Unified Power Quality Conditioner Performance based on Multi-level Inverter Topologies using Intelligent Controllers

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Abstract: This paper presents unified power quality conditioner (UPQC) system based on three-level neutral point clamped (NPC) using Fuzzy and ANN controllers. The proposed UPQC is able to mitigate source current harmonics and compensate all voltage disturbances. It is designed by the integration of series and shunt active filters (AFs) sharing a common DC bus capacitor. The DC voltage is maintained constant using proportional integral voltage controller. The synchronous reference frame (SRF) theory is used to get the reference signals for the shunt APF and the power reactive theory (P-Q theory) for the series APF.Conventional control schemes require complex calculations, the use of intelligent systems help to reduce the control system size and the operation complexity. The shunt and series active power filter (APF) reference signals derived from the control algorithm are injected in Fuzzy and Ann intelligent controllers to generate switching signals. The performances of the proposed UPQC system are evaluated using Matlab-Simulink software and SimPowerSystem Toolbox under various operation conditions. The simulation results show the performance of the proposed UPQC based on intelligent controllers to improve the power quality in steady and transient conditions operation.

Keywords: Three-level (NPC) inverter, UPQC, Fuzzy logic, Artificial neural network, Voltage disturbance compensation, Power quality improvement, Total Harmonic Distortion (THD)

1. INTRODUCTION

There has been a continuous rise of nonlinear loads over the years due to intensive use of power electronic control in industry. 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 the compensation process involve precise control with fast dynamic response and online elimination of load harmonics. In the past, these identified power quality problems were mitigated by using switched capacitor and thyristor controlled inductor coupled with conventional passive filters [1],[2]. But limitations, such as fixed compensation, resonance with source impedance and the difficulty in tuning time dependence of filter parameters, have ignited the need for active power filters (APFs) [3],[4]. The unified power quality conditioner (UPQC) is one of the best solutions to compensate both current-and voltage-related problems simultaneously [5],[8]. It is the integration of shunt and series APFs through a common DC link capacitor [6].UPQC has been widely studied to eliminate or mitigate the disturbances propagated from the source side and the other loads interconnected [7],[8]. In the normal operation, the shunt APF control circuit calculates the harmonic currents compensation and generates the inverter pulses to power circuits (shunt APF). The series APF compensates the harmonics and the all other voltage disturbances. The arrangement of series and shunt filters are interchangeable. In general, when a UPQC is used in a power distribution system, the series filter is installed ahead of the shunt filter [9]. The controller is the core of any APF operation and has been the subject of numerous researches in recent years [10]. The conventional control scheme to generate pulses, based on hysteresis technique control, presents several drawbacks such us uneven switching frequency that causes acoustic noise and difficulty in designing input filters in case of SAPF. To improve the APF performance, the tendency has been to use intelligent control techniques. The use of these techniques in power electronics applications has generated considerable interest [11],[12]. Their advantages are robustness, no need accurate mathematical model, etc.

This paper presents UPQC system based on three-level neutral point clamped (NPC)

inverter using intelligent control techniques. The series APF 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 APF is controlled to mitigate the supply current harmonics. The performances of the proposed UPQC system are verified through simulations using Matlab-Simulink software and SimPowerSystem Toolbox.

2. UPQC SYSTEM

The Figure 1 shows the proposed UPQC connected to the power system feeding a nonlinear load. It consists of two three-level NPC inverters, one for the shunt and the other for a series active filter. The DC link of both active power filters (APFs) is connected to a 3000 µF common DC capacitor. 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 Csf filter [13] is used with inductance to eliminate the high switching ripple content in the series active filter injected voltage. The three-level inverters are designed with insulated gate bipolar transistors (IGBTs) [14]. The three leg shunt active filter is connected ahead of a series filter using a small capacity rated inductive filter. The control algorithm of UPQC is based on the synchronous reference frame detection method (SRF) for the shunt AF and instantaneous reactive power theory for the series AF [15, 16].

