Simple Control Method for Unified Power Quality based on Five-level Inverter Topologies Operating under all Voltage Disturbances

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Abstract: This paper proposes a simple control scheme for UPQC (Unified Power Quality Conditioner) system based on five-level NPC (Neutral Point Clamped) inverter capable to compensate all disturbances under all voltage conditions. The proposed UPQC is designed by the integration of shunt and series APFs (Active Power Filters) sharing a common dc bus capacitor. The dc voltage is maintained constant using proportional integral voltage controller. To get the reference signals for shunt and series APFs, synchronous current detection method (SCD) and instantaneous reactive power (PQ) strategies are adopted. These reference signals are derived from the control algorithm and injected in LS-SPWM (Level Shifted-Sin Pulse Width Modulation) controllers to generate the switching signals. The performance of proposed UPQC system is evaluated using MATLAB-Simulink software and SimPowerSystem Toolbox for all voltage disturbances compensation. The simulation results demonstrate the effectiveness of proposed UPQC system to improve the power quality at the common connection point of the non-linear load in steady and transient conditions operation.

Keywords: Five-level (NPC) inverter, UPQC, Voltage disturbance compensation, Power quality improvement, Total Harmonic Distortion (THD)

1. INTRODUCTION

The There has been a continuous rise of nonlinear loads over the years due to intensive use of power electronic control in industry [1]. The utility supplying these nonlinear loads has to supply large vars. Moreover, the harmonics generated by the nonlinear loads pollute the utility. The basic requirements for compensation process involve precise control with fast dynamic response and on-line elimination of load harmonics. The traditional compensation methods using switched capacitor and thyristor controlled inductor [2] coupled with passive filters are increasingly replaced by active power filters (APFs) [3],[4]. The two types of APFs are shunt and series, The shunt active power filter (APF) is usually connected across the loads to compensate all current-related problems such as the reactive power compensation, power factor improvement, current harmonic compensation and load unbalance compensation [5], whereas the series APF is connected in a series with a line through series transformer. It acts as controlled voltage source and can compensate all voltage related problems, such as voltage harmonics, voltage sag, voltage swell, flicker, etc. One of the best solutions to compensate both current and voltage related problems, simultaneously, is the use of Unified Power Quality Conditioner (UPQC) [6]. A UPQC can be installed to protect the sensitive load inside the plant as well as to restrict entry of any distortion from load side. This dual functionality makes the UPQC as one of the most suitable devices that could solve the problems of both consumers as well as of utility. UPQC thus can help to improve voltage profile and hence the overall health of power distribution system. The application of UPQC to compensate reactive power, current harmonics and voltage harmonics are some of the functions suggested [7],[8]. Recently more attention is being paid on mitigation of voltage sags, voltage swells and unbalance compensation by using UPQC.

This paper presents a UPQC system based on five-level (NPC) inverter using simple control scheme. The series AF is controlled to maintain voltage load to the reference level and to eliminate supply voltage sag/swell, harmonics and unbalance from the load terminal voltage. The shunt AF is controlled to mitigate the supply current harmonics. The performances of the proposed UPQC system are verified through simulation using Matlab- Simulink software and SimPowerSystem Toolbox.

2. UPQC SYSTEM

Figure 1 shows the proposed UPQC connected to a power system feeding a nonlinear load. It consists of two five-level (NPC) inverters one for the shunt APF and the second for a series APF. The dc link of both active filters is connected to a common dc capacitor of 3000µF. The series filter is connected between the supply and load terminals using three single phase transformers with turn's ratios of 1:1. In addition to injecting the voltage, these transformers are used to filter the switching ripple of the series active filter. A small capacity rated C_{sf} filter [5],[9] is used with inductance L_{sf} to eliminate the high switching ripple content in the series active filter injected voltage. The five-level inverters for both the active filters are designed with IGBTs (Insulated Gate Bipolar Transistors). The three leg shunt active filter is connected ahead of a series filter through a small capacity rated inductive filter. The control algorithm of UPQC is based on synchronous current detection method for the shunt APF [10] and instantaneous reactive power theory for the series APF [11].

