is the voltage drop value in pu:

$$V_{s2} = (1-x)V_{s1} = V_o(1-x) \text{ p.u.} \quad (8)$$

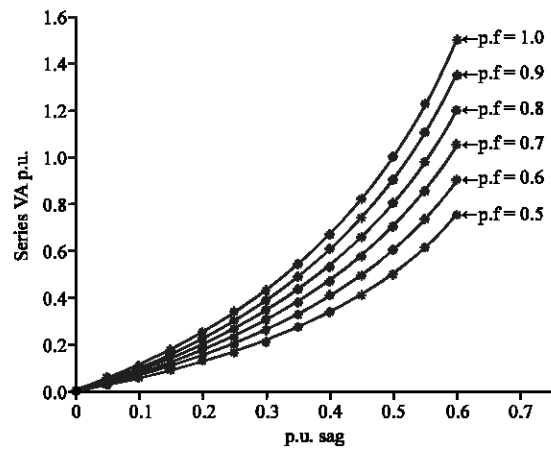


Fig. 6: Comparison of VA loading for series inverter of UPQC at different power factor and p.u voltage sag values

Following relation should be valid to have the constant active power in both load and source sides:

$$V_{s2} = (1-x)V_{s1} = V_o(1-x) \text{ p.u.} \quad (9)$$

where, I_{S2} can be expressed as follow:

$$I_{S2} = \frac{V_{S1} I_L \cos\phi}{V_{S1}(1-x)} = \frac{I_o \cos\phi}{1-x} \text{ p.u.} \quad (10)$$

So, the nominal power of series inverter ($S_{seinv.}$) is as follow:

$$S_{seinv.} = V_{inj^2 s2} = \frac{V_o I_o (x \cos\phi)}{1-x} \text{ p.u.} \quad (11)$$

The current injected by shunt inverter in p.u is:

$$I_{C2} = \sqrt{I_{L1}^2 + I_{S2}^2 - 2I_{L1}I_{S2} \cos\phi} = I_o \frac{\sqrt{(1-x)^2 + \cos^2\phi\{1-2(1-x)\}}}{1-x} \quad (12)$$

So, the nominal power of shunt inverter ($S_{shinv.}$) is:

$$S_{shinv.} = V_o I_o \frac{1}{1-x} \sqrt{(1-x)^2 + \cos^2\phi\{1-2(1-x)\}} + \frac{I_o^2 (1-x)^2 + \cos^2\phi\{1-2(1-x)\}}{(1-x)^2} Z_{shinv.} \text{ p.u.} \quad (13)$$

Adding the nominal powers of series and shunt inverters, the nominal power of UPQC is obtained.

Results shown in Fig. 6 present that the loading of series inverter is similar during low voltage drops for

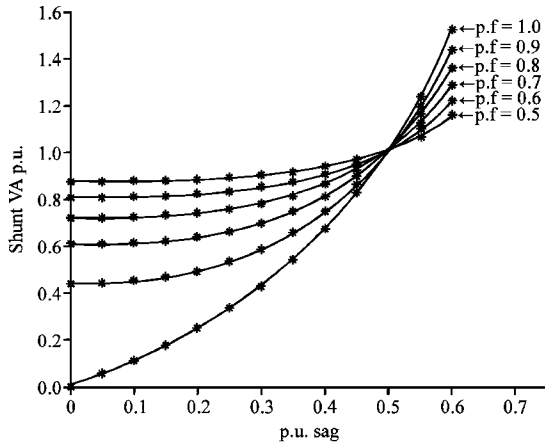


Fig. 7: Comparison of VA loading for shunt inverter of UPQC at different power factor and p.u voltage sag values

different power factors and is the function of load power factor in high voltage drops. If the power factor is high the loading ratio of series inverter is high too. Finally, the maximum loading occurs for unit power factor.

Results shown in Fig. 7 present that in shunt inverter, voltage drop value is the function of power factor and if the power factor is low, the loading is high which seems logical. This is because of the fact that if power factor is low, the shunt inverter should inject more current to compensate the power factor. For high values of voltage drop, the loading of the shunt inverter greatly increases which is because of the fact that series inverter requires more current to compensate the voltage drop. This current is provided by shunt inverter.

