International Journal of Innovation Sciences and Research
Vol.6, No, 01, pp. 957-962, January 2017
Available online at
http://www.ijisr.com

RESEARCH ARTICLE

APPLICATIONS OF UPQC FOR POWER QUALITY IMPROVEMENT

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Accepted 18th December, 2016; Published Online 30th January, 2017

ABSTRACT

In this paper, different applications of a Unified Power Quality (UPQC) for the improvement in power quality is presented. In addition to the power-factor correction, load balancing and mitigation of voltage and current harmonics, it can regulate the load voltage against voltage sag/swell and voltage dip in a three-phase three-wire distribution system for different combinations of linear and non-linear loads. The synchronous reference frame (SRF) theory is used to get the reference signals for series and shunt active power filters (APFs). The reference signals for the shunt and series APF of UPQC are derived from the control algorithm and sensed signals are used in a hysteresis controller to generate switching signals for shunt and series APFs. The UPQC is realized using two voltage source inverters (VSI) connected back to back, to a common dc link capacitor. MATLAB/Simulink based simulations are obtained, which support the functionality of the UPQC.

Key words: Power Quality, UPQC, Harmonics, Load Balancing, Power Factor Correction, voltage sag, voltage swell, voltage dip, SPS Matlab/Simulink.

INTRODUCTION

The prime objective of power utility companies is to provide their consumers an uninterrupted sinusoidal voltage of onstant amplitude. In addition to this, adherence to different power quality standards laid down by different agencies (1) has become a figure of merit for the power utilities. Unfortunately, this is becoming increasingly difficult to do so, because the size and number of non-linear and poor power-factor loads such as adjustable speed drives, computer power supplies, furnaces, power converters and traction drives are finding its applications at domestic and industrial levels. These nonlinear loads draw non-linear current and degrade electric power quality. The quality degradation leads to low power-factor, low efficiency, overheating of transformers and so on (Gunther, 1995). Apart from this, the over all load on the distribution system is seldom found to be balanced. In the past, efforts have been made to mitigate these identified power quality problems using conventional passive filters. But their limitations such as, fixed compensation, resonance with the source impedance and the difficulty in tuning time dependence of filter parameters (Das, ?) have ignitedthe need of active and hybrid filters (Singh *et al*., 1999; Akagi, 1996; Singh *et al*., 2005). Under this circumstance, a new technology called custom power emerged (Arindam Ghosh, 2002; Hingorani, 1995), which is applicable to distribution systems for enhancing the reliability and quality of the power supply. Ideally. Voltage and current waveforms are in phase, power factor of load equals unity, and the reactive power consumption is zero; this situation enables the most efficient transport of active power, leading of the cheapest distribution system.

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The Unified Power Quality Conditioner (UPQC) is one of the key custom power device, which can compensate both current and voltage related problems, simultaneously (Aredes *et al*., 1998; Fujita, 1998; Han *et al*., 2006). As the UPQC is a combination of series and shunt APFs, two APFs have different functions. The series APF suppresses and isolates voltage-based distortions. The shunt APF cancels current-based distortions. At the same time, it compensates reactive current of the load and improves power factor. There are many control strategies reported in the literature to control the UPQC for power quality improvements, the most common are the instantaneous active and reactive power theory (the *p-q* theory) proposed by Akagi (1984), symmetrical component transformation (Ghosh, 2002), synchronous reference frame(SRF) theory (Pengcheng *et al*., 2003), and unit template technique (UTT) technique (Khadkikar *et al*., 2004) etc. In this work SRF theory is used for the control of UPQC. The UPQC configuration and the load under consideration load are discussed in Section II. The control algorithm for UPQC is discussed in Section III. The SIM POWER SYSTEM (SPS), Matlab/ Simulink based simulation results are discussed in Section IV and finally Section V concludes the paper.