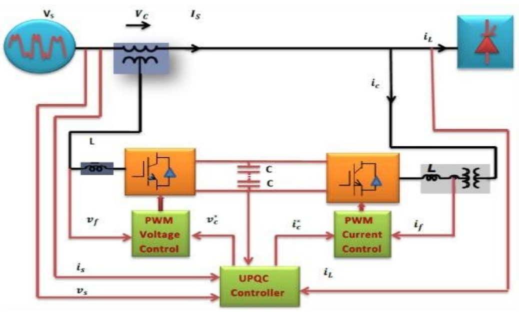


Fig. 1 UPQC configuration system

3. FIVE-LEVEL (NPC) INVERTER

The power circuit of the five-level NPC (Neutral Point Clamped) inverter is given by Fig. 2; the DC bus capacitor is split into four, providing a three neutral-point. Each arm of the inverter is made up of eight IGBTs devices, and six clamping diodes connected to the neutral-point. The diodes are used to create the connection with the point of reference to obtain midpoint voltages. This structure allows the switches to endure larger dc voltage input on the premise that the switches will not raise the level of their withstand voltage. For this structure, five output voltage levels can be obtained, namely, Udc/2, Udc/4, 0, -Udc/4 and -Udc/2 corresponding to five switching states A, B, 0, C and D [12],[13]. Table (1) shows the switching states of this inverter [14].

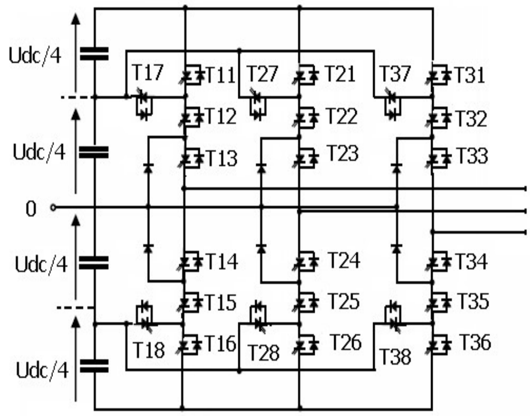


Fig. 2 Five-level (npc) inverter

Different modulation schemes have been adapted or developed depending on the application and the converter topology, and each has its unique advantages and disadvantages. The most common modulation method in industry is carrier-based SPWM. The Level Shifted-Sin Pulse Width Modulation (LS-SPWM) method is especially useful for NPC converters [15].

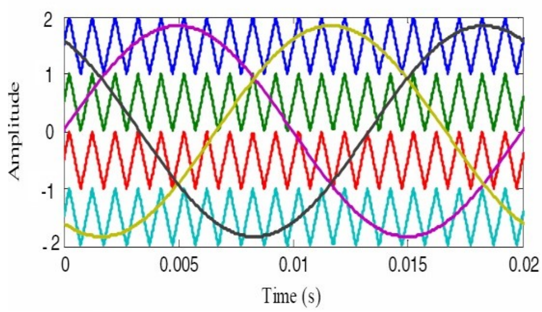


Fig. 3 Four unipolar carriers Uref: 1,2,3,4

The difference between the injected currents (voltages) and the reference currents (voltages) determines the reference signals. These signals are compared with four triangular-carrying identical waves shifted from one to the other by a (+2U_{pm} +U_{pm}, -U_{pm} and -2U_{pm}) and generating switching pulses for the shunt and series APFs. The logic control of the five-level (NPC) inverter is summarized in the two following stages: Determination of the intermediate signals VK1 and VK0:

- If error $E_c \geq$ carrying 1 Then $V_{k11}=U_{dc}/4$,

- If error Ec $<$ carrying 1 Then V_{K11}=0,
- If error Ec $\geq$ carrying 2 Then V_{K12}=Udc/4,
- If error Ec $<$ carrying 2 Then V_{K12}=0.
- If error Ec $\geq$ carrying 3 Then V_{K10}=0,
- If error Ec $<$ carrying 3 Then V_{K01}= -Udc/4,
- If error Ec $\geq$ carrying 4 Then V_{K02}=0,
- If error Ec $<$ carrying 4 Then V_{K02}=-Udc/4,

Determination of control signals of the switches Tij (i=1, 2, 3; j=1, 2, 3):

- If (V_{K1}+V_{K0})= +Udc/2 Then T_{i1}=1, T_{i2}=1, T_{i3}=0,
- If (V_{K1}+V_{K0})= +Udc/4 Then T_{i1}=1, T_{i2}=1, T_{i3}=0,
- If (V_{K1}+V_{K0})= 0 Then T_{i1}=1, T_{i2}=0, T_{i3}=0,
- If (V_{K1}+V_{K0})= -Udc/4 Then T_{i1}=0, T_{i2}=0, T_{i3}=1,
- If (V_{K1}+V_{K0})= -Udc/2 Then T_{i1}=0, T_{i2}=0, T_{i3}=0,

The Simulink model of the logic control designed for the five-level (NPC) inverter is shown in Fig. 4.

