Three-level (NPC) Series Active Filter based on Fuzzy Logic Voltage Controller to Compensate Voltage Sags, Swells, Harmonics and Unbalances

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Abstract: *This paper presents a new control scheme for three-phase three-wire series active power filter to compensate all load voltage perturbations: harmonics unbalances sags and swells. The conventional configuration of three-phase series active power filter is based on the two-level voltage source inverter with classical controllers requiring a complex and a complicated mathematical model. In order to overcome these drawbacks and improve the APF there is a great tendency to use multilevel converters based on intelligent technique controllers. Today three-level inverter topology and fuzzy logic controllers are successfully employed in various industrial applications; in order to get benefits of their advantages a new control scheme for series active power filter is proposed in this paper. The fuzzy voltage controller is designed to improve compensation capability of active power filter by adjusting the voltage error using a fuzzy rule. The control strategy use instantaneous reactive power theory easy to implement and gives a good performances. The numerical simulation results, using MATLAB-Simulink and SimPowerSystem BlockSet Toolbox, from complete structure including control and power circuits are presented and discussed.*

Key words: *Series active power filter, Fuzzy logic voltage controller, voltage perturbations, power quality, Three-level (NPC) inverter.*

1. Introduction

With the continuous proliferation of non linear loads, harmonic pollution is being considered as one of the major problems that degrade the power quality. So far, active power filters have been proposed as an interesting and high performance solution to improve the power quality [1]. The shunt active power is used to compensate current harmonics. The different types of voltage perturbations considered are: voltage unbalances, voltage harmonics, voltage sags, and voltage swell are frequently met on the electrical supply network and have harmful effects on the electric equipments [2]. Series active filter acts as a voltage source it is used to compensate all voltage load perturbations. The usual configuration used is based on PWM-Voltage Source Inverter; it is inserted in series between the load and the source voltage. Three single phase transformers are used to perform the series connection. The two level topologies are limited to low power applications, for medium or high voltage three-level inverter is recommended.

The controller is the main part of any active power filter operation and has been a subject of many researches in recent years [3,4], to improve the APF performances there's a great tendency to use intelligent control techniques, particularly fuzzy logic controllers. Fuzzy logic control theory is a mathematical discipline based on vagueness and uncertainty. The fuzzy control does not need an accurate mathematical model of a plant. It allows one to use non-precise or ill-defined concepts. Fuzzy logic control is also nonlinear and adaptive in nature that gives it robust performance under parameter variation and load disturbances. This control technique relies on the human capability to understand the system's behavior and is based on qualitative control rules. Thus, control design is simple since it is only based on if....then linguistic rules [5,6,7].

The investigation in this paper concentrates on the fuzzy control approaches for the three-phase three-level series APF to compensate all voltage perturbations. The control strategy used is the instantaneous reactive power theory [14].

The performance of the proposed series active filter is evaluated using Matlab-Simulink and SimPowerSystem Toolbox under different voltage perturbations. The obtained results show the effectiveness of the proposed control scheme.

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

2. Series active power filter

The circuit configuration of the series active filter is shown in Fig. (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 [8].

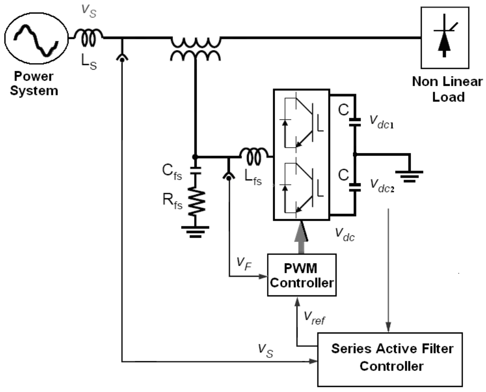

Fig.1. Three-level (NPC) Series active filter

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. Fig. (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 [10,11].