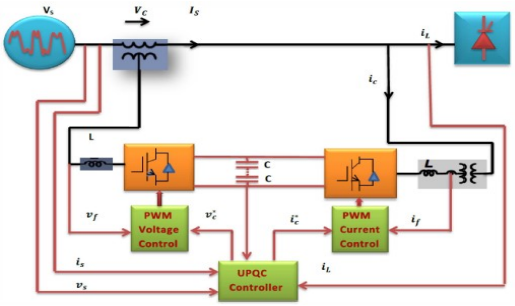


Fig. 1 UPQC configuration system

3. 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 [17]. 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.

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]. 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:

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

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

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

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

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:

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

Series APF

The control strategy used to extract the reference voltages of series APF is based on the p-q theory [19]. 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:

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

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

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

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:

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

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

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

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:

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

4. UPQC SYSTEM LOGIC CONTROL

Shunt APF

Artificial Neural Networks have provided an alternative modelling approach for power system applications [20]. It is essentially a cluster of suitably interconnected non-linear elements of very simple form that possess the ability of learning and adaptation. These networks are characterized by their topology, the way in which they communicate with their environment, the manner in which they are trained and their ability to process information. The MLPNN (Multi-Layer Perceptron Neural Network) shown in Figure (2) is one of the most popular topologies in use today [21].

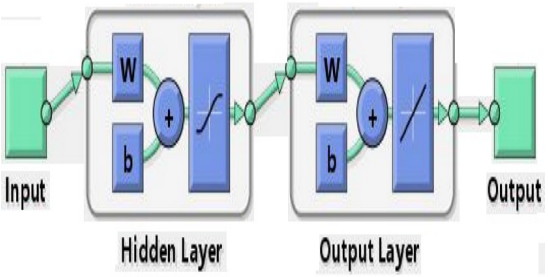


Fig. 2 Multi-Layer neural network

Figure 3 shows the artificial neural network for Shunt APF, it consists of input layer, output layer and hidden layer, each layer has many neurons. The input layer offers connection point to transmit the input signal to the hidden layer. The choose of in appropriate number of neurons of the hidden layer is specified as the minimum number that produce the permitted training criterion, The training criterion taken is the mean square error [22]. The network has a 3-12-6 structure: 3 input neurons, 12 hidden layer neurons with a sigmoid activation function and 6 output neurons with a linear activation function. The input pattern are the error values (Eca, Ecb and Ecc) between the measured filter currents (ifa, ifb and ifc) and the compensating reference currents (ifa*, ifb* and ifc*) whereas the outputs values are the switching states T11, T12, T21, T22, T31 and T32 [23]. The neural network was trained with 10000 training examples using Levenberg-Marquardt back propagation algorithm.