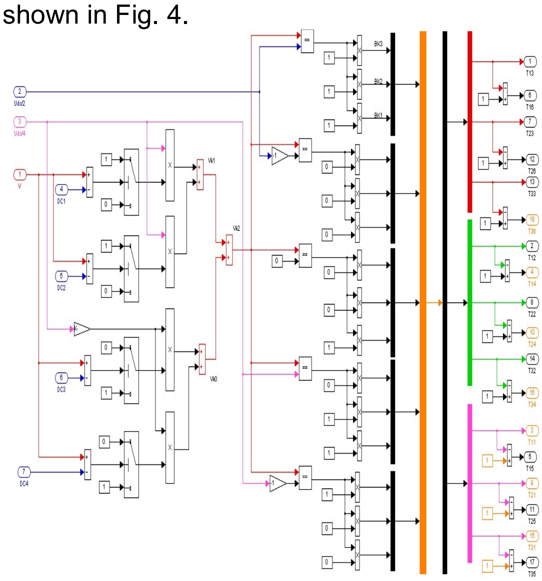


Fig. 4 Five-level (NPC) inverter logic control

4. CONTROL STRATEGIES

The control strategy is basically the way to generate reference signals for both shunt and series APFs of UPQC. The compensation effectiveness of the UPQC depends on its ability to follow with a minimum error and time delay the reference signals to compensate the distortions, unbalanced voltages or currents or any other undesirable condition [16]. The conventional techniques reported in literature produce poor results under distorted and/or unbalanced input/utility voltages, and they involve many calculations. The proposed control scheme is a simple scheme to achieve effective compensation for source current harmonics, reactive power compensation and voltage harmonic mitigation even under distorted and/or unbalanced input/utility voltages [17].

4.1 Shunt APF

The shunt APF control strategy adopted here to compensate harmonic currents is based on the SRF detection method. The principle of this technique is described below [18], [19]. The three-phase load currents iLa, iLb and iLc are transformed from three phase (abc) reference frame to two phase's (α-β) stationary reference frame currents iα and iβ using:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

Using a phase locked loop (PLL), cos(θest) and sin(θest) can be generated from the phase voltage source usa, usb and usc. The iα and iβ currents expression in (d-q) reference frame are given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

The id current is transformed to DC and harmonic components using a low pass filter:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ i_q \end{bmatrix} \quad (3)$$

The expression of the reference current iα-ref and iβ-ref are given by:

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ i_q \end{bmatrix} \quad (5)$$

The correspondent reference currents in the (abc) frame are given by:

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \quad (6)$$

Finally, the compensation currents icomp-a, icomp-b and icomp-c are given by:

$$\begin{bmatrix} i_{comp-a} \\ i_{comp-b} \\ i_{comp-c} \end{bmatrix} = \begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} - \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (7)$$

To compensate the inverter losses and regulate the DC link voltage Udc, a proportional integral voltage controller is used. The control loop consists of the comparison of the measured voltage (Udc1 + Udc2) with the reference voltage Udc-ref. The loop generates corresponding current Ic,los is given by:

$$I_{c,los} = K_p \Delta U_{dc} + K_i \int \Delta U_{dc} dt \quad (8)$$

4.2 Series APF

The control strategy used to extract the reference voltages of series APF is based on the p-q theory [20]. The three-phase voltage source in the grid is assumed to be symmetric and distorted:

$$\begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty} \sqrt{2} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin((n\omega t - \frac{2\pi}{3}) + \theta_n) \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin((n\omega t + \frac{2\pi}{3}) + \theta_n) \end{bmatrix} \quad (9)$$

Where Un and θn are respectively the rms voltage and initial phase angle, n is the harmonic order. When n=1, it means three-phase fundamental voltage source:

$$\begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty} \sqrt{2} U_1 \sin(n\omega t + \theta_1) \\ \sum_{n=1}^{\infty} \sqrt{2} U_1 \sin((\omega t - \frac{2\pi}{3}) + \theta_1) \\ \sum_{n=1}^{\infty} \sqrt{2} U_1 \sin((n\omega t + \frac{2\pi}{3}) + \theta_1) \end{bmatrix} \quad (10)$$