System Discription

The system under consideration is shown in Fig.1.The UPQC is connected before the load to make the load voltage free from any distortions and at the same time, the reactive current drawn from source should be compensated in such a way that the currents at source side i_s, would be in phase with utility voltages. Provisions are made to realize voltage harmonics, voltage sag and swell in the source voltage by switching on/off the three-phase rectifier load, R-L load and R-C load respectively.

In order to create a voltage dip in source voltage an induction motor is connected suddenly on the load side. The UPQC, realized by using two VSI is shown in Fig.2. One acting as a shunt APF, while the other as series APF. Both the APFs share a common dc link in between them. Each inverter is realized by using six IGBT (Insulated Gate Bipolar Transistor) switches. The voltage at the source side before UPQC, the load voltage at load, the voltage injected by series APF and the dc link voltage between two inverters are represented by v_s, v_L, v_{inj} and V^{dc} respectively. Whereas, the current on the source side, total current drawn by all the loads and the current injected by shunt APF are represented by i_s, i_l, and i_{sh} respectively. The load under consideration is a combination of linear and non-linear loads. A three-phase R-L load is taken as a linear load, where as a three-phase diode bridge rectifier with a resistive load on dc side is considered as a non-linear load. The values of the circuit parameters and load under consideration are given in Appendix.

CONTROL STRATEGY OF UPQC

The proposed control strategy is aimed to generate reference signals for both shunt and series APFs of UPQC. In the following section, an approach based on SRF theory is used to get reference signals for the series and shunt APFs.

Reference voltage signal generation for series APF

The control strategy for series AF is shown in Fig.3. Since, the supply voltage is distorted, a phase locked loop (PLL) is used to achieve synchronization with the supply voltage (Hingorani, 1995). Three-phase distorted supply voltages are sensed and given to PLL which generates two quadrature unit vectors (sin*wt,* coswt).The sensed supply voltage is multiplied with a suitable value of gain before being given as an in put to PLL. A distortion free, balanced and a constant magnitude three-phase voltage has'd' component only, while 'q' and '0' component will be zero. Hence, with the help of unit vectors (sin*wt,*coswt) obtained from PLL, an inverse Parks transformation is done for the desired peak value of the PCC voltage(ie.325V) using eqn.(1) as:

$$\begin{bmatrix} v_{la}^* \\ v_{lb}^* \\ v_{lc}^* \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & -\sin\left(\theta - \frac{2\Pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\Pi}{3}\right) & -\sin\left(\theta + \frac{2\Pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} v_d \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

The computed reference voltages from eqn.(1) are then given to the hysteresis controller along with the sensed three phase actual load voltages (v_{la}, vl_b and v_{lc}) .The output of the hysteresis controller is switching signals to the six switches of the VSI of series AF. The hysteresis controller generates the switching signals such that the voltage at PCC becomes the desired sinusoidal reference voltage. Therefore, the injected voltage across the series transformer through the ripple filter cancels out the harmonics present in the supply voltage.

Reference voltage signal generation for shunt APF

The control scheme to ger the reference source (i^*_{sa}, i^*_{sb} and i^*_{sc}) using SRF theory is depicted in Fig.4. With the help of unit vectors (sin*wt,*coswt) the load currents are transformed in to d-q-0 components using Park's transformation as per the After calculating the d-q-0 component of the load currents, the the 'd' component is passed through a low pass filter to extract dc component of iLd. A SRF controller extracts dc quantities by a low pass filter and hence non-dc quantities(harmonics) are separated from the reference signal. The d-axis current consist of fundamental and harmonic component as,