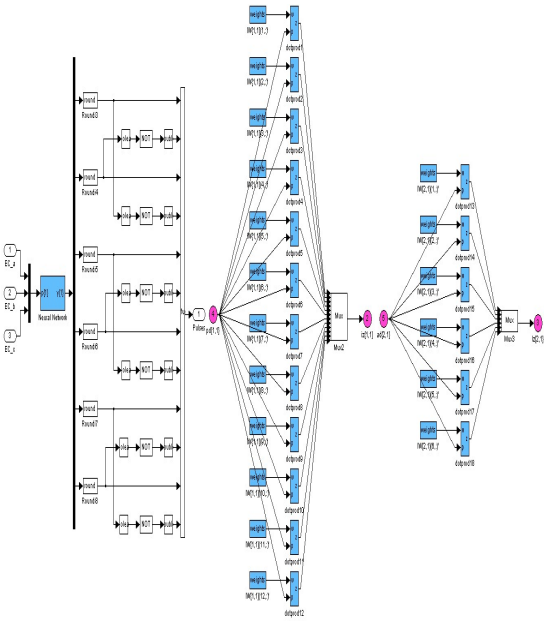


Fig. 3 SAPF Artificial Neural Network controller

Series APF

Fuzzy logic controllers (FLCs) have been an interesting and good alternative in more power electronics application. Their advantages are robustness, non-requirement of a mathematical model, and acceptance of non-linearity. To benefit from these advantages, a fuzzy logic voltage controller is proposed to use for the three-level NPC series APF. The controller is designed to improve the compensation capability of APF by adjusting the voltage error using fuzzy rules. Fuzzy logic control is the evaluation of a set of simple linguistic rules to determine the control action. The desired inverter switching signals of the three-level series active filter are determined according to the error between the compensation voltages and reference voltages. In this case, the fuzzy logic voltage controller has two inputs, error “e” and change of error “de”, and one output “s” [16]. To convert the inputs into linguistic variable, three fuzzy sets are used: N (Negative), ZE (Zero), and P (Positive). The fuzzy controller for every phase is characterized by three fuzzy sets for each input; five fuzzy sets for output; Gaussian membership function for the input and triangle membership function for the output; implication using the “min” operator, Mamdani fuzzy inference mechanism based on fuzzy implication; and defuzzification using the “centroid” method.

The errors for each phase are discretized by the zero order hold blocks. The error rate is derivative of the error and is obtained by the

use of unit delay block. The saturation block imposes the upper and lower bounds on a signal. When the input signal is within the range specified by the lower limit and upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound. The output of the saturation blocks are the input to fuzzy logic controllers. The outputs of these fuzzy logic controllers are used in the generation of pulse switching signals of the three-level inverter [24]. The switching signals are generated by comparing a two-carrier signal DS1 and DS2 with the output of the fuzzy logic controller. The Simulink model of the fuzzy logic switching signal generation is depicted in Figure 4.

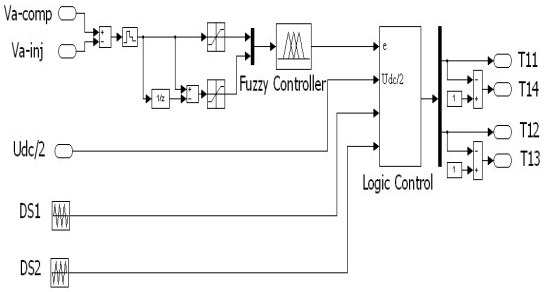


Fig. 4 Series APF logic switching signal generation based on fuzzy logic controller

The Logic control of the series APF inverter is summarized in the following two steps:
Determination of the intermediate signals Vi1 and Vi2:

- If error Ec $\geq$ carrying 1, then Vi1=1;
- If error Ec $<$ carrying 1, then Vi1=0;
- If error Ec $\geq$ carrying 2, then Vi2=0;
- If error Ec $<$ carrying 2, then Vi2=–1.

Determination of control signals of the switches Tij (i=1, 2, 3; j=1, 2, 3, 4):

- If (Vi1+ Vi2) = 1, then Ti2=1, Ti1=1, Ti3=0, Ti4=0;
- If (Vi1+ Vi2) = 0, then Ti2=0, Ti1=1, Ti3=1, Ti4=0;
- If (Vi1+ Vi2) =–1, then Ti2=0, Ti1=0, Ti3=1, Ti4=1.

Figure 5 shows the logic control of three-level (NPC) inverter.

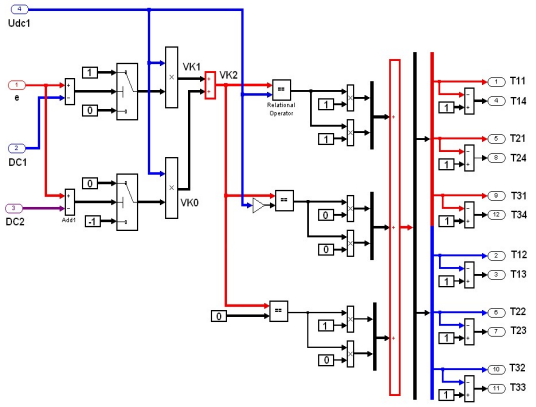


Fig. 5 Three-level NPC inverter logic control

5. SIMULATION RESULTS AND DISSCUSSION

Figure 6 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 Vs=220 V, frequency fs=50 Hz, resistor Rs=0.1 mΩ, inductance Ls=0.0002 mH, resistor Rl =48.6 Ω, inductance Ll=40 mH, Cdc=3000 µF, resistor Rc=0.27 mΩ, and Lc=0.8 mH.