Equation (10) is transformed into (α-β) reference frame:

$$\begin{bmatrix} U_{s\alpha} \\ U_{s\beta} \end{bmatrix} = C_{32} \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} = \sqrt{3} \begin{bmatrix} \sum_{n=1}^{\infty} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \mp U_n \sin(n\omega t + \theta_n) \end{bmatrix} \quad (11)$$

$$C_{32} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (12)$$

The three-phase positive fundamental current template is constructed as:

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \quad (13)$$

Equation (13) is transformed to (α-β) reference frame:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = C_{32} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) \\ -\cos(\omega t) \end{bmatrix} \quad (14)$$

According to the instantaneous reactive power theory, then:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_{s\alpha} & u_{s\beta} \\ u_{s\beta} & -u_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (15)$$

Where DC and AC components are included:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \quad (16)$$

Where p and q are passed through low pass filter (LPF), and DC component are obtained by:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \sqrt{3} \begin{bmatrix} U_1 \cos(\theta_1) \\ U_1 \sin(\theta_1) \end{bmatrix} \quad (17)$$

According to Eq. (15), transformation is made:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_{s\alpha} & u_{s\beta} \\ u_{s\beta} & -u_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \\ -i_{s\beta} & i_{s\alpha} \end{bmatrix} \begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} \quad (18)$$

The DC components of p and q:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} u_{s\alpha} & u_{s\beta} \\ u_{s\beta} & -u_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \\ -i_{s\beta} & i_{s\alpha} \end{bmatrix} \begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} \quad (19)$$

The fundamental voltages in (α-β) reference frame are:

$$\begin{bmatrix} u_{s\alpha f} \\ u_{s\beta f} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \\ -i_{s\beta} & i_{s\alpha} \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & -i_{s\beta} \\ i_{s\beta} & i_{s\alpha} \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \quad (20)$$

The three-phase fundamental voltages are given by:

$$\begin{bmatrix} U_{saf} \\ U_{sbf} \\ U_{scf} \end{bmatrix} = C_{23} \begin{bmatrix} u_{s\alpha f} \\ u_{s\beta f} \end{bmatrix} = \sqrt{2} U_1 \begin{bmatrix} \sin(\omega t + \theta_1) \\ \sin(\omega t + \theta_1 - \frac{2\pi}{3}) \\ \sin(\omega t + \theta_1 + \frac{2\pi}{3}) \end{bmatrix} \quad (21)$$

Where:

$$C_{23} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}^T \quad (22)$$

5. SIMULATION RESULTS AND DISSCUSSION

Figure 5 displays the model of the proposed UPQC. The simulation is performed using Matlab-Simulink and SimPowerSystem Toolbox. The performances are evaluated in terms of sags, swells and voltage unbalances compensation. The parameters of the proposed UPQC are V_s=220 V, frequency f_s=50 Hz, resistor R_s=0.1 mΩ, inductance L_s=0.0002 mH, resistor R_l =48.6 Ω, inductance L_l=40 mH, C_{dc}=3000 μF, resistor R_c=0.27 mΩ, and L_c=0.8 mH.

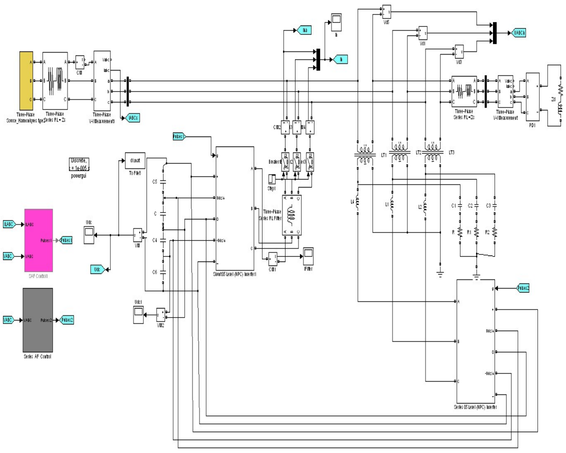
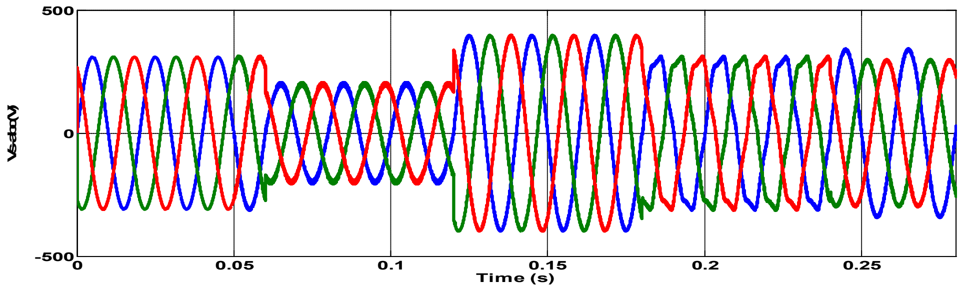