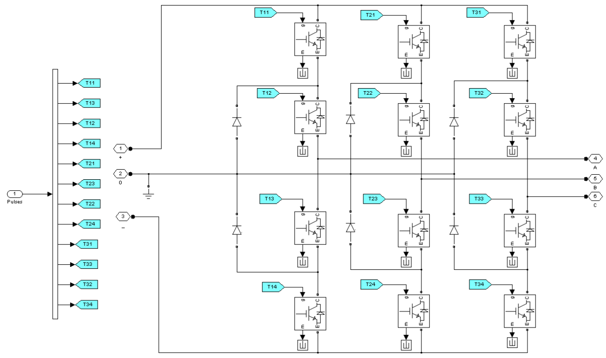

Fig. 2. Three-level NPC inverter

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

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

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:

$$\begin{aligned} F_{K4} &= 1 - F_{K1} \\ F_{K3} &= 1 - F_{K2} \end{aligned} \quad (2)$$

Half leg connection function F^b_{Km} is defined as:

$$\begin{aligned} F^b_{K4} &= F_{K1}F_{K2} \\ F^b_{K0} &= F_{K3}F_{K4} \end{aligned} \quad (3)$$

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_{i1} and T_{i2} are turned on, the switching state is P. When the medium switches T_{i2} and T_{i3} are turned on switching state is O. When the lower switches T_{i3} and T_{i4} are turned on, the switching state is N [11,12].

Switching States	Voltage output	T_{i1}	T_{i2}	T_{i3}	T_{i4}
P	$U_d/2$	ON	ON	OFF	OFF
0	0	OFF	ON	ON	OFF
N	$-U_d/2$	OFF	OFF	ON	ON

Table (1) Switching states of three-level inverter

4. Voltage reference identification

The proposed series active filter is adopted to compensate all voltage perturbations. The control strategy used for extracting the reference voltages is based on the p-q theory described in [13,14]. In case when the three-phase voltage source in the grid is symmetric and distorted:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty} \sqrt{2} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin\left[(n\omega t - \frac{2\pi}{3}) + \theta_n\right] \\ \sum_{n=1}^{\infty} \sqrt{2} U_n \sin\left[(n\omega t + \frac{2\pi}{3}) + \theta_n\right] \end{bmatrix} \tag{4}$$

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:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \begin{bmatrix} \sqrt{2} U_1 \sin(\omega t + \theta_1) \\ \sqrt{2} U_1 \sin\left[(\omega t - \frac{2\pi}{3}) + \theta_1\right] \\ \sqrt{2} U_1 \sin\left[(\omega t + \frac{2\pi}{3}) + \theta_1\right] \end{bmatrix} \tag{5}$$

Equation (1) is transformed into (α–β) reference frame:

$$\begin{bmatrix} U_\alpha \\ U_\beta \end{bmatrix} = C_{32} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \sqrt{3} \begin{bmatrix} \sum_{n=1}^{\infty} U_n \sin(n\omega t + \theta_n) \\ \sum_{n=1}^{\infty} \mp U_n \sin(n\omega t + \theta_n) \end{bmatrix} \tag{6}$$

Where:

$$C_{32} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{7}$$

Three-phase positive fundamental current template is constructed:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \tag{8}$$

Equation (5) is transformed to (α–β) reference frame:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \sin(\omega t) \\ -\cos(\omega t \end{bmatrix} \tag{9}$$

According to the instantaneous reactive power theory [15], then:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{10}$$

Where DC and AC components are included:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} \tag{11}$$

P and q are passed through low pass filter (LPF) and DC component are got:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \sqrt{3} \begin{bmatrix} U_1 \cos(\theta_1) \\ U_1 \sin(\theta_1) \end{bmatrix} \tag{12}$$

According to (7), transformation is made:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \tag{13}$$

As for DC components of p and q:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} u_{\alpha f} & u_{\beta f} \\ u_{\beta f} & -u_{\alpha f} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} \tag{14}$$

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

$$\begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \tag{15}$$

The three-phase fundamental voltage is:

$$\begin{bmatrix} U_{af} \\ U_{bf} \\ U_{cf} \end{bmatrix} = C_{23} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \sqrt{2} U_1 \begin{bmatrix} \sin(\omega t + \theta_1) \\ \sin(\omega t + \theta_1 - \frac{2\pi}{3}) \\ \sin(\omega t + \theta_1 + \frac{2\pi}{3}) \end{bmatrix} \tag{16}$$