$i_{Ld} = i_{d\,dc} + i_{d\,ac}$

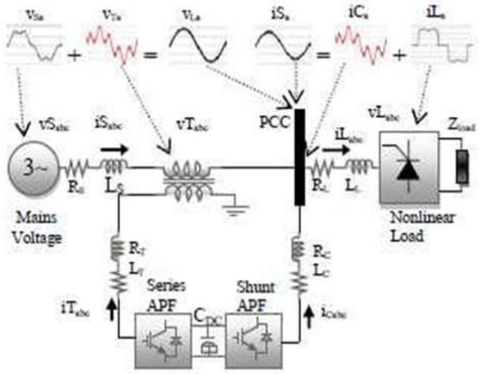

Fig.1. System under consideration

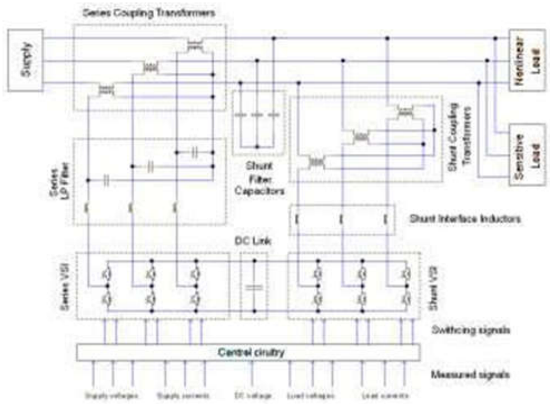

Fig. 2.UPQC Block Diagram

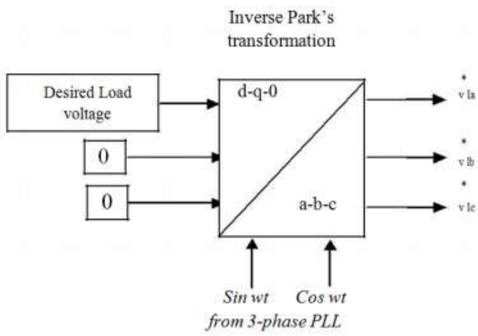

Fig.3. Control Scheme of Series APF using SRF Theory

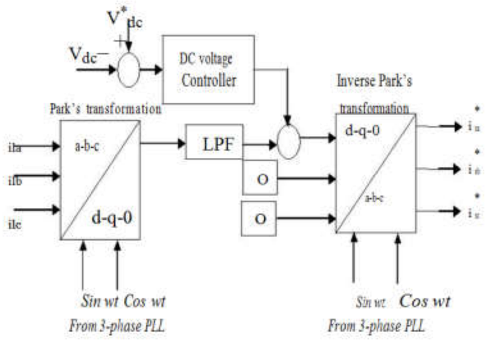

Fig. 4. Control Scheme of Shunt APF using SRF Theory

The control strategy of the shunt AF considers that the source must deliver the dc component of the direct-axis component of the load current (id dc) along with the active power current component for maintaining the dc bus and meeting the losses (iloss) in shunt AF. The output of PI (proportional-integral) controller at the dc bus voltage of the common dc link voltage of UPQC is considered as the current (Iloss) for meeting its losses.

$$I_{lossn)}=I_{loss(n-1)}+K_{pd}\{v_{de(n)}-v_{de(n-1)}\}+K_{id}v_{de(n)} \quad (3)$$

where $v_{de(n)}=v_{dcr}-v_{dca(n)}$ denotes the error in V_{dc} calculated over reference value of V_{dc}. and average value of V_{dc}. K_{pd} and Kid are proportional and integral gains of the DC bus voltage PI controller. The reference direct axis source current is there fore as,

$$i^{*}_{d}=i_{d\,dc}+i_{loss}$$

Three-phase reference source currents are obtained by reverse Park's transformation using eqn.(5) with the i^{*}_{d} as in (4) and

$$I_s = i_L - i_{sh}$$

$$= I_{1P} \sin(\omega t - \theta_{1P}) \cos \Psi_{1P}$$

I In this proposed control algorithm, the sensed(isa, isb and isc)and reference source currents(i*sa, i*sb and i*sc) are compared in a hysteresis current controller to generate the switching signals to the switches of the shunt APF which makes the supply currents sinusoidal, balanced in- phase with the voltage at PCC. Hence the supply current contains no harmonics or reactive power component. 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.

RESULTS AND DISCUSSION

The proposed control scheme has been simulated using MATLAB/ Simulink and its Sim-Power System toolbox. The performance of UPQC is evaluated in terms of voltage and Fig.5 (e) shows that after 0.1 sec the source voltage and source current in phase 'a' are exactly in phase. At t=0.2 sec the load is changed from three phase to two phase to make the load unbalanced.

