Impact Factor (SJIF): 3.632

International Journal of Advance Research in Engineering, Science & Technology

e-ISSN: 2393-9877, p-ISSN: 2394-2444

(Special Issue for ITECE 2016)

Unified Power Quality Conditioner (UPQC) : A Compensating Custom Power Device

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Abstract *— Widespread applications of power electronic based loads in industry have increased the importance and application of power quality studies. Decrease in the cost of power electronic devices , fast switching characteristics of converters and improvements in the efficiency of both power converters and energy storage components have increased the applicability of new technological solutions such as Custom Power (CP) and Flexible AC Transmission Systems (FACTS) Devices. Unified Power Quality Conditioner (UPQC, a combination of series and shunt power filters) is one of the CP devices and compensates voltage and current quality problems. UPQC has become very popular in recent years both in low voltage and medium voltage applications. In this study, an attempt has been made to model the UPQC for voltage and current compensation with the help of two different control schemes. The current harmonics as well as voltage sag and swells compensation are shown.*

Keywords— *Power Quality, Active power Filter, Modeling of UPQC.*

I. INTRODUCTION

Power Quality (PQ) has become an important issue to electricity consumers at all levels of usage. The PQ issue is defined as “Any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipment.” The development of power electronic based equipment has a significant impact on quality of electric power supply. The switch mode power supplies (SMPS), dimmers, current regulator, frequency converters, low power consumption lamps, arc welding machines, etc, are some out of the many vast applications of power electronics based devices. The operation of these loads/equipments generates harmonics and thus, pollutes the modern distribution system. The growing interest in the utilization of renewable energy resources for electric power generation is making the electric power distribution network more susceptible to power quality problems. In such conditions both electric utilities and end users of electric power are increasingly concerned about the quality of electric power [1].

Many efforts have been taken by utilities to fulfill consumer requirement, some consumers require a higher level of power quality than the level provided by modern electric networks. This implies that some measures must be taken so that higher levels of Power Quality can be obtained.

Active power filters (APF) have been proposed as efficient tools for power quality improvement. Active power filters can be classified as series or shunt according to their system configuration. The series APF generally takes care of the voltage based distortions, while shunt APF mitigates current based distortions. The combination of series and shunt active power filter is called the unified power quality compensator (UPQC). UPQC mitigates the voltage and current based distortion simultaneously as well as independently. In this paper the main focus is on UPQC.

II. UNIFIED POWER QUALITY CONDITIONER

Unified Power Quality Conditioner (UPQC) is a multifunction power conditioner that can be used to compensate various voltage disturbance of the power supply, to correct voltage fluctuation, and to prevent harmonic load current from entering the power system. It is a custom power device designed to mitigate the disturbances that affect the performance of sensitive and/or critical loads. UPQC has shunt and series compensation capabilities for (voltage and current) harmonics, reactive power, voltage disturbances (including sag, swell, flicker etc.), and power-flow control. Normally, a UPQC consists of two voltage-source inverters with a common dc link designed in single-phase, three-phase three-wire, or three phase four-wire configurations. One inverter is controlled as a variable voltage source in the series active power filter (APF). The other inverter is controlled as a variable current source in the shunt active power filter (APF). The series APF compensates for voltage supply disturbances (e.g., including harmonics, imbalances, negative and zero sequence components, sag, swell, and flickers). The shunt APF converter compensates for load current distortions (e.g., caused by harmonics, imbalances) and reactive power, and perform the dc link voltage regulation [2,3].

