A SIMPLIFIED CONTROL SCHEME FOR THREE-PHASE THREE-LEVEL (NPC) SERIES ACTIVE FILTER TO COMPENSATE ALL VOLTAGE PERTURBATIONS

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ABSTRACT

This paper presents a simplified control scheme for three-phase three-level series active power filter to compensate all load voltage perturbations such us harmonic unbalances, sags and swells. The standard configuration of three-phase series active power filter uses the two-level three-phase voltage source inverter with hysteresis controller. This configuration presents some drawbacks and is limited to low power systems. Today three-level (NPC) inverter is one of the most successfully employed topology in various industrial applications. In this paper a new scheme to increase the capability of series Active Power Filter (APF) voltage controller based on three-level inverter using simplified Pulse Width Modulation (PWM), is proposed. The control strategy adopted use instantaneous reactive power theory, easy to implement and gives good performance for all load voltage perturbations. The numerical simulation results carried with MATLAB-Simulink and SimPowerSystem Toolbox show the effectiveness of the proposed control scheme.

Keywords: *Logic voltage controller, Three-level (NPC) inverter, Series active power filter, Voltage perturbation compensation, Matlab-Simulink and SimPowerSystem Toolbox*

1. INTRODUCTION

With proliferation of nonlinear loads, harmonic pollution is being considered as one of the major problems that degrade the power quality [1]. So far, shunt active power filters have been proposed as an interesting and high performance solution to improve the power quality, the shunt active power filter is used for reactive power and load current compensation by injecting equal but opposite harmonics current [2].

To protect sensible loads and improve the power quality in the distribution system, some solutions have been proposed by several authors. Among them the series active power filters have proven as an important and flexible alternative to compensate most important voltage perturbations [3].

The series active filter is especially used for compensation of voltage: unbalances, sags, swells and harmonics. The series active filter injects a voltage component in series with the supply voltage and can be regarded as a controlled voltage source [4]. The standard configuration is based on PWM-Voltage Source Inverter inserted in series between the load and the source voltage. Three single phase transformers are used to perform the series connection. This structure is limited to low power applications, for medium or high voltage three-level inverter is recommended.

The performance of any Series AF is based on three essentials design criteria: inverter topology, method used to determining the reference voltage compensation and lastly the controller capable to generate the inverter switching pulses. Today three-level inverter is one of the most widely employed multilevel topology and is applied in medium and high power applications [5]-[6]. The principally control techniques used to determining the compensation reference voltage are the instantaneous power theory [7] and the synchronous reference frame detection method [8]. The controller is the main part of any active power filter operation and has been a subject of many researches in recent years [9], pwm controller is a one of most commonly used controller with good performance compared to conventional hysteresis controller.

This paper presents a new pwm voltage controller for three-level neutral point clamped (NPC) series active filter for protecting sensible and critical voltage loads under all voltage perturbations.

Simulation results are presented in order to emphasize the good performance of the proposed series power filter topology. The systems performance is evaluated using Matlab-Simulink and SimPowerSystem Toolbox under different voltage perturbations in terms of source voltage Total Harmonic Distortion (THD) and robustness compensation under different source perturbations. The obtained results show the effectiveness of the proposed control scheme.

The organization of this paper begins with series active filter configuration based on three-level inverter, followed by control strategy adopted to calculate compensation voltages, before coming to the results simulation and discussion, and ended with conclusions.

2. SERIES ACTIVE FILTER CONFIGURATION

The circuit configuration of the series active filter is shown in figure 1. The Series AF is inserted between the perturbed voltage source and a protected load. It is composed of three phase voltage source converter, L_fC_f filter to suppress switching ripples and series transformers which inject the compensating voltage to the line [10].
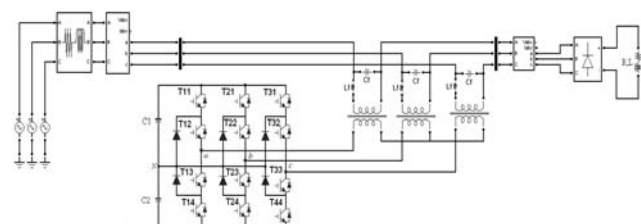