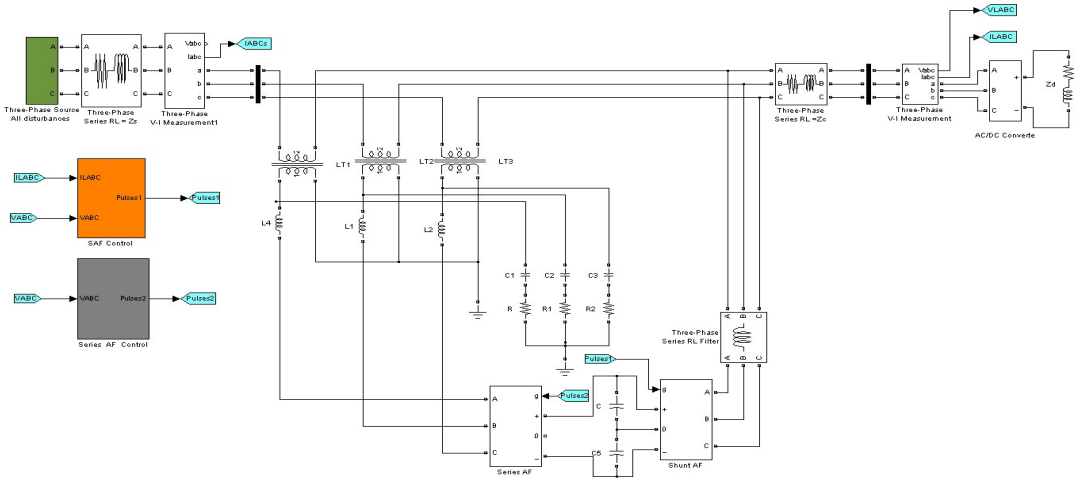


Fig. 6 Matlab-Simulink UPQC system model

The performance of the proposed UPQC is tested under all voltage disturbances simultaneously. The voltage sags (25%) is introduced voluntary between t1=0.06 s and t2=0.12 s. After that, a voltage swells (35%) is introduced between t2=0.12 and t3= 0.18 s. The voltage harmonics is introduced between t3=0.18 s and t4=0.24 s. The unbalances is introduced between t4=0.24 s and t5=0.3 s. The system is again at normal working condition.

Figure 7 and 8 shows the load voltage and source current before compensation.

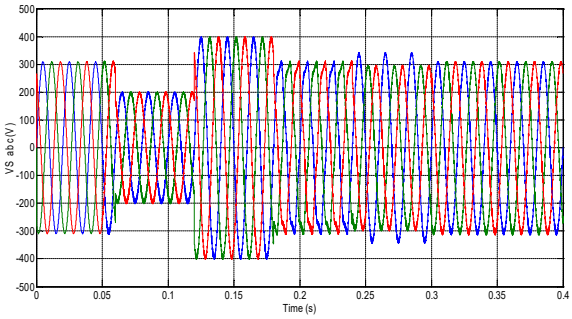


Fig. 7 Load voltages before compensation

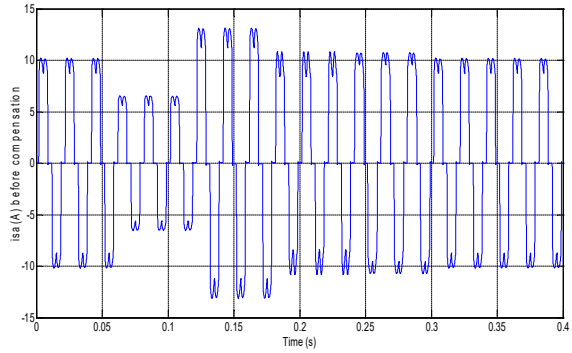


Fig. 8 Source current before compensation

Before compensation, it is shown that the source current is highly distorted and rich in harmonics.