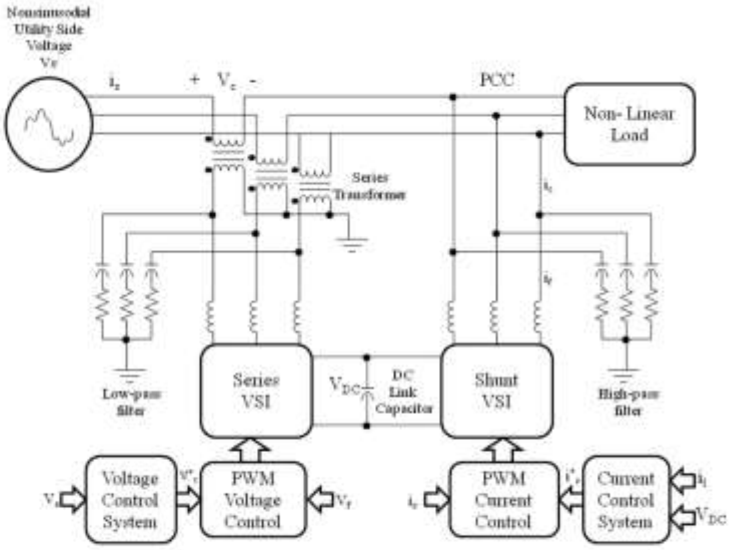

Fig. 2.1: Detailed configuration of UPQC

Fig. 2.1 shows system configuration of a three-phase UPQC. The key components of UPQC are as follows:

- **Series inverter:** It is a voltage-source inverter connected in series with AC line through a series transformer and acts as a voltage source to mitigate voltage distortions. It eliminates supply voltage flickers and imbalances from the load terminal voltage. Control of the series inverter output is performed by using pulse width modulation (PWM). Among the various PWM technique, the hysteresis band PWM is frequently used because of its ease of implementation. Also, besides fast response, the method does not need any knowledge of system parameters. In this work hysteresis band PWM is used for the control of inverters. The details of the hysteresis control technique are analyzed in the subsequent sections.
- **Shunt inverter**: It is a voltage-source inverter connected in shunt with the same AC line which acts to cancel current distortions, compensate reactive current of the load and improve the power factor of the system. It also performs the DC-link voltage regulation, resulting in a significant reduction of the DC capacitor rating. The output current of shunt converter is adjusted using a dynamic hysteresis band by controlling the status of the semiconductor switches such that output current follows the reference signal and remains in a predetermined hysteresis band.
- **DC link capacitor:** the two VSIs are connected back to back with each other through this capacitor. The voltage across this capacitor provides the self-supporting DC voltage for proper operation of both the inverters. With proper control, the DC link voltage acts as a source of active as well as reactive power and thus eliminates the need of external DC source like battery.
- **Low-pass filter** is used to attenuate high-frequency components of the voltages at the output of the series converter that are generated by high-frequency switching of VSI.
- **High-pass filter** is installed at the output of shunt converter to absorb ripples produced due to current switching[2].
- **Series transformer:** The necessary voltage generated by the series inverter to maintain a pure sinusoidal load voltage and at the desired value is injected in to the line through these series transformers. A suitable turns ratio is often considered to reduce the current flowing through the series inverter.

III. UPQC CONTROL STRATEGY

3.1 Control of Series APF

A simple algorithm is developed to control the series filters. The control strategy is based on the extraction of Unit Vector Templates (UVT) from the distorted supply[4]. 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 load Terminal (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 APF is shown in Fig. 3.1. Since the supply voltage is unbalanced and or distorted, a phase locked loop (PLL) is used to achieve synchronization with the supply [5]. Three phase distorted/unbalanced supply

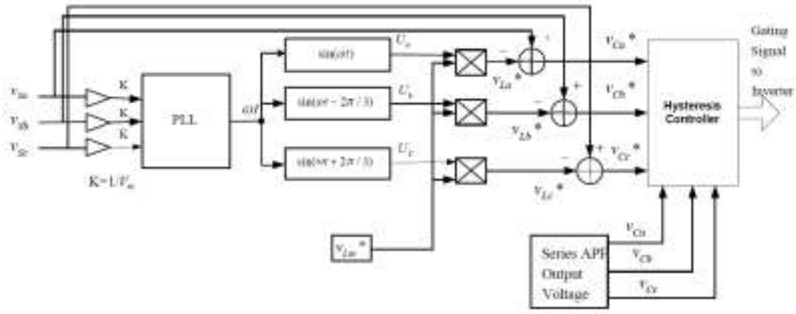

Fig. 3.1: Control scheme of series APF

voltages are sensed and given to the PLL which generates angle (ωt) varying between 0 and 2*π radian, synchronized on zero crossings of the fundamental (positive-sequence) of phase A. The sensed supply voltage is multiplied with a suitable value of gain before being given as an input to the PLL. The angle (ωt) output from the PLL is used to compute the supply in phase, 120^0 displaced three unit vectors (Ua , Ub ,Uc) using equation (3.1).