Where:

$$C23 = \begin{bmatrix} 1 & 0 \\ -1/2 & \frac{\sqrt{3}}{2} \\ -1/2 & \frac{\sqrt{3}}{2} \end{bmatrix} \tag{17}$$

5. Fuzzy logic controller

Fuzzy logic controllers (FLCs) have been interest a good alternative in more power electronics application. Their advantages are robustness, not need a mathematical model and accepting non-linearity [16,17]. To benefit of these advantages new simple fuzzy logic voltage controller for three-level inverter is designed. Fuzzy logic unlike Boolean or crisp logic, deal with problems that have vagueness, uncertainty or imprecision and uses membership functions with values varying between 0 and 1. Fig. (3) shows a schematic block diagram of fuzzy inference system or fuzzy controller [18].

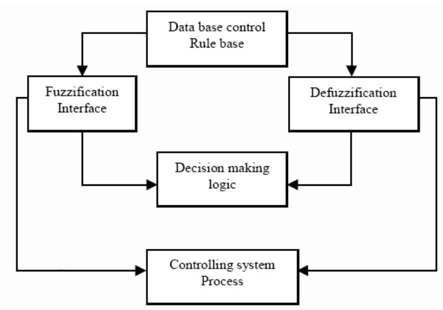

Fig. 3. Fuzzy inference system

The fuzzy voltage controller proposed in this paper is designed to improve compensation capability of series APF by adjusting the voltage error using fuzzy rules. The desired inverter switching signals of the three-level series active filter are determined according the error between the compensate 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. To convert it into linguistic variable, we use seven fuzzy sets: NL (Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive Large). Fig. (4) shows the membership functions used in fuzzification and defuzzification.

The fuzzy controller for every phase is characterized for the following:

- Sept fuzzy sets for each input,
- Sept fuzzy sets for output,
- Triangular and trapezoidal membership function for the inputs and output,
- Implication using the "min" operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication,
- Defuzzification using the "centroid" method.

The fuzzy rules are given by Table (2).

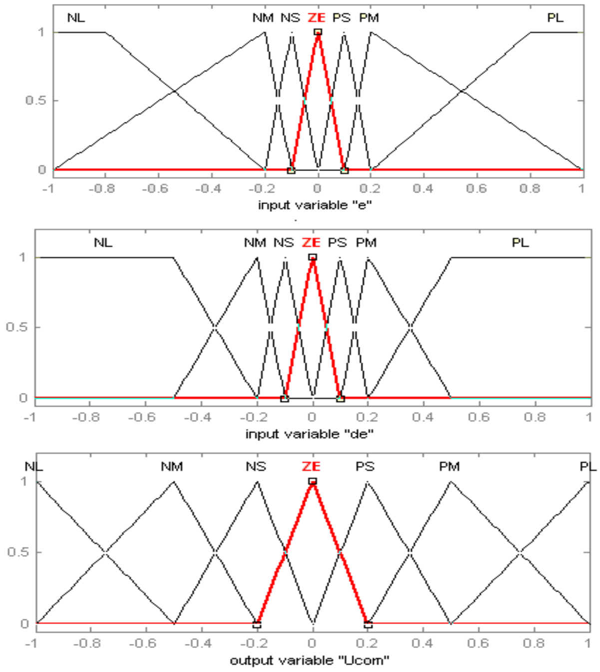

Fig. 4. Membership function for the inputs and output variables

e de/dt	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NM	NM	NS	NS	EZ
NM	NL	NM	NM	NS	NS	EZ	PS
NS	NM	NM	NS	NS	EZ	PS	PS
ZE	NM	NS	NS	EZ	PS	PS	PM
PS	NS	NS	EZ	PS	PS	PM	PM
PM	NS	EZ	PS	PS	PM	PM	PL
PL	EZ	PS	PS	PM	PM	PL	PL

Table (2) Fuzzy rules

Errors for each phase are discretized by the zero order hold blocks. The error rate is derivative of the error and it is obtained by the use of unit delay block. The saturation block imposes 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, he signal is clipped to the upper or lower bound. The output of the saturation blocks are inputs to fuzzy logic controllers. The outputs of these fuzzy logic controllers are used in generation of pulses switching signals of the three-level inverter. The switching signals are generated by means of comparing a two carrier signals with the output of the fuzzy logic controllers. The simulink model of the fuzzy logic switching signals generation is given by Fig. (5).