Fig. 1 Three-level (NPC) series active filter

3. THREE-LEVEL (NPC) INVERTER

Multilevel inverters are being investigated and recently used for active filter topologies. Three-level inverters are becoming very popular today for most inverter applications, such as machine drives and power factor compensators. The advantages of these converters are reduction of the harmonic content generated by the active filter and decreasing the voltage or current ratings of the semiconductors. Figure 2 shows the three-level inverter based on the six main switches (T_{11}, T_{21}, T_{31}, T_{14}, T_{24}, T_{34}) of the traditional two-level inverter, adding two auxiliary switches (T_{12}, T_{13}, T_{22}, T_{23}, T_{32}, T_{33}) and two neutral clamped diodes on each bridge arm respectively, the diodes are used to make the connection with the point of reference to obtain Midpoint voltages. For this structure, three kinds of output voltage level can obtain $U_{dc}/2$, 0 and $-U_{dc}/2$ corresponding to three kinds of switching states P, 0, N. As a result, there exist 27 kinds of switching output from the three-phase three-level inverter [11], [12].
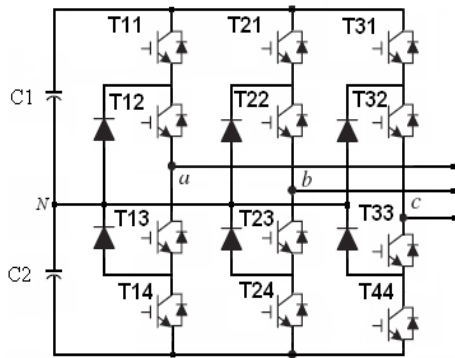

Fig. 2 Three-level NPC inverter

The switch connection function F_{KS} indicates the opened or closed state of the switch T_{KS} [12]:

$$F_{KS} = \begin{array}{ll} 1 & If \quad T_{ks} \quad close \\ 0 & If \quad T_{ks} \quad open \end{array} \qquad (1)$$

For a leg K of the three phases three-level NPC VSI, several complementary control laws are possible. The optimal control law of this inverter is:

$$\begin{array}{l} F_{K4} = 1 - F_{K1} \\ F_{K3} = 1 - F_{K2} \end{array} \qquad (2)$$

Half leg connection function F_{km}^{b} is defined as:

$$\begin{array}{l} F_{K4}^{b} = F_{K1} F_{K2} \\ F_{K0}^{b} = F_{K3} F_{K4} \end{array} \qquad (3)$$

With m=1 for the lower half leg and m=0 for the upper half leg.

As indicated in Table 1, each leg of the inverter can have three possible switching states, P, O, or N. When the top two switches T_{k1} and T_{k2} are turned on, the switching state is P. When the medium switches T_{k2} and T_{k3} are turned on switching state is O. When the lower switches T_{k3} and T_{k4} are turned on, the switching state is N [13].

Table 1 Switching states of three-level inverter

Switching States	Voltage output	Tk1	Tk2	Tk3	Tk4
P	$U_d/2$	ON	ON	OFF	OFF
0	0	OFF	ON	ON	OFF
N	$-U_d/2$	OFF	OFF	ON	ON

4. REFERENCE VOLTAGE IDENTIFICATION

The proposed series active filter adopted the power reactive theory to compensate all voltage perturbations. To extract the reference voltages a p-q theory described in [7], [8] is used. When the three-phase load instantaneous voltages U_{lu}, U_{lv}, U_{lw} and currents I_{lu}, I_{lv}, I_{lw}, are transformed into two-phase (α–β) coordinates, two phase voltages $\vec{u}_\alpha$, $\vec{u}_\beta$ and currents $\vec{i}_\alpha$, $\vec{i}_\beta$ are respectively given by:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix} = C_{32} \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix} \qquad (4)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{lu} \\ i_{lv} \\ i_{lw} \end{bmatrix} = C_{32} \begin{bmatrix} i_{lu} \\ i_{lv} \\ i_{lw} \end{bmatrix} \qquad (5)$$

On the (α–β) plane, $\vec{u}$ can be considered to be composed of $\vec{u}_\alpha$ and $\vec{u}_\beta$ and $\vec{i}$ of $\vec{i}_\alpha$ and $\vec{i}_\beta$:

$$\begin{array}{l} \vec{u} = \vec{u}_\alpha + \vec{u}_\beta \\ \vec{i} = \vec{i}_\alpha + \vec{i}_\beta \end{array} \qquad (6)$$

Assume that u_p is the projection of $\vec{u}$ in the direction of $\vec{i}$ and u_q the projection of $\vec{u}$ in the vertical direction of $\vec{i}$; u_p and u_q can be represented by:

$$\begin{bmatrix} u_p \\ u_q \end{bmatrix} = \begin{bmatrix} \sin \omega t & -\cos \omega t \\ -\cos \omega t & -\sin \omega t \end{bmatrix} \left(\sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \right) \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix}$$

$$\begin{bmatrix} u_p \\ u_q \end{bmatrix} = C_{pq} C_{32} \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix} \qquad (7)$$

Where C_{pq} is the pq transformation matrix, which executes the calculation to convert the two-phase voltages u_α and u_β into u_p and u_q.

When Ulu, Ulv and Ulw are the three-phase voltage source, the respective components $\overline{u_p}$ and $\overline{u_q}$ in u_p and u_q are corresponding to the positive sequence fundamental active and reactive components in three-phase voltages.