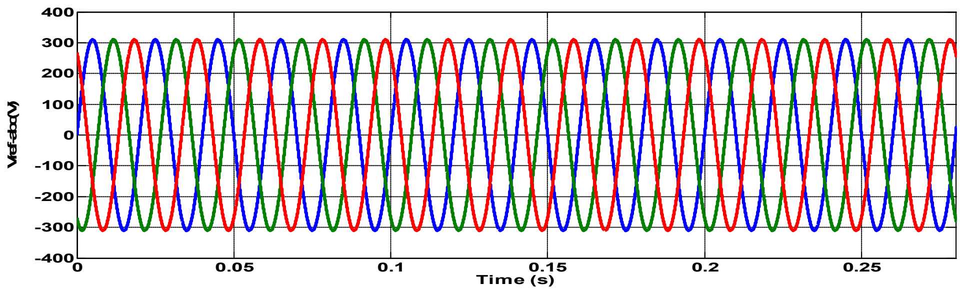
Fig. 5 Matlab-Simulink UPQC system

5.1 UPQC performances for all voltage disturbances compensation

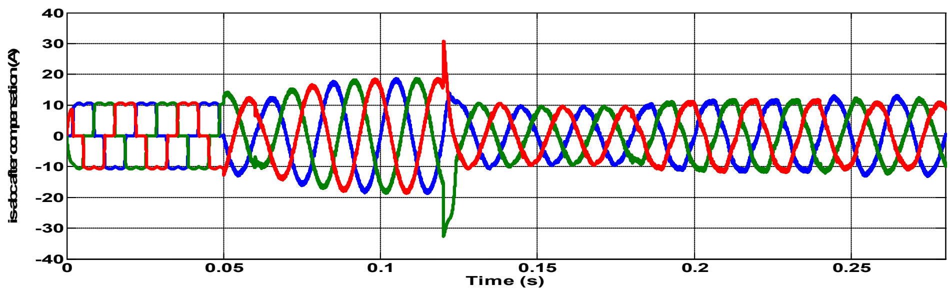
The performance of proposed UPQC is tested under all voltage disturbances simultaneously. The simulation results are shown in Fig. 6. The voltage sags (25%) is introduced voluntary between t_1=0.06 sec and t_2=0.12 sec. After that, a voltage swells (35%) is introduced between t_2=0.12 and t_3=0.18 sec. The voltage harmonics is introduced between t_3=0.18 sec and t_4=0.24 sec. The unbalances is introduced between t_4=0.24 sec and t_5=0.3 sec. After t_5=0.3 sec the system is again at normal working condition. It is illustrated that the proposed UPQC is capable to mitigate all voltage disturbances and does not show any significant effect of disturbance type present in the utility voltages on its compensation capability.



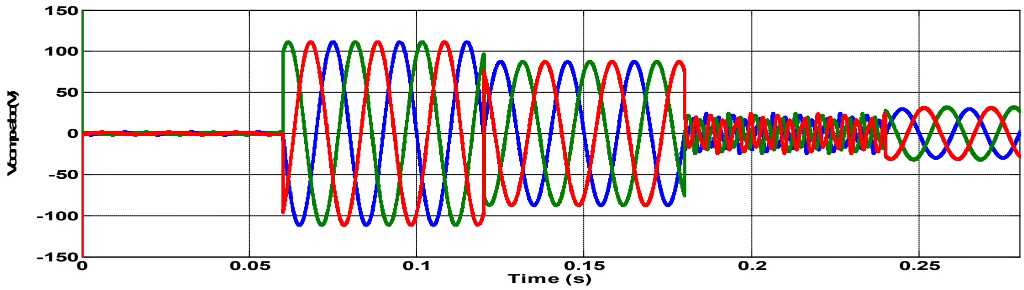
(a) Load voltages VL-abc(V) before compensation