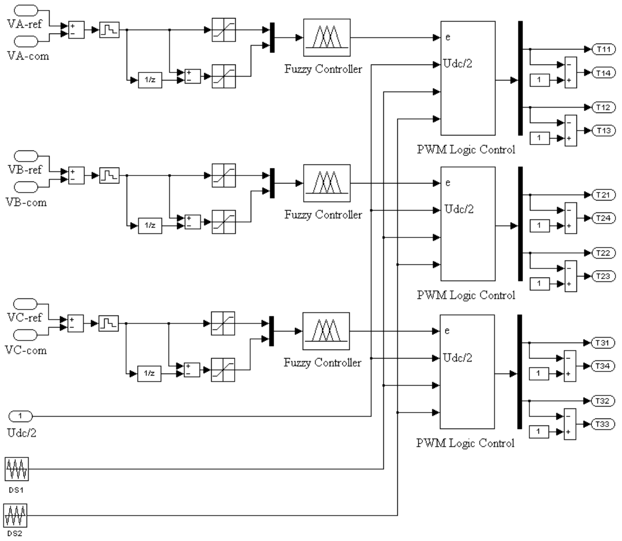

Fig. 5. Switching signals generation for the series AF based on three-level inverter

The controller calculates the difference between the injected voltage and the reference voltage that determines the error voltage, this error voltage pass through fuzzy controller. The fuzzy voltage error is compared with two carrying triangular identical waves shifted one from other by a half period of chopping and generate switching pulses [19],[20].

The control of inverter is summarized in the two following stages:
Determination of the intermediate signals V_{i1} and V_{i2}:

- If error $E_c \geq$ carrying 1 Then V_{i1}= 1
- If error $E_c <$ carrying 1 Then V_{i1}= 0
- If error $E_c \geq$ carrying 2 Then V_{i2}=0
- If error $E_c <$ carrying 2 Then V_{i2}=-1

Determination of control signals of the switches T_{ij} and V_{i2} (i=1,2,3 ; j=1,2,3,4):

- If ($V_{i1}+V_{i2}$)=1 Then T_{i1}=1, T_{i2}=1, T_{i3}=0, T_{i4}=0,
- If ($V_{i1}+V_{i2}$)=0 Then T_{i1}=0, T_{i2}=1, T_{i3}=1, T_{i4}=0,
- If ($V_{i1}+V_{i2}$)=-1 Then T_{i1}=0, T_{i2}=0, T_{i3}=1, T_{i4}=1,

6. Simulation model

The Matlab-Simulink simulation block diagram of the proposed three-level series active filter based on fuzzy logic voltage controller is shown in Fig. (6). The model parameters used for simulation are: Voltage source V_s=220V, Frequency F_s=50Hz, Resistor R_s=0.1mΩ, Inductance L_s=0.0002mH, Resistor R_{ch} =48.6Ω, Inductance L_{ch}=40mH, Capacitance C_{dc}=3000μF, Resistor R_c=0.27m Ω, Inductance L_c=0.8mH.

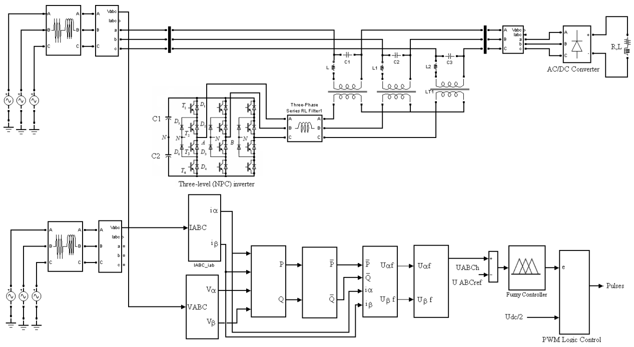

Fig. 6. Three-level series active filter controlled by fuzzy voltage controller based on p-q theory

7. Simulation results and discussion

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 Figs. 8 to 13 and discussed in the following subsections.