$$U_a=\sin\omega t\,;\ U_b=\sin(\omega t-120^0)\,;\ U_c=\sin(\omega t+120^0) \tag{3.1}$$

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 load voltages as from equation (3.2).

$$\begin{bmatrix} v_{La}^* \\ v_{Lb}^* \\ v_{Lc}^* \end{bmatrix} = [v_{Lm}^*]\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \tag{3.2}$$

In order to have distortion less load voltage, the load voltage must be equal to the computed reference voltages from equation (3.2).To generate injected voltages, supply voltage signals are compared with these reference signals and these signals are then given to the hysteresis controller along with the sensed series APF output voltages. The output of the hysteresis controller controls the six switches of the VSI of the series APF. The hysteresis controller generates the switching signals such that the voltage at the load 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.

3.2 Control of Shunt APF

Instantaneous reactive power theory, also known as p-q theory [3], is utilized to generate the reference signals for the shunt APF. Fig. 3.2 describes the control strategy of the shunt APF. According to this theory the three phase voltages and currents are measured instantaneously and by the use of equation (3.3) and (3.4) are converted to α-β-0 coordinates [3].

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix} \tag{3.3}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{3.4}$$

Equation (3.5) shows calculation of instantaneous real power (p), imaginary power (q) and zero sequence power (p_0) components drawn by the load

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{3.5}$$

$$p = \bar{p} + \tilde{p} \quad ; \quad q = \bar{q} + \tilde{q} \tag{3.6}$$

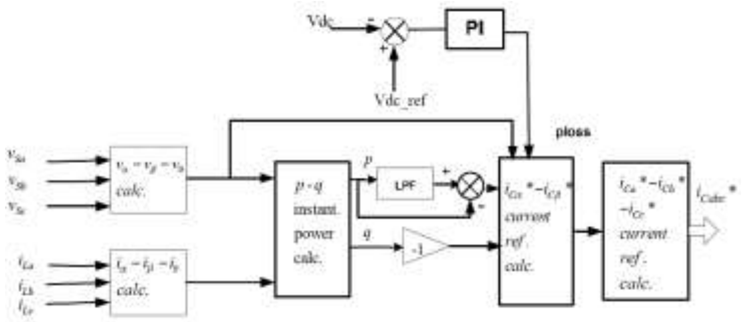

Fig. 3.2: Control block diagram of shunt APF

In general, each one of the active and reactive instantaneous power contains a direct component and an alternating component. The direct component of each presents the power of the fundamentals of current and voltage. The alternating term is the power of the harmonics of currents and voltages. For harmonic and reactive power compensation the direct and alternating components of the imaginary power and harmonic component of the real power is selected as compensation power references and compensation current reference is calculated using equation (3.7). There will be no zero sequence power (p_0) as the load is balanced.

$$\begin{bmatrix} i^*_{C\alpha} \\ i^*_{C\beta} \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} -\tilde{p}+\bar{p}_{loss} \\ -\tilde{q} \end{bmatrix} \tag{3.7}$$

The Loss signal is used as an average real power and is obtained from the voltage regulator. DC-link voltage regulator is designed to give both good compensation and an excellent transient response. The actual DC-link capacitor voltage is compared by a reference value and the error is processed in a proportional-integral (PI) controller, which is employed for the voltage control loop since it acts in order to minimize the steady-state error of the DC-link voltage to zero [6].
Equation (3.7) represents the required compensating current references ($i^*_{C\alpha}$, $i^*_{C\beta}$) in α-β coordinates to match the power demand of the load. Equation (3.8) is used to obtain the compensating phase currents (i^*_{Ca} , i^*_{Cb} , i^*_{Cc}) in the a–b–c axis in terms of the compensating currents in the α-β coordinates:

$$\begin{bmatrix} i_{Ca}^* \\ i_{Cb}^* \\ i_{Cb}^* \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{C\alpha}^* \\ i_{C\beta}^* \end{bmatrix} \tag{3.8}$$

3.3 Hysteresis controller

The basic implementation of hysteresis control is based on deriving the switching signals from the comparison of the voltage or current error with a fixed tolerance band [2]. This control is based on the comparison of the actual phase voltage or current with the tolerance band around the reference voltage or current associated with that phase.