The fundamental components Uluf, Ulvf and Ulwf in load voltages can be obtained by an inverse transformation of (7):

$$\begin{bmatrix} U_{luf} \\ U_{lvf} \\ U_{lwf} \end{bmatrix} = \left(\sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \right) \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \begin{bmatrix} \overline{u_p} \\ \overline{u_q} \end{bmatrix}$$

(8)

$$\begin{bmatrix} U_{luf} \\ U_{lvf} \\ U_{lwf} \end{bmatrix} = C_{23} C_{pq}^{-1} \begin{bmatrix} \overline{u_p} \\ \overline{u_q} \end{bmatrix}$$

Where C_{pq}^{-1} is the inverse matrix of C_{pq}, which executes the calculation to convert $\overline{u_p}$ and $\overline{u_q}$ back into (α–β) coordinates. Hence the voltage compensation can be calculated out as:

$$\begin{bmatrix} U_{luc} \\ U_{lvc} \\ U_{lwc} \end{bmatrix} = \begin{bmatrix} U_{lu} \\ U_{lv} \\ U_{lw} \end{bmatrix} - \begin{bmatrix} U_{luf} \\ U_{lvf} \\ U_{lwf} \end{bmatrix}$$

(9)
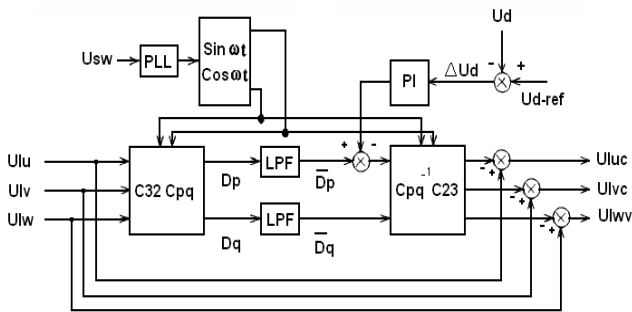
Fig. 3 Reference compensation voltage calculation

5. SERIES ACTIVE FILTER LOGIC CONTROL

The PWM logic controller for three-level (NPC) inverter proposed to replace conventional hysteresis controller is shown in figure 4. The difference between the injected voltage and the reference voltage determines the reference voltage (e), this output voltage is compared with two carrying triangular identical waves shifted one from other by a half period of chopping and generate switching pulses[14].
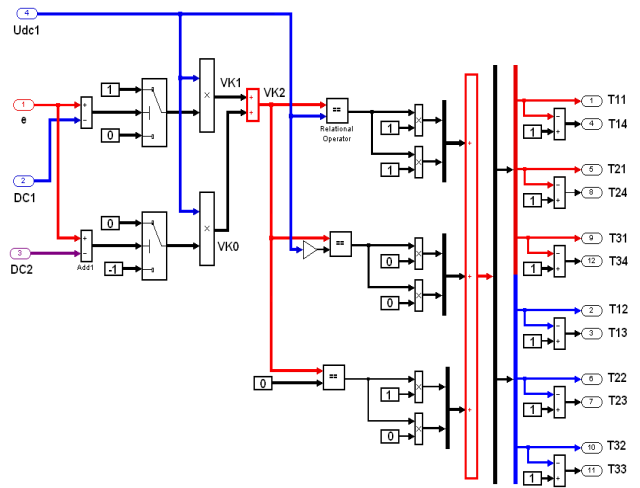

Fig. 4 PWM logic control

The control of inverter is summarized in the two following stages:
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 Ti1=1, Ti2=1, Ti3=0, Ti4=0,
- If (Vi1+Vi2)=0 Then Ti1=0, Ti2=1, Ti3=1, Ti4=0,
- If (Vi1+Vi2)=-1 Then Ti1=0, Ti2=0, Ti3=1, Ti4=1.

6. SIMULATION RESULTS AND DISSCUSSION

The Matlab-Simulink simulation block diagram of the proposed three-level series active filter based on pwm voltage controller is shown in figure 5. The model parameters used for simulation are: Voltage source Vs=220V, Frequency Fs=50Hz, Resistor Rs=0.1mΩ, Inductance Ls=0.0002mH, Resistor Rl =48.6Ω, Inductance Ll=40mH, Capacitance C1= C2=300μF, Resistor Rc=0.27m Ω, Inductance Lc=0.8mH.
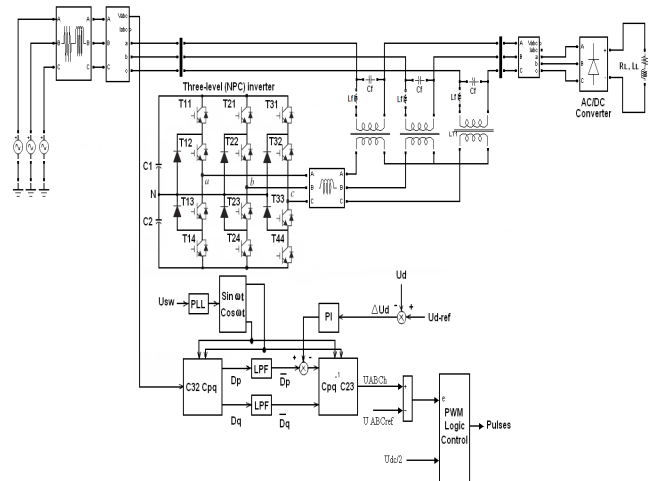