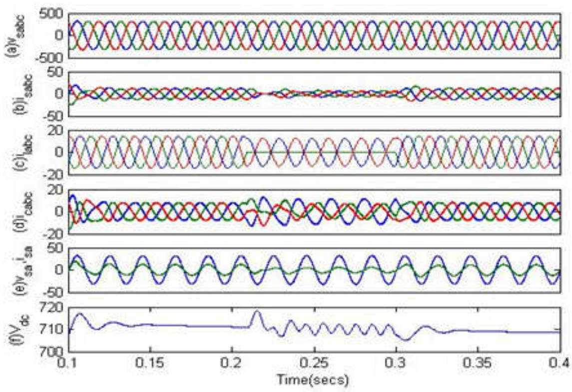

Fig. 5. Performance of UPQC for load balancing and power factor correction

The shunt APF compensates for the unbalanced load and source currents are still balanced and in phase with the source voltages. It is also observed from Fig. 5 (f) that during unbalanced load operation, the dc voltage increases and settles to it previous steady state value, once load is balanced.

B. Performance of UPQC for load balancing, power-factor correction and current harmonic mitigation In order to demonstrate the response of UPQC for load balancing, power factor correction and current harmonic mitigation, the load under consideration is a combination of a three-phase diode bridge rectifier with resistive load on dc side and unbalanced R-L load in phase 'a' and 'b' only. It is observed that the supply currents are balanced, sinusoidal and in-phase with the voltages as is shown in Fig.6 (b).

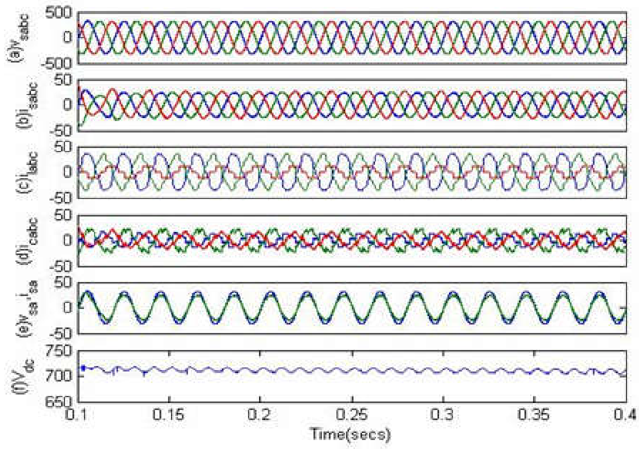

Fig. 6. Performance of UPQC for load balancing, power factor correction and current harmonic mitigation

Performance of UPQC for load balancing, power-factor correction, current and voltage harmonic mitigation

Fig.7 shows the response of UPQC for load balancing, power factor correction, voltage harmonic mitigation and current harmonic mitigation. In order to verify the effectiveness of control algorithm for voltage harmonic mitigation, a three-phase diode bridge rectifier with resistive load on dc side is switched on at 0.05 sec. Because of this the voltage across the load becomes distorted. To visualize the shunt APF and series APF performance individually, both APF's are put into operation at different instant of time. At time t_1=0.1 sec, shunt APF is put into operation first. It is observed that the supply currents are balanced; sinusoidal and in-phase with the voltages even under non- sinusoidal utility voltage. The source current THD in phase 'c' is improved form 15.50 % to 3.40 %. At time t_2=0.25 sec the series APF is put into the operation. The series APF starts compensating voltage harmonics immediately by injecting out of phase harmonic voltage, making the load voltage at load distortion free. The voltage injected by series APF is shown in Fig. 7(c). Here load voltage THD is improved form 7.02 % to 0.58 %. The harmonic spectra of the source current and the load voltage in phase 'c' with compensation and without compensation are shown in Fig. 8.

Performance of UPQC for load balancing, power- factor correction, current harmonic and voltage sag mitigation

The simulation results for voltage sag compensation are shown in Fig. 9.