Figure 9 and 10 shows the compensation voltages and the source current after compensation using proposed UPQC system.

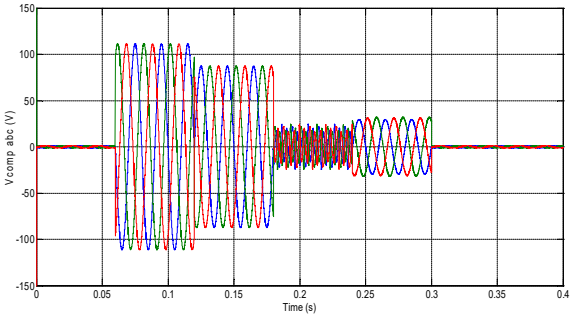


Fig. 9 Compensation voltages

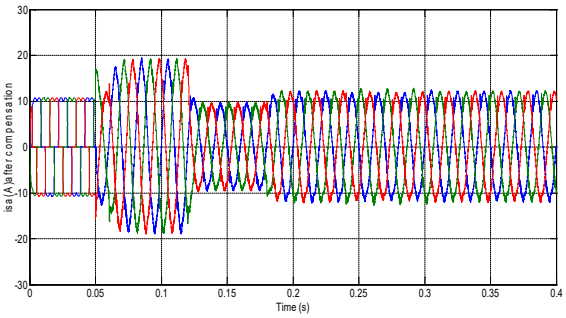


Fig. 10 Source current after compensation

Using proposed UPQC system, the source current after compensation is sinusoidal with minimum distortion.

Figure 11 and 12 shows the DC link voltage and the load voltage after compensation.

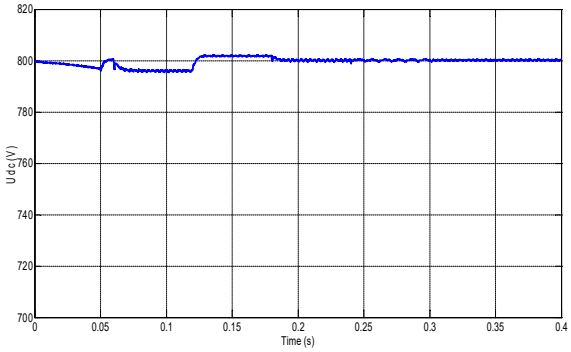


Fig. 11 DC link voltages

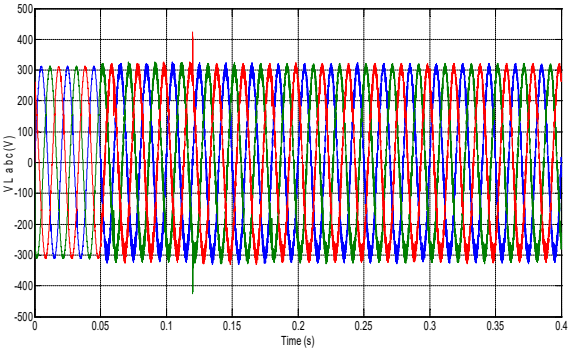


Fig. 12 Load voltages after compensation

The simulation results obtained show 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.

In order to evaluate the performance of the proposed UPQC under transient condition, the load on the system is changed suddenly. The simulation results under this condition are shown in Figure 13 to (16). Before t1=0.05 s, the shunt and series APFs are not working, the source current is highly distorted. After t1=0.05 s the UPQC system

is on operation (the source current is nearly sinusoidal and in phase with the source voltage). The source voltage disturbances such as sag, swell, unbalance and harmonic voltages introduced between t2=0.05 s and t3=0.3 s, are effectively improved using the proposed UPQC. When the sudden load current disturbance is introduced voluntarily between t4=0.25 s and t5=0.35 s, the UPQC acts immediately without any delay, and the shunt APF injects a current equal to the sum of harmonic. In all the dynamic condition, the DC voltage is maintained constant and equal to the reference value Udc-ref = 800 V using proportional integral voltage controller. It is observed that the DC voltage passes through a transitional period of 0.02 s before stabilization and reaches its reference with moderate peak voltage approximately equal to 4 V. Before the shunt AF application, the source current is distorted with poor power factor, but after compensation the source current shown in Figure 14 is sinusoidal and in phase with the source voltage for all voltage disturbances. The effectiveness of UPQC in reducing the supply current and load voltage harmonics for all disturbance conditions is proved.