Fig. 5 Three-level series active filter using pwm voltage controller based on p-q theory

The proposed series active power filter is simulated under MATLAB-Simulink and SimPower System environment to estimate its' performance. It is tested for several different operating conditions such as steady-state, transient condition for voltage sag, swell, unbalance and under balanced distorted utility voltages, intending to validate the Series APF system performance. The simulation results obtained for all voltage perturbations are shown in figures 6 to 12 and discussed in the following subsections.

6.1. Voltage harmonics compensation

When the three-phase voltages are balanced-distorted, the mains voltages contain the fundamental component and harmonic components. The expression of the balanced-distorted voltages source used is expressed bellow:

$$v_{sa} = 311\sin(\omega t) + 141\sin(2\omega t) + 35\sin(4\omega t) + 14\sin(5\omega t)$$

$$v_{sb} = 311\sin(\omega t + \frac{4\pi}{3}) + 141\sin(2\omega t + \frac{2\pi}{3})$$

$$+ 35\sin(4\omega t + \frac{4\pi}{3}) + 14\sin(5\omega t + \frac{2\pi}{3}) \qquad (10)$$

$$v_{sc} = 311\sin(\omega t + \frac{2\pi}{3}) + 141\sin(2\omega t + \frac{4\pi}{3}) + 35\sin(4\omega t + \frac{2\pi}{3})$$

$$+ 14\sin(5\omega t + \frac{4\pi}{3})$$

At time t_1=0.1s to t_2=0.2s, harmonic voltage perturbation is introduced voluntarily in the utility. The series APF is put into the operation; it starts immediately the process of compensation. The load voltage before series active filter operation, three-phase fundamental voltages, injected voltages by series APF and the three-phase compensated voltages delivered to critical load are shown in figure 7. After compensation the THD of the load voltage is reduced from 46.93% to 3.52% in conformity with IEEE-519 standard Norms.
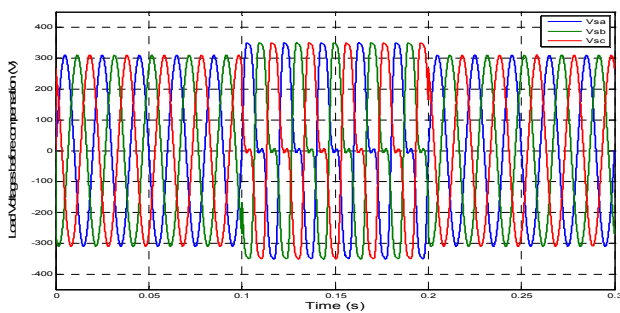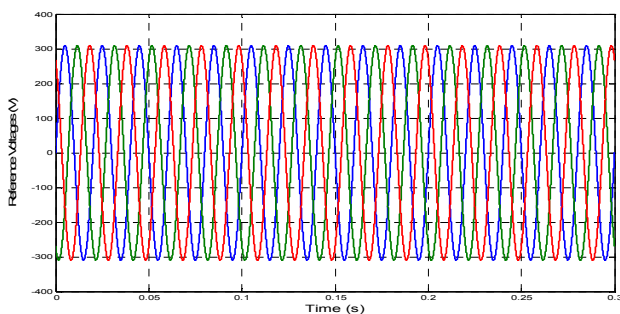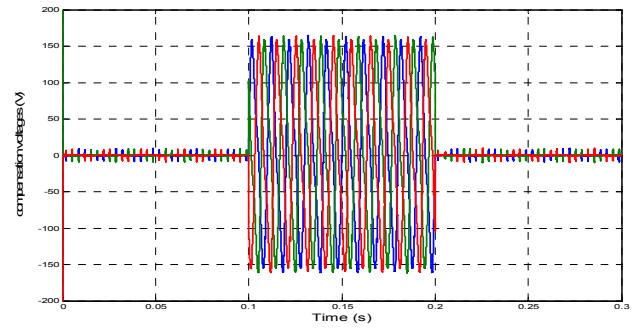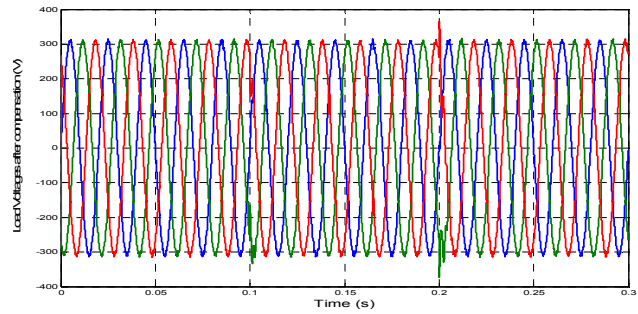
(c)   Compensation voltages