RESULTS AND DISCUSSION

In this study, power circuit is modeled as a 3-phase 3-wire system with a non linear load comprised of RC load which is connected to grid through 3-phase diode bridge. Circuit parameters used in simulation are shown in Table 1.

The simulated load is a RC diode nonlinear 3-phase load which imposes a non sinusoidal current to grid with more than 40% THD. Load current is shown in Fig. 8.

In Fig. 9 the source current, injected current and total harmonic distortion before and after being compensated by shunt inverter are shown. Shunt inverter is activated in 0.04 sec of operation. Immediately, the source current is corrected. The results shown in Fig. 9 present that the shunt part has been able to correct the source current appropriately. Also, the THD of load current is reduced to 5 from 40% of source current.

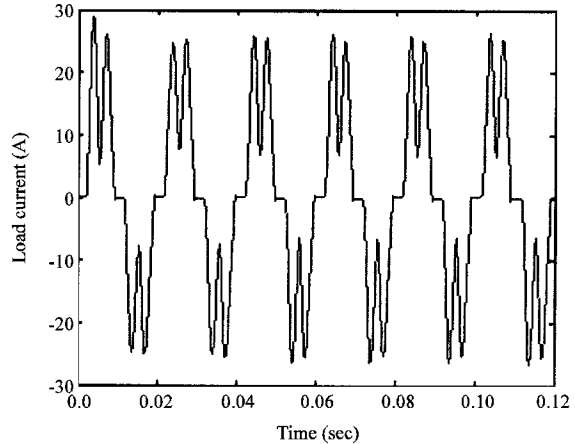


Fig. 8: Nonlinear load current (A)

Table 1: Circuit parameters

Parameters	Values
Source phase voltage (rms)	220 V/50Hz
DC link voltage	600 V
Shunt inverter rating	15 kVA
Series inverter rating	15 kVA
Shunt inverter inductance (L_s)	3 mH
Shunt inverter capacitance (C_s)	10 μ F
Switching frequency	20 kHz
Series inverter inductance (L_s)	3 mH
Series inverter capacitance (C_s)	15 μ F
Series inverter resistance (R_s)	12 μ F

Figure 10 shows the source side voltage, load side voltage and the voltage injected by the series inverter to simulate swell and sag of the voltage. As shown in Fig. 10 the voltage distortions imposed to load from the grid are properly compensated by series inverter. In this simulation, series inverter operates at 0.02 sec and voltage source faces with 100 V voltage sag. A voltage swell with 50 V voltage peak occurs in 0.08 sec. Simulation results show that the load voltage is constant during the operation of UPQC series inverter.

DC link voltage is shown in Fig. 11. In this simulation, series and shunt inverters start to operate at 0.02 sec. As it is seen, capacitor voltage is decreasing until this moment. By operating shunt inverter, the capacitor voltage increases and reaches to the reference value (600 V). At 0.04 sec of operation voltage sag with 100 V amplitude occurs in source voltage. The average value of capacitor voltage drops about 10 V occurring this voltage sag and faces with small oscillations in lower values. At 0.08 sec of operation voltage swell with about 50 V amplitude occurs at 0.08 sec of operation. The average value of capacitor increases about 15 V occurring this swell and faces with small oscillations in voltages around 600 V. Figure 11 shows the exact operation of control loop of DC link capacitor voltage. RL load with 6 kW active