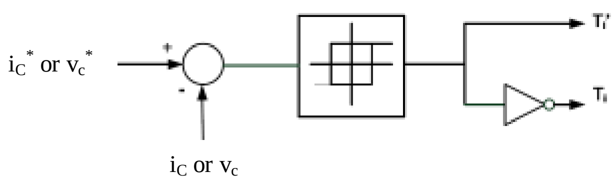

Fig. 3.3: Simplified model for fixed hysteresis-band voltage or current control

IV. SIMULATION RESULTS OF UPQC

In this section the simulation analysis of UPQC is described. In this two filters are used i.e. shunt active power filter and series active power filter. The developed model of UPQC in MATLAB/SIMULINK environment is shown in Fig. 4.1. The shunt active power filter compensates current disturbances and also maintains the dc link voltage to reference value. While series active power filter compensates voltage related problems for maintaining required load voltage.

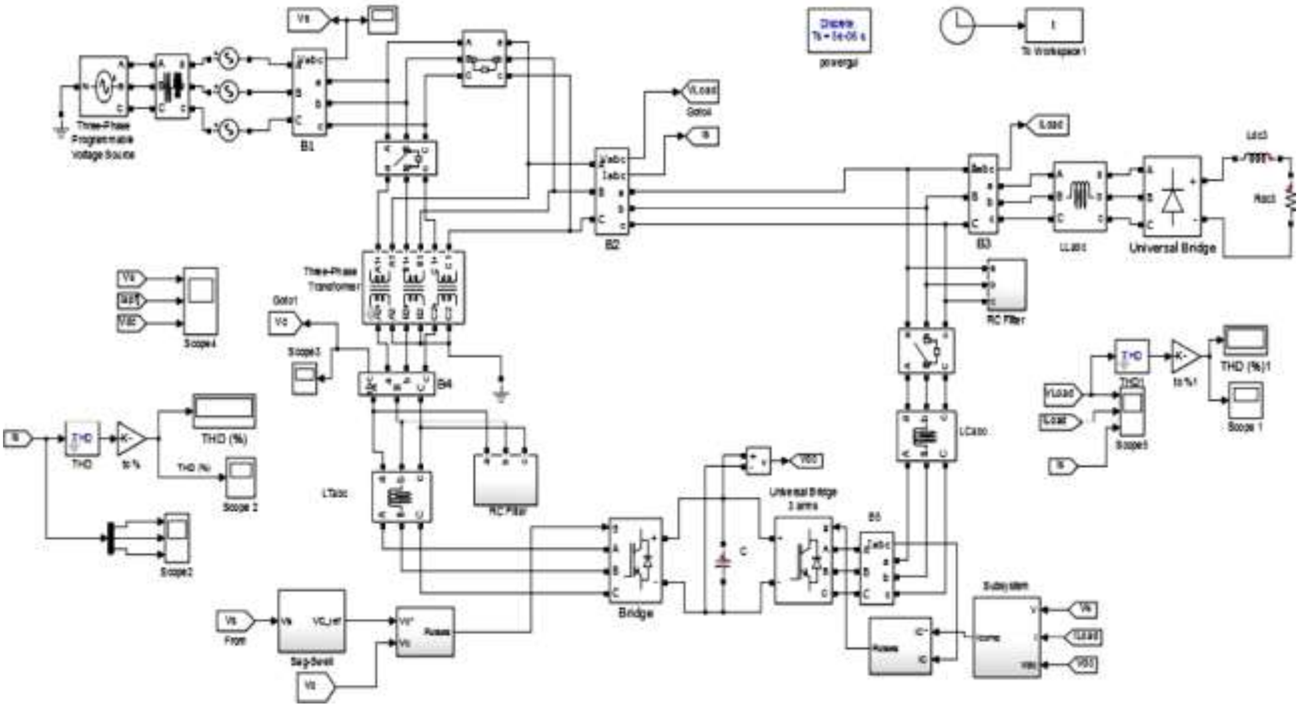

Fig. 4.1: Simulink model of UPQC

Fig. 4.2 shows the simulation results for UPQC working as current harmonics compensator. In this case, the terminal voltages are assumed pure sinusoidal, the UPQC is put into the operation at instant 0.1sec. Within the very short time period shunt APF maintains the dc link voltage at constant