(d)   Load voltages after compensation

Fig. 6 Simulation results with harmonics voltage compensation

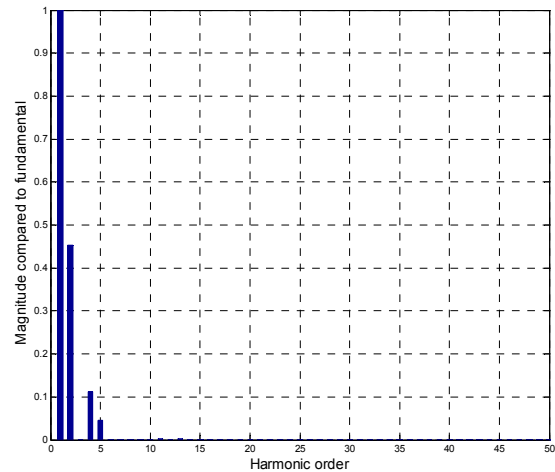**Fig. 7** Load voltage harmonic spectrum without Series AF (Fundamental (50Hz) = 310.1, THD=46.93%)
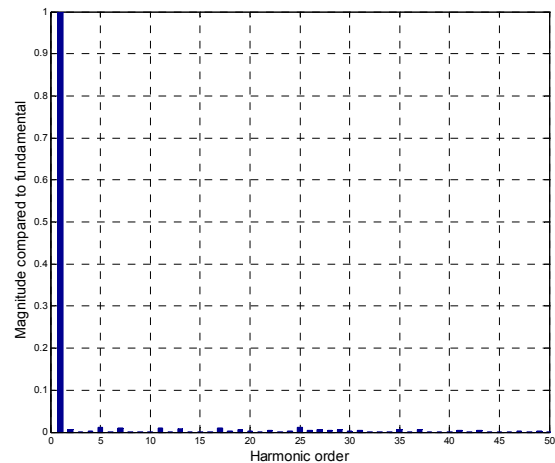
(a)   Load voltages before compensation

(b)   Reference voltages

Fig. 8 Load voltage harmonic spectrum with Series AF (Fundamental (50Hz) = 308.2, THD=3.52%)

6.2. Voltage unbalances compensation

In this case, the three phase voltages sources are unbalanced, but do not contain harmonic components, their expressions are given in (11):

$$v_{sa} = 311\sin(\omega t) + 31\sin(\omega t)$$

$$v_{sb} = 311\sin(\omega t + \frac{4\pi}{3}) + 31\sin(\omega t + \frac{2\pi}{3}) \qquad (11)$$

$$v_{sc} = 311\sin(\omega t + \frac{2\pi}{3}) + 31\sin(\omega t + \frac{4\pi}{3})$$