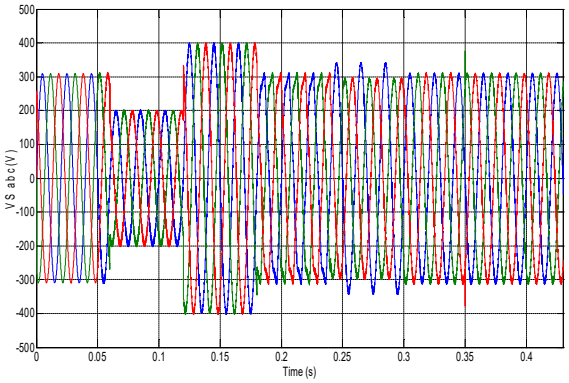


Fig. 13 Load voltage before compensation

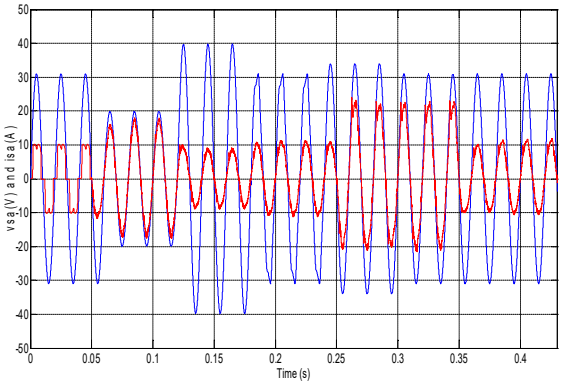


Fig. 14 Source current isa(A) and source voltage vsa(V) after compensation in case of sudden load change between t4=0.25 s and t5=0.35 s

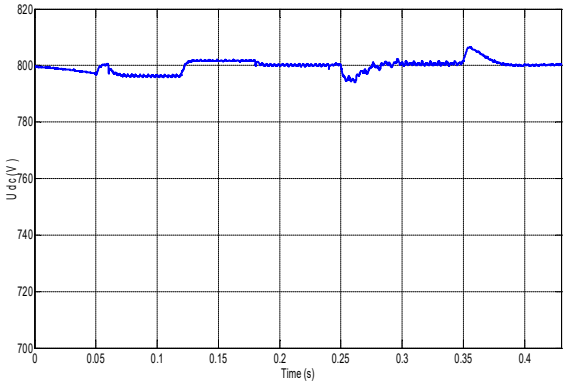


Fig. 15 DC link voltage Udc(V)

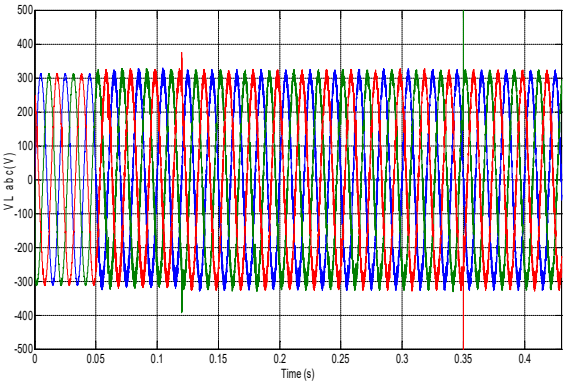


Fig. 16 Load voltage after compensation

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 three-level NPC inverter using fuzzy and Ann controllers 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 sufficient for all power quality improvements like voltage harmonics mitigation, current harmonic mitigation, voltage sag, swell and unbalance compensation. The proposed UPQC system does not show any significant effect of disturbance type present in the utility voltages on its compensation capability and acts immediately (fast dynamic responses) with a small delay in the operation and has been found satisfactory under transient conditions.

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