level as shown in Fig. 4.2 (d). In addition to this the shunt APF also helps in compensating the current harmonics generated by the non-linear load. The load current is shown in Fig. 4.2(a). The shunt APF injects a current (Fig. 4.2(c)) in such a manner that the source current becomes sinusoidal. At the same time, the shunt APF compensates for the reactive current of the load and improves power factor. The improved source current profile is shown in Fig. 4.2(b).

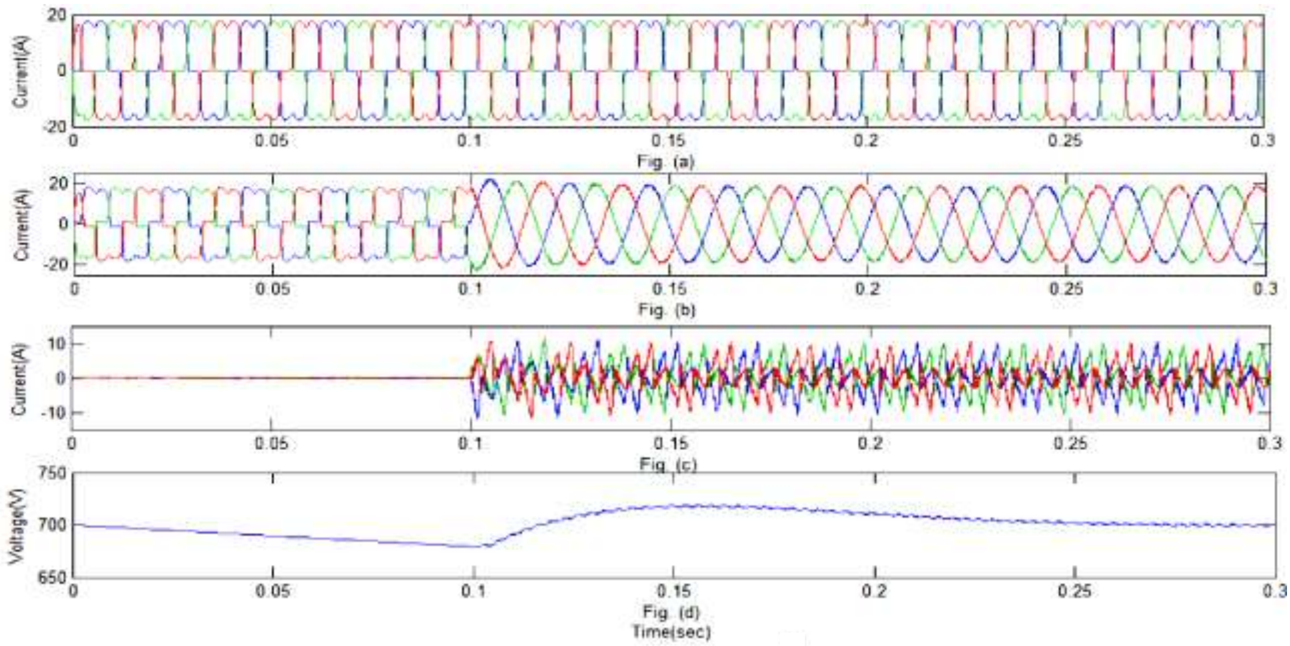

Fig. 4.2: Simulated results of UPQC (a) Load current (b) Source current (c) Shunt APF current (d) capacitor voltage

Fig 4.3(a-b) shows the harmonic spectrum of load current and source current for phase-aafter shunt APF is put in operation. THD of load current is 25.84%. With shunt APF in operation there is a significant reduction in THD at source side current, from 25.84 % to 2.61 %. Shunt inverter is able to reduce the current harmonics entering into the source side.