Figure 9 shows the three-phase voltage load, three-phase fundamental voltages, three-phase voltage compensation and the three-phase compensated load voltage with unbalance voltage perturbation introduced voluntary between t1=0.1s and t2= 0.2s.
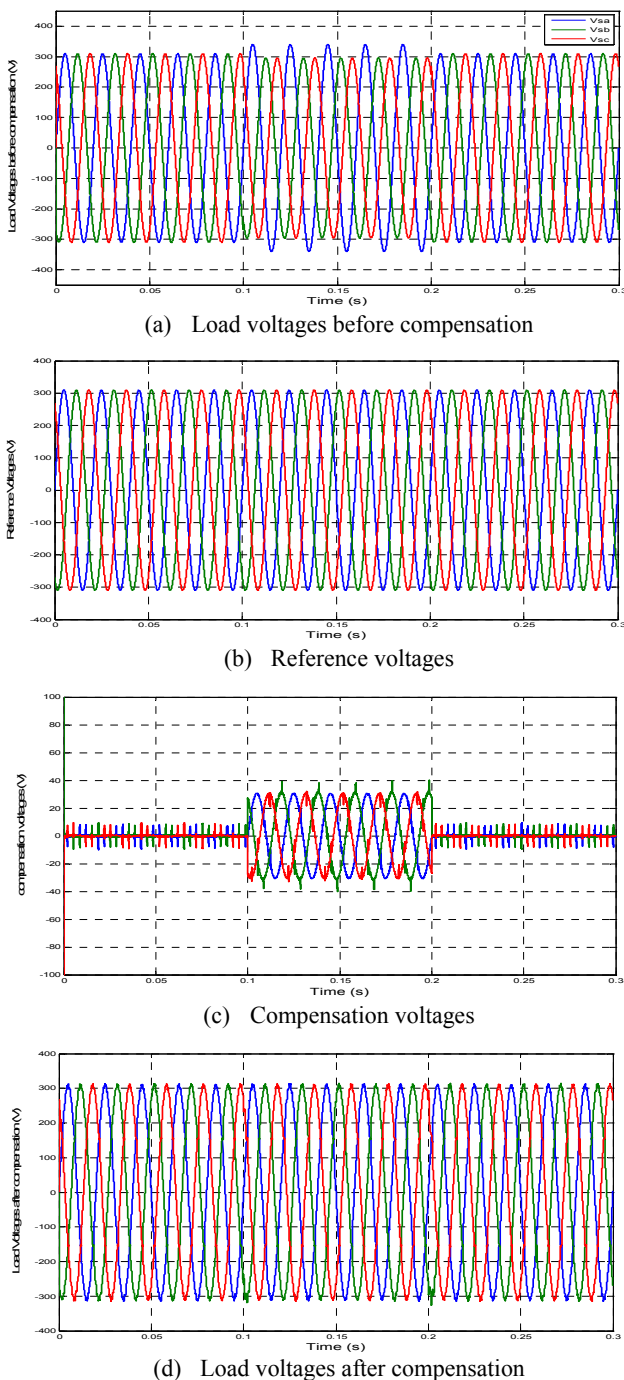
6.3. Voltage sags compensation

To study the performance of series active filter during voltage sag conditions, we suppose that the load voltage is sinusoidal and the sag (35%) is introduced voluntary between instants t1=0.1s and t2=0.2s. The expression of the sag voltage is given by equation (12):

$$v_{sa} = 200\sin(\omega t)$$

$$v_{sb} = 200\sin(\omega t + \frac{4\pi}{3}) \qquad (12)$$

$$v_{sc} = 200\sin(\omega t + \frac{2\pi}{3})$$

The series APF is put into operation instantly to compensate this perturbation. After instant t2=0.2s, the system is again at normal working condition. The load
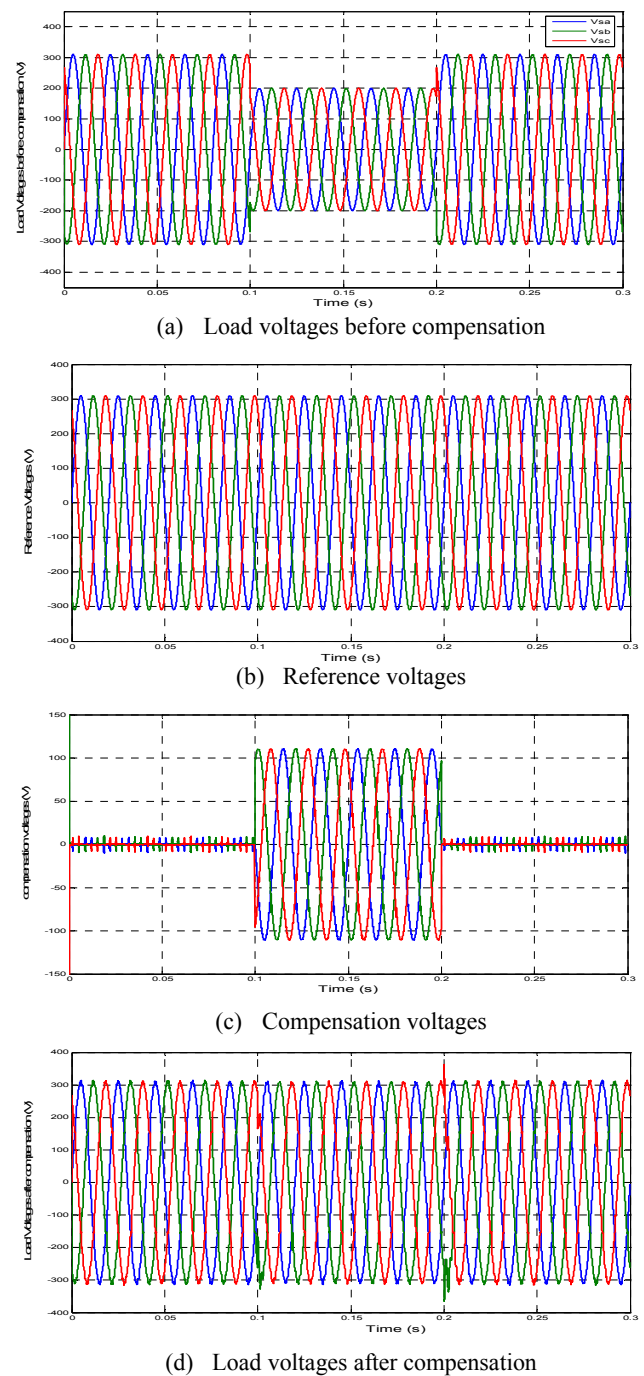