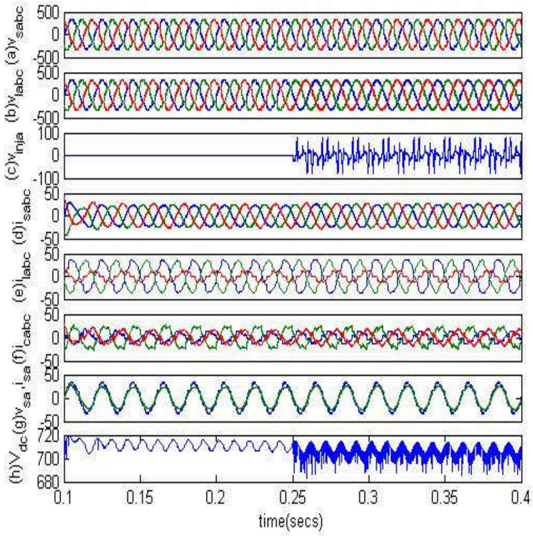

Fig.7 Performance of UPQC for load balancing, power factor correction, current and voltage harmonic mitigation

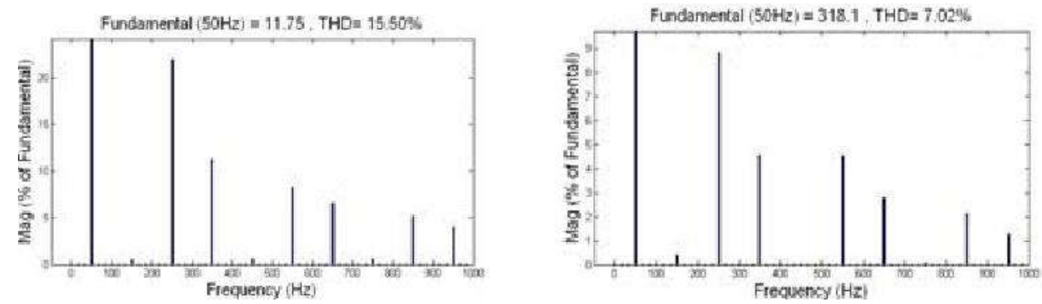

Fig. 8. (a) - (b) Source current and Load voltage without compensation

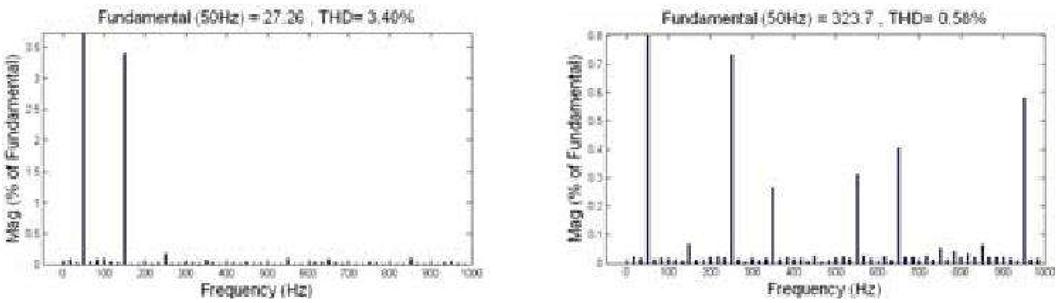

Fig. 8. (c) - (d) Source current and Load voltage with compensation

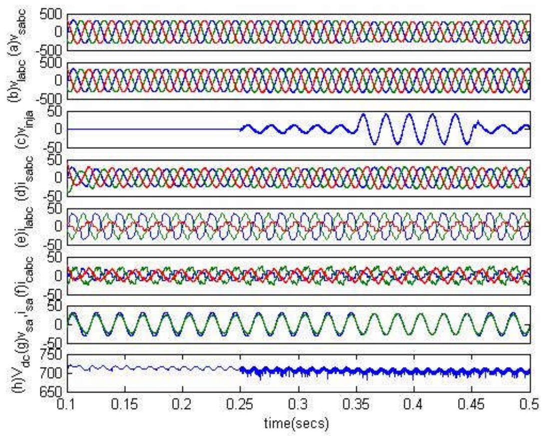

Fig.9 Performance of UPQC for load balancing, power factor correction, current harmonic and voltage sag mitigation