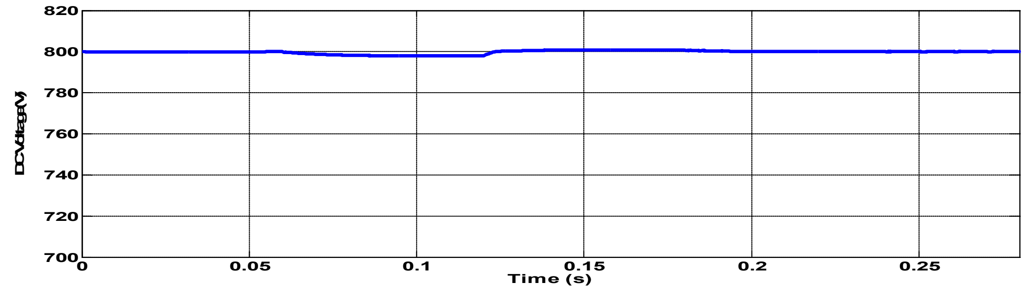
(b) Reference voltages Vref-abc(V)



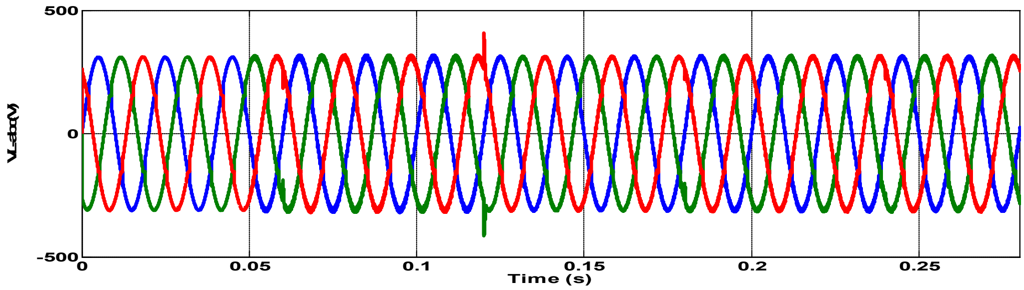
(c) Source current is-abc(A) before and after compensation



(d) Compensation voltages Vcomp-abc(V)



(e) DC link voltage Udc(V)