(a) Load voltages before compensation

(b) Reference voltages

(c) Compensation voltages

(d) Load voltages after compensation

Fig. 9 Simulation results with unbalances voltage compensation

(a) Load voltages before compensation

(b) Reference voltages

(c) Compensation voltages

(d) Load voltages after compensation

Fig. 10 Simulation results with sags voltage compensation

voltages, three-phase fundamental voltages, compensating voltages and the load voltages after compensation obtained by simulation are shown in figure 10.
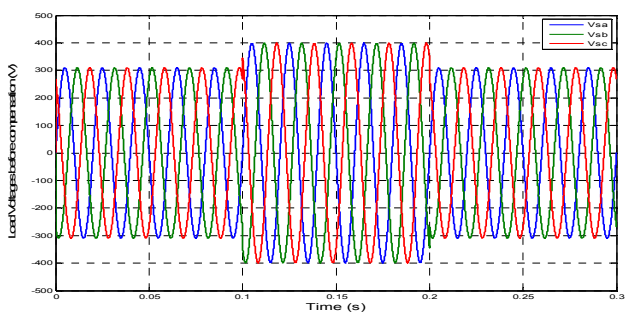
6.4. Voltage swells compensation

A swell (35%) is now introduced on the system during the time t1=0.1 sec to t2=0.2 sec. Under this condition the series APF injects an out of phase compensating voltage (≈30%) in the line through series transformers, equal to the difference between the reference load voltage and voltage without compensation. As shown in figure 11 the load voltage profile before compensation, three-phase fundamental voltages, the compensating voltages in and the load voltages after compensation using the proposed series active filter. The expression of the swell voltage is given by equation (13):

$$v_{sa} = 400\sin(\omega t)$$
$$v_{sb} = 400\sin(\omega t + \frac{4\pi}{3}) \qquad (13)$$
$$v_{sc} = 400\sin(\omega t + \frac{2\pi}{3})$$

### 6.5. All voltage perturbation compensation

The performance of the proposed Series active power filter system is also tested under all voltage perturbations simultaneously. The simulation results are shown in figure 13. The voltage swell is introduced voluntarily in the utility voltage (35%) between t1=0.1s and t2=0.16s. And after that, a voltage sags (30%) is introduced between t2=0.16s and t3=0.22s. The voltage harmonics is introduced between t3=0.22s and t4=0.28s. The voltage

(a)   Load voltages before compensation
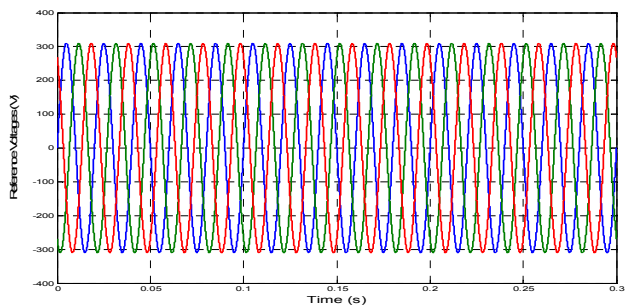
(b)   Reference voltages
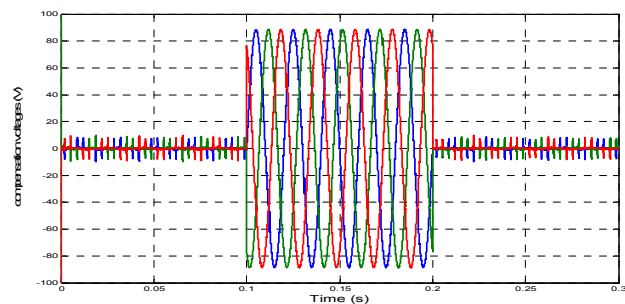
(c)   Compensation voltages