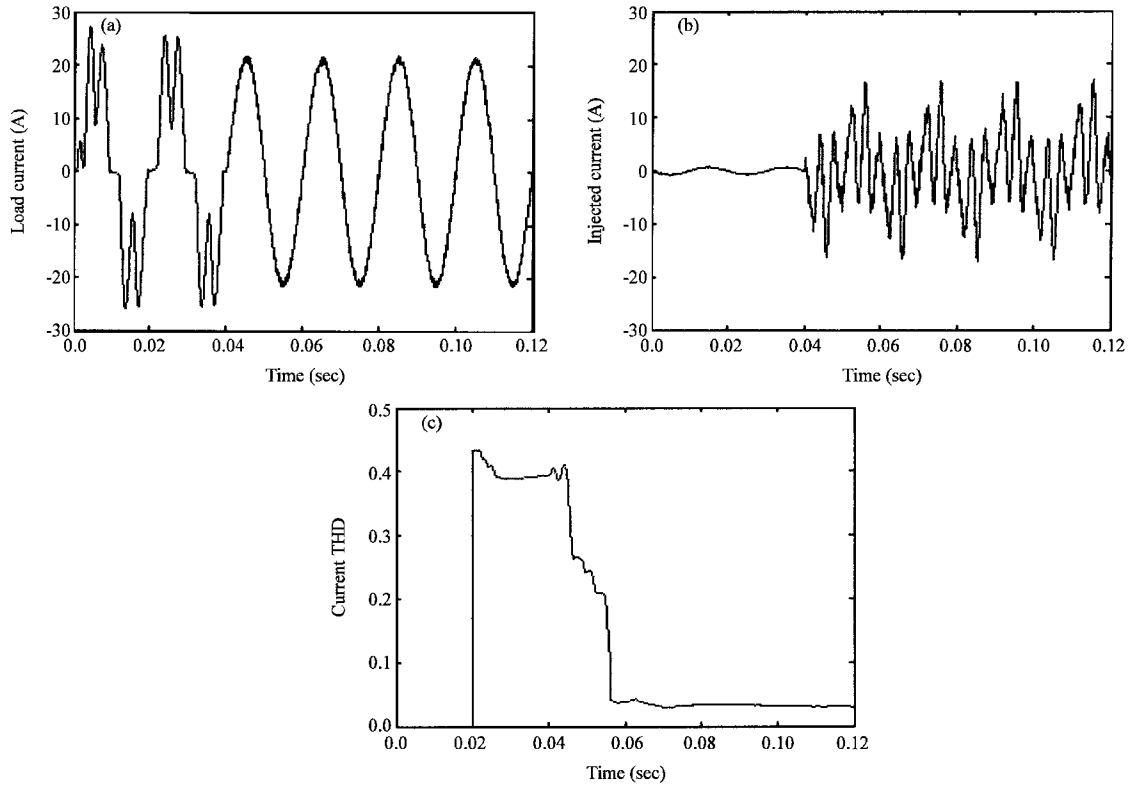


Fig. 9: (a) Source current, (b) Injected current and (c) Source current THD, before and after compensation