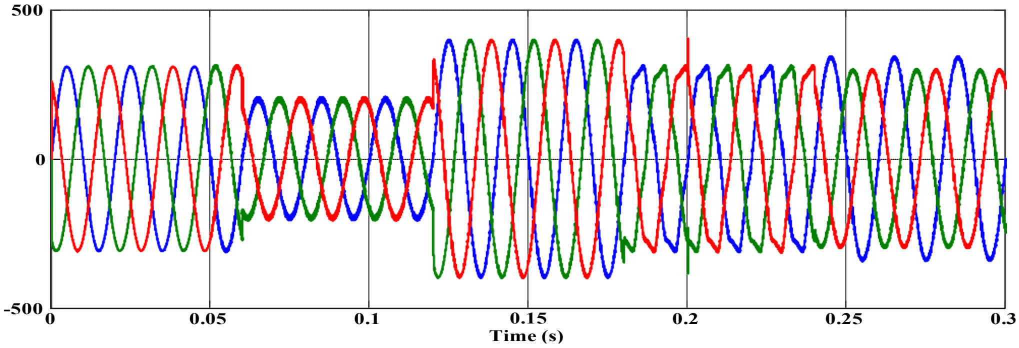


(f) Load voltages VL-abc(V) after compensation

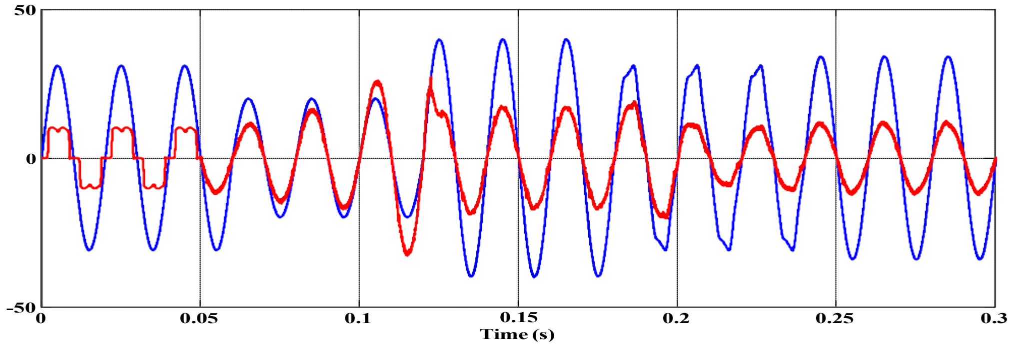
Fig. 6. UPQC performances for all voltage disturbances compensation

5.2 UPQC dynamic performances under all voltage disturbances

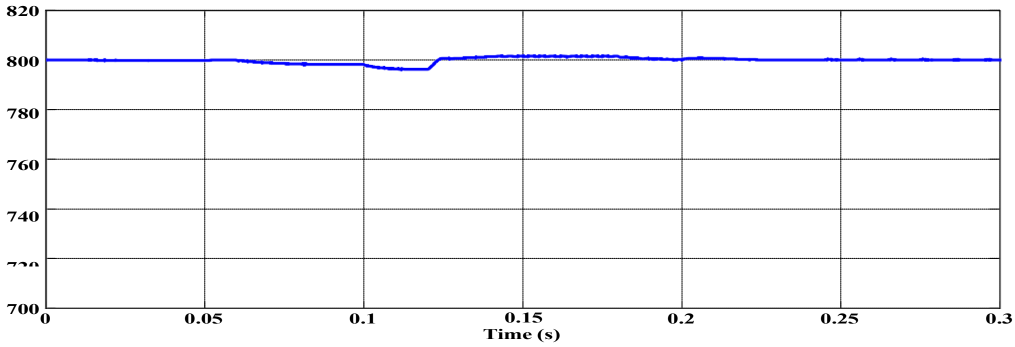
In order to evaluate the UPQC performances during transient condition, the load on the system is changed suddenly. The simulation results during this condition are shown in the Fig. 7. Before time t_1=0.05 sec, the shunt and series APFs are not working, the source current is highly distorted. After t_1=0.05 sec the shunt active filer is only on operation (the source current after compensation is nearly sinusoidal and in phase with the source voltage). The source voltage disturbances: sag, swell, unbalance and harmonic voltages are introduced between t_2=0.05 sec and t_3=0.3 sec, are effectively improved using the proposed UPQC. When the sudden load current disturbance is introduced voluntary between t_4=0.1 sec and t_5=0.2 sec, the UPQC controller acts immediately without any delay, the shunt APF injects a current equals to sum of harmonic. In all dynamic condition the dc voltage is maintained constant and equal to the reference value $U_{dc\text{-}ref}$ = 800 V using proportional integral voltage controller. It is observed that the dc voltage passes through a transitional period of 0.02 sec before stabilization and reaches its reference with moderate peak voltage approximately equal to 5 V. Before Shunt AF application the source current is distorted with poor power factor, after compensation the source current shown in Fig. 7(b) is sinusoidal and in phase with the source voltage for the all voltage disturbances. The effectiveness of the UPQC to enhancement the power quality under all voltages conditions is proved.



(a)Load voltage before compensation



(b)Source current isa(A) and source voltage vsa(V)



(c)DC link voltage

Fig. 7 UPQC: dynamic performances for sudden load change between t4=0.1 sec and t5=0.2 sec

6. CONCLUSION

To enhance the power quality by reducing the source current harmonics and improve the voltage delivered to sensitive loads, a novel UPQC configuration system based on five-level NPC inverter has been proposed in this paper. The adopted control strategy is based on the SRF detection method for the shunt AF and the instantaneous power method PQ for the series AF. The UPQC model is developed and validated using Matlab-Simulink software and SimPowerSystem simulation toolbox. The control algorithm of UPQC has been observed to be satisfactory for various power quality improvements like voltage harmonics mitigation, current harmonic mitigation, voltage sag, swell and unbalance compensation. The UPQC performance during transient conditions has been found satisfactory, the UPQC controller acts immediately without any delay in the operation with fast dynamic response. The result of this study may be useful for potential UPQC applications. The performance of proposed UPQC can be further improved by using intelligent controllers.

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