(d)   Load voltages after compensation

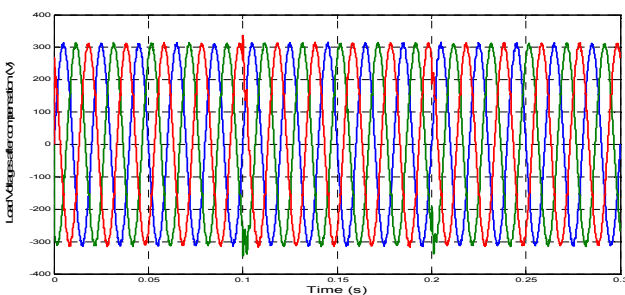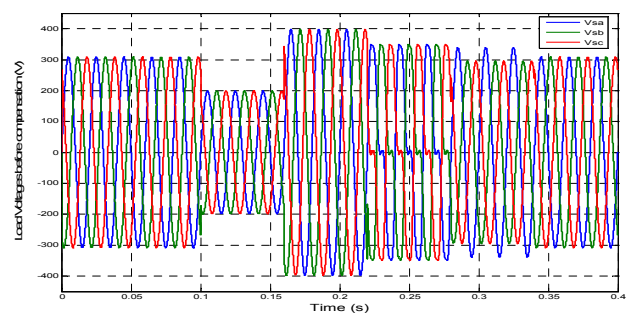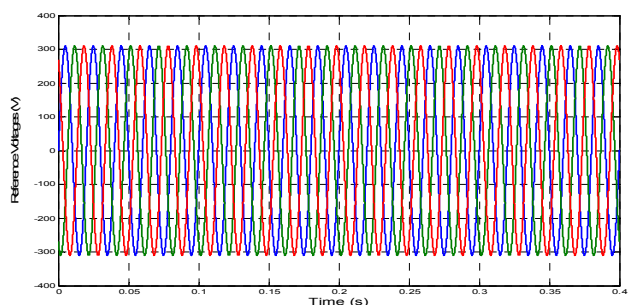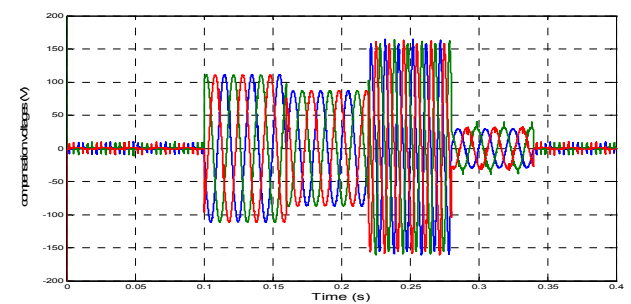**Fig. 11** Simulation results with swells voltage compensation
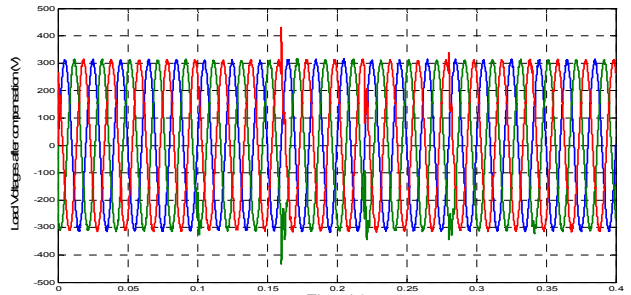

(a)   Load voltages before compensation

(b)   Reference voltages

(c)   Compensation voltages

(d)   Load voltages after compensation

Fig. 12 Simulation results with all voltage compensation

unbalances is introduced between t4=0.28s and t5=0.34s. After t5=0.34s the system is again at normal working condition. The load voltages, three-phase fundamental voltages, compensating voltages and the load voltages after compensation obtained by simulation are shown in figure 12. It is illustrate that the proposed system does not show any significant effect of distortion present in the utility voltages on its compensation capability and the load voltage under all voltage perturbations is maintained constant and sinusoidal.

The performance of the proposed series AF system is tested under all voltage perturbations separately and simultaneously: harmonics, swells, sags and unbalances. Figures 7 and 8 show respectively the harmonic spectrum of the voltage delivered to sensible loads before and after application of the series active filter. It is observed that the load voltage harmonics is widely reduced from 46.93% to 3.52% in conformity with standard Norms. In cases of voltage swell (35%), voltage sag (30%) and unbalances introduced voluntarily in the supply voltage between t1=0.1s and t2= 0.2s, the load voltage is instantly compensated. The effectiveness of the proposed series active filter has been demonstrated in maintaining the three-phase load voltages balanced and sinusoidal, moreover the proposed system does not show any significant effect of perturbation type present in the utility voltages on its compensation capability and the load voltage under all voltage perturbations is maintained constant and sinusoidal.

7. CONCLUSIONS

To enhance the power quality and improve the voltage delivered to sensible and critical loads, a new series active power filter configuration using pwm voltage controller based on three-level (NPC) inverter topology has been proposed in this paper. The voltage perturbations studied in this paper concern voltage: harmonics, sags, swells and unbalances, all these perturbations are successfully compensated using the proposed system. The load voltage harmonic levels are maintained below IEEE-519 standard Norms when the source voltage is distorted, the THD of the load voltage is significantly reduced from 46.93% to 3.52%. The simulation results show that the new system is efficacies and compensates all type of voltage perturbations. However, the current source is highly distorted and rich on harmonics. To eliminate this drawback, the future research work will be focused on current source compensation using hybrid series active filter configuration or Unified Power Quality Conditioner system.

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