There are four instants; t_1, t_2, t_3 and t_4. At time t_1=0.10 s, the shunt APF is put into the operation and its operation is as discussed previously. At time t_2=0.25 s, series APF is put into operation. Now a 10 kW, 40 Kvar (inductive) load is switched on at t_3=0.35 s and switched off at t=.045 sec. Because of this a sag is developed on the system at time t_3=0.35 s. This sag lasted till time t_4=0.45 s, as shown in Fig. 9 (a). After time t_4=0.45 s, the system is again at normal working condition. During this voltage sag condition, the series APF is providing the required voltage by injecting in phase compensating voltage equals to the difference between the reference load voltage and supply voltage, as shown in Fig. 9 (c) . The load voltage profile in Fig. 9 (b) shows that UPQC is maintaining it at desired constant voltage level at load even during the sag on the system such that the loads cannot see any voltage variation.

Performance of UPQC for load balancing, power-factor correction, current harmonic and voltage swell mitigation

At time t_1=0.10 s, the shunt APF is put into the operation and at time t_2=0.25 s, series APF is put into operation. A swell is now introduced on the system by switching on a 10 kW, 40 Kvar (capacitive) from time t_3=0.35 s to t_4=0.45 s, as shown in Fig. 10. Under this condition the series APF injects an out of phase compensating voltage in the line through series transformers, equal to the difference between the reference load voltage and supply voltage, as shown in Fig.10 (c). The load voltage profile in Fig.10 (b) shows the UPQC is effectively maintaining the load bus voltage at desired constant level.

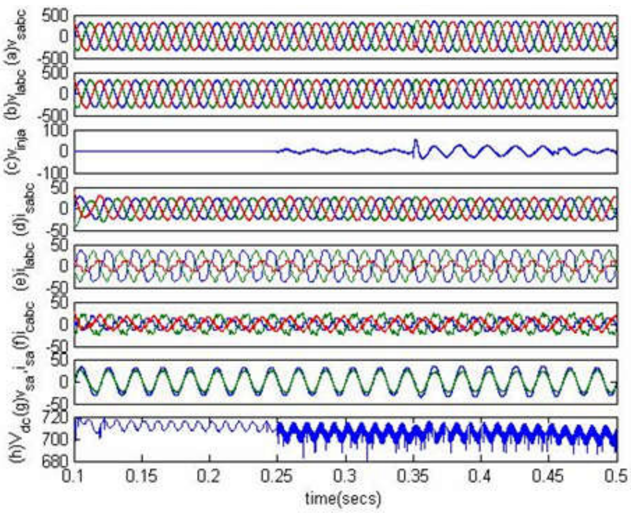

Fig.10 Performance of UPQC for load balancing, power factor correction, current harmonic and voltage swell mitigation

Performance of UPQC for power-factor correction and voltage dip mitigation

Fig 11 shows the response of the UPQC during the start up of an induction motor. An induction motor load is a typical load on the supply system. An induction motor draws a heavy inrush current, which leads to a voltage dip. The shunt APF is switched on at t=0.10s and the series APF is switched on at 0.25 s. An induction motor load is connected at t=0.20 s. There is high inrush current during the starting of the induction motor as shown in Fig.11 (d). The series APF injects in phase compensating voltage equals to the difference between the reference load voltage and actual load voltage, as shown in