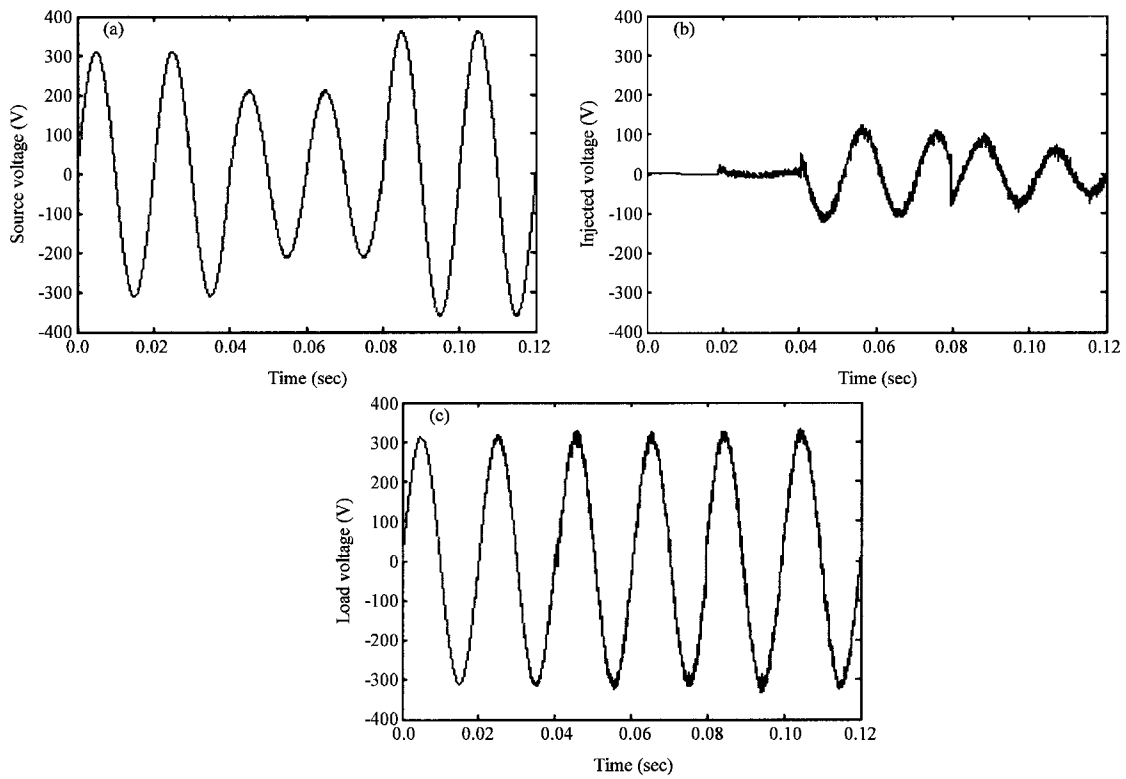


Fig. 10: (a) Source voltage, (b) Injected voltage and (c) load voltage, before and after compensation

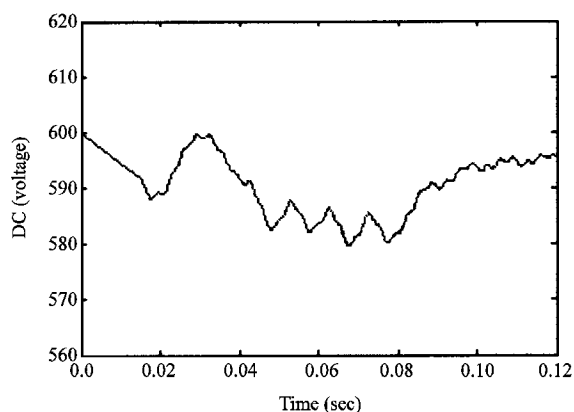


Fig. 11: DC link voltage

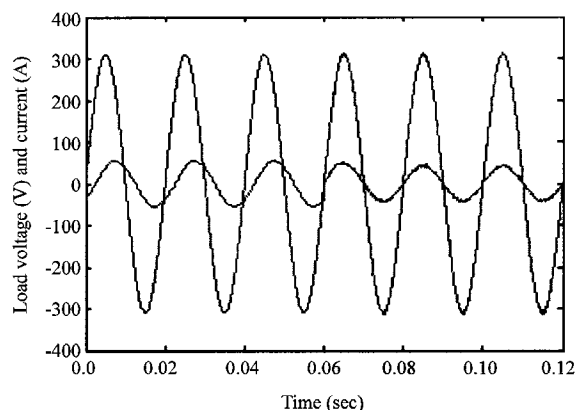


Fig. 12: Power factor correction

power and 6 kVAR reactive power is applied in simulation to study how reactive power is compensated by shunt inverter. Simulation results show that the phase difference between voltage and current is cleared by shunt inverter operation. In other words, UPQC compensates the reactive power with 0.7 power factor and so there is unit power factor in source side of system. Actually, by operating UPQC, required reactive power is provided via., UPQC.

Figure 12 shows the load current and voltage. As it is shown, load current phase leads voltage phase initially. At 0.06 sec of operation and operating shunt inverter the phase difference between voltage and current gets zero.

Comparison of this study results with related studies, indicates that the proposed system compensates voltage and current distortions accurately and the response time of the control system is relatively low and also the proposed control system is simply applicable.

CONCLUSION

In this study Unified Power Quality Conditioner (UPQC) is designed and simulated through synchronous

reference frame theory. Simulation results show the proposed system's ability in voltage distortion, reactive power and current harmonics compensation. PI controller balances the power between series and shunt inverters by stabilizing DC link voltage.

Loading of shunt and series inverters are being operated through phasor method which greatly assists the proper designation of inverters. The operation of proposed system is analyzed using MATLAB/SIMULINK software. Simulation results confirm the correct operation of the proposed system.

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