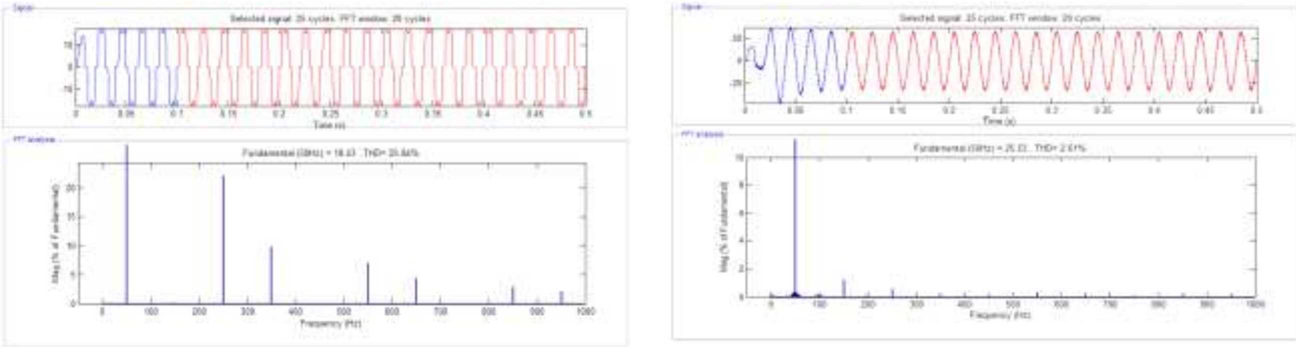

Fig.4.3: THD (a) distorted source current (b) compensated source current

The simulation result of voltage sag compensation is shown in Fig. 4.4. The UPQC is put in operation at 0.05 sec. A sag (20%) is introduced to the supply voltage at 0.1sec. and lasts till the instant 0.25 sec. as shown in Fig. 4.4(a). During the voltage sag condition, the series APF injects an in-phase voltage (20%) equals to the difference between the desired load voltage and actual source voltage, as seen from Fig. 4.4(b). Thus, UPQC helps to maintain the load voltage profile (Fig. 4.4(c)) at desired level such that the sag in source voltage does not appear at the load terminals. In order to inject the in-phase voltage the UPQC requires certain amount of active power. This active power comes from the source, extracted by shunt inverter, by taking extra fundamental current component to maintain the DC link voltage at constant level.

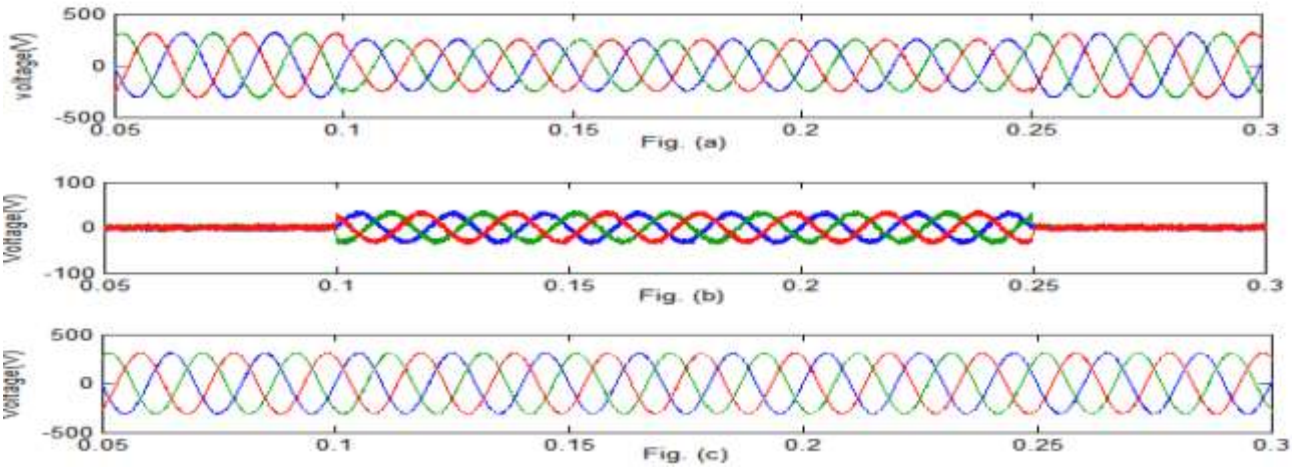

Fig. 4.4: Simulated results of UPQC (a) Source voltage (b) series injected voltage (c) Load Voltage