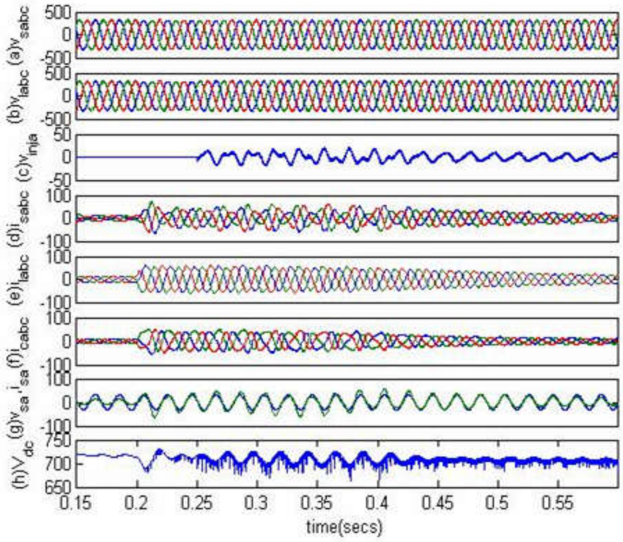

Fig.11 Performance of UPQC for power factor correction and voltage dip mitigation

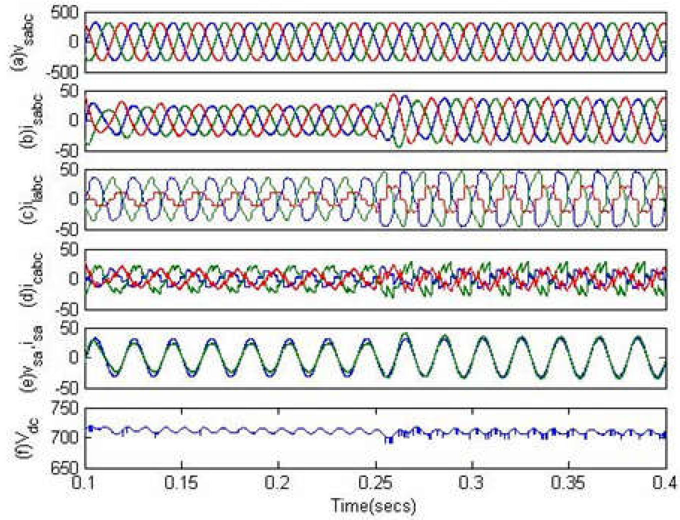

Fig.12. Performance of UPQC during sudden load change

Fig. 11 (c). The load voltage profile in Fig.11 (b) shows the UPQC is effectively maintaining the load voltage at desired constant level even during starting of an induction motor and there is no voltage dip. In addition to this, Fig.11. (g) shows that the voltage and current are in phase even during heavy inrush current.

Performance of UPQC during sudden change of load

In order to show the response of UPQC for sudden load change the load across the dc side of the rectifier is increased at t=0.25 s. It is observed from Fig.12(b) that in addition to the load balancing, power factor correction and current harmonic mitigation, the UPQC controller acts immediately without any delay in the operation and gain the new steady state. It is also observed from Fig. 12 (f) that there is small dip in dc voltage at t=0.25 s, but dc link is able to regulate the dc voltage to its previous value.

Conclusion

The proposed control scheme for UPQC has been validated through simulation results using MATLAB software along with simulink and sim-power system toolbox.

The performance of the UPQC has been observed to be satisfactory for various power quality improvements like load balancing, power-factor correction, voltage and current harmonic mitigation, mitigation of voltage sag, swell and voltage dip. The source current THD is improved from 15.50 % to 3.40 %, while the load voltage THD is improved form 7.02 % to 0.58 %. In addition to this the performance of UPQC has been found satisfactory during transient conditions.

APPENDIX

The system parameters used are as follows:

Supply voltage and line impedance: 415 V L-L, f=50 Hz, R_s=0.1ohm, L_s=1.5Mh Filter:R=7Ω,C=5μF DC bus capacitance: C_{dc}=3000μF Transformer: 250MVA, 58KV/12KV Loads: Three-Phase Rectifier Load R=50 Ω and R_a=R_b=10 Ω, L_a=5mH,L_b=20mH,R_c=L_c=0. Induction Motor Load: 3 HP, 50 Hz, 415 V L-L, wound rotor.

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