The simulation result of voltage swell compensation is shown in Fig. 4.5. The UPQC is put in operation at 0.05 sec. A swell (20%) is introduced to the supply voltage at 0.1sec. and lasts till the instant 0.25 sec as shown in Fig. 4.5(a). The voltage swell phenomenon is exact opposite to the voltage sag condition. Therefore, during a swell on the source side voltage, the series APF now injects out-of phase voltage (20%) equals to the difference between the desired load voltage and actual source voltage (Fig. 4.5(b)). Thus, the UPQC cancels the increased source voltage that may appear at the load side and maintains the load voltage profile (Fig. 4.5(c)) at desired level.

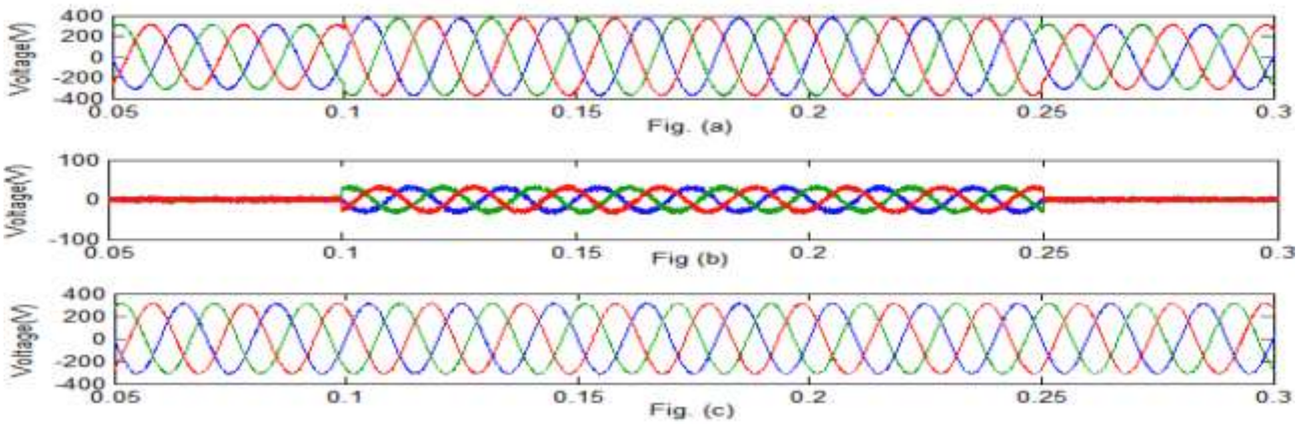

Fig. 4.5: Simulated results of UPQC (a) Source voltage (b) series injected voltage (c) Load voltage

The rise in source voltage means the utility is supplying some extra power to the load. This may damage equipments and loads due to the increase in the current drawn by them. At the same time, the rise in source voltage also causes the DC link voltage to increase. Under such condition, the shunt APF injects fundamental out-of phase current component, between instants 0.1sec. and 0.25 sec. to maintain the DC link voltage at constant level. Therefore, the source current magnitude decreases.

V. CONCLUSION

This work proposes a control scheme for UPQC based on hysteresis voltage and current controller. In this scheme the series APF and the shunt APF of the UPQC are controlled by the combination of UVT and instantaneous p-q theory. The UPQC model was developed and simulated in MATLAB/SIMULINK environment. The performance of the model has been studied under non-linear load. The performances of the models have been observed to be satisfactory for load harmonic and reactive current compensation, mitigation of voltage sag and swells. It is observed that source current 5 % , the THD limit imposed by IEEE 519-1992.

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