7.1 Voltage harmonic compensation

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

$$
\begin{aligned}
v_{sa} &= 311\sin(\omega t) + 141\sin(2\omega t) + 35\sin(4\omega t) + 14\sin(5\omega t) \\
v_{sb} &= 311\sin(\omega t + \frac{4\pi}{3}) + 141\sin(2\omega t + \frac{2\pi}{3}) \\
&\quad + 35\sin(4\omega t + \frac{4\pi}{3}) + 14\sin(5\omega t + \frac{2\pi}{3}) \qquad (18) \\
v_{sc} &= 311\sin(\omega t + \frac{2\pi}{3}) + 141\sin(2\omega t + \frac{4\pi}{3}) + 35\sin(4\omega t + \frac{2\pi}{3}) \\
&\quad + 14\sin(5\omega t + \frac{4\pi}{3})
\end{aligned}
$$

At time t1=0.1s to t2=0.16s, harmonic voltage perturbation is introduced voluntarily in the utility. The series APF is put into the operation; it starts immediately the process of compensation by injecting sum of the 5th, 7th, 9th, and 11th harmonics. 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 Fig.(7). In this case the load voltage THD is significantly reduced from 46.93 % to 3.66 % in conformity with IEEE-519 standard Norms.

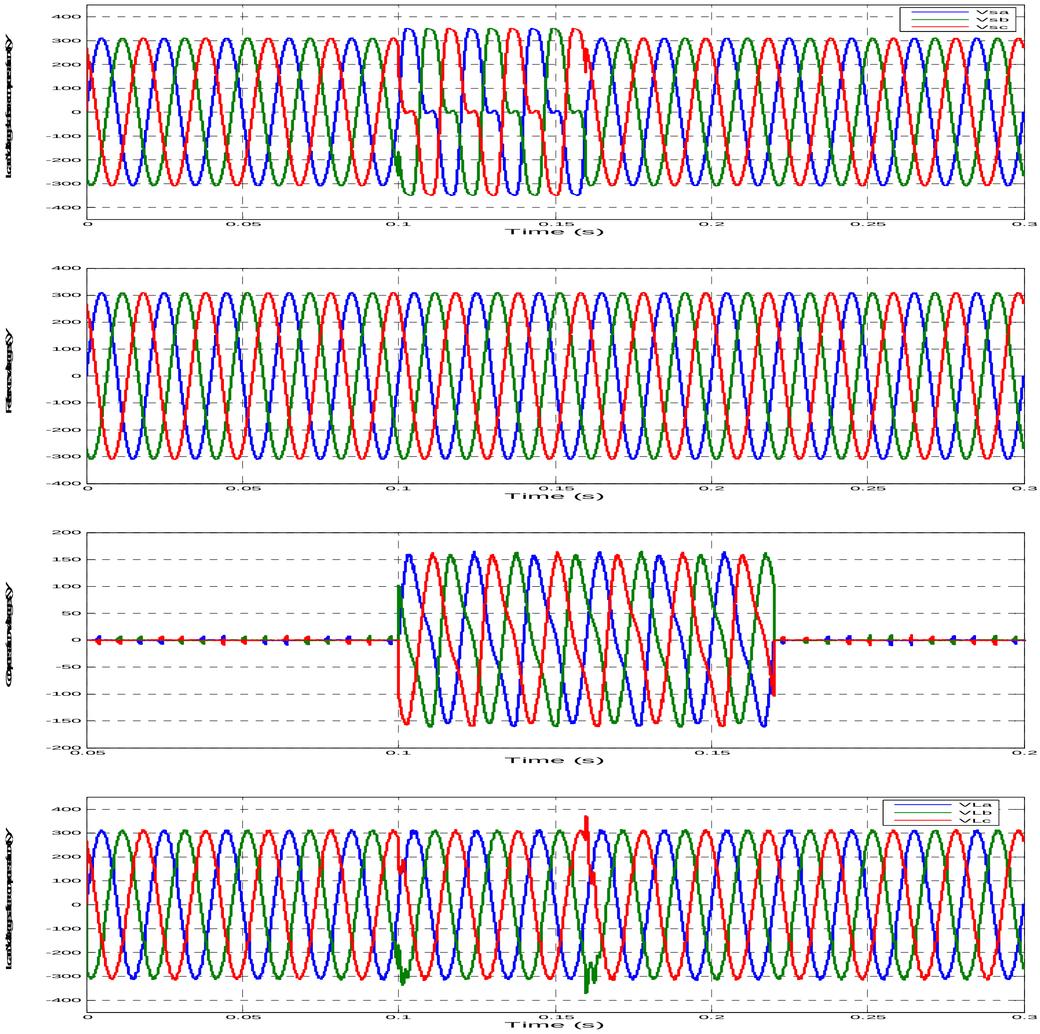

Fig. 7. Three-phase load voltage, three-phase fundamental voltages, three-phase compensating voltage and three-phase load voltage after compensation with harmonic voltage perturbation introduced between t1=0.1s and t2=0.16s

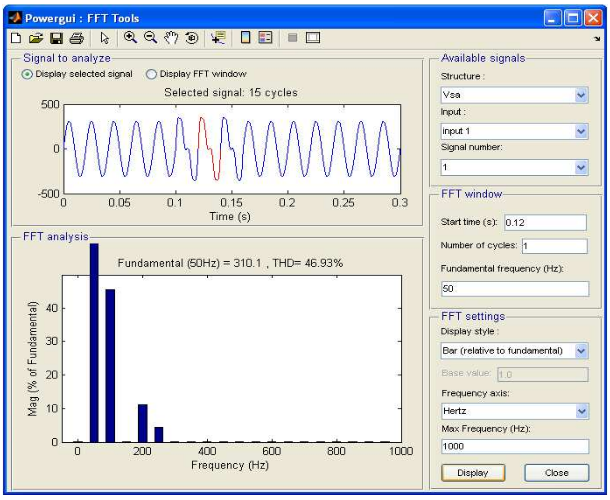

Fig. 8. Load voltage harmonic spectrum without Series AF (THD=46.93%)

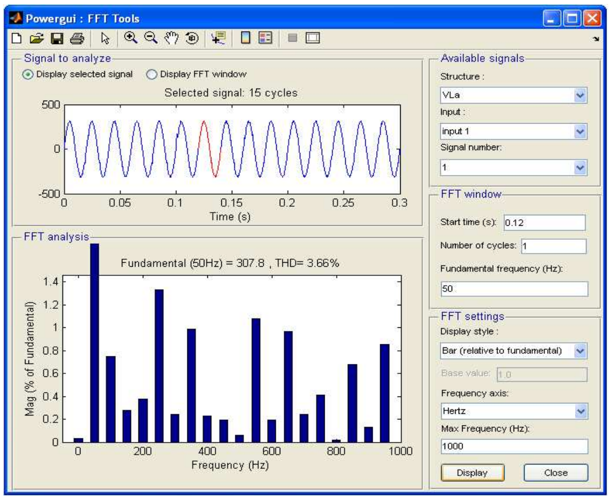

Fig. 9. Load voltage harmonic spectrum with Series AF (THD=3.66%)

7.2 Voltage unbalance compensation

In this case, the three phase voltages sources are unbalanced, but do not contain harmonic components, their expressions are given in (19):

Fig. 10, 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 0.16s.

$$
\begin{aligned}
v_{sa} &= 311\sin(\omega t) + 31\sin(\omega t) \\
v_{sb} &= 311\sin(\omega t + \frac{4\pi}{3}) + 31\sin(\omega t + \frac{2\pi}{3}) \\
v_{sc} &= 311\sin(\omega t + \frac{2\pi}{3}) + 31\sin(\omega t + \frac{4\pi}{3})
\end{aligned}
\qquad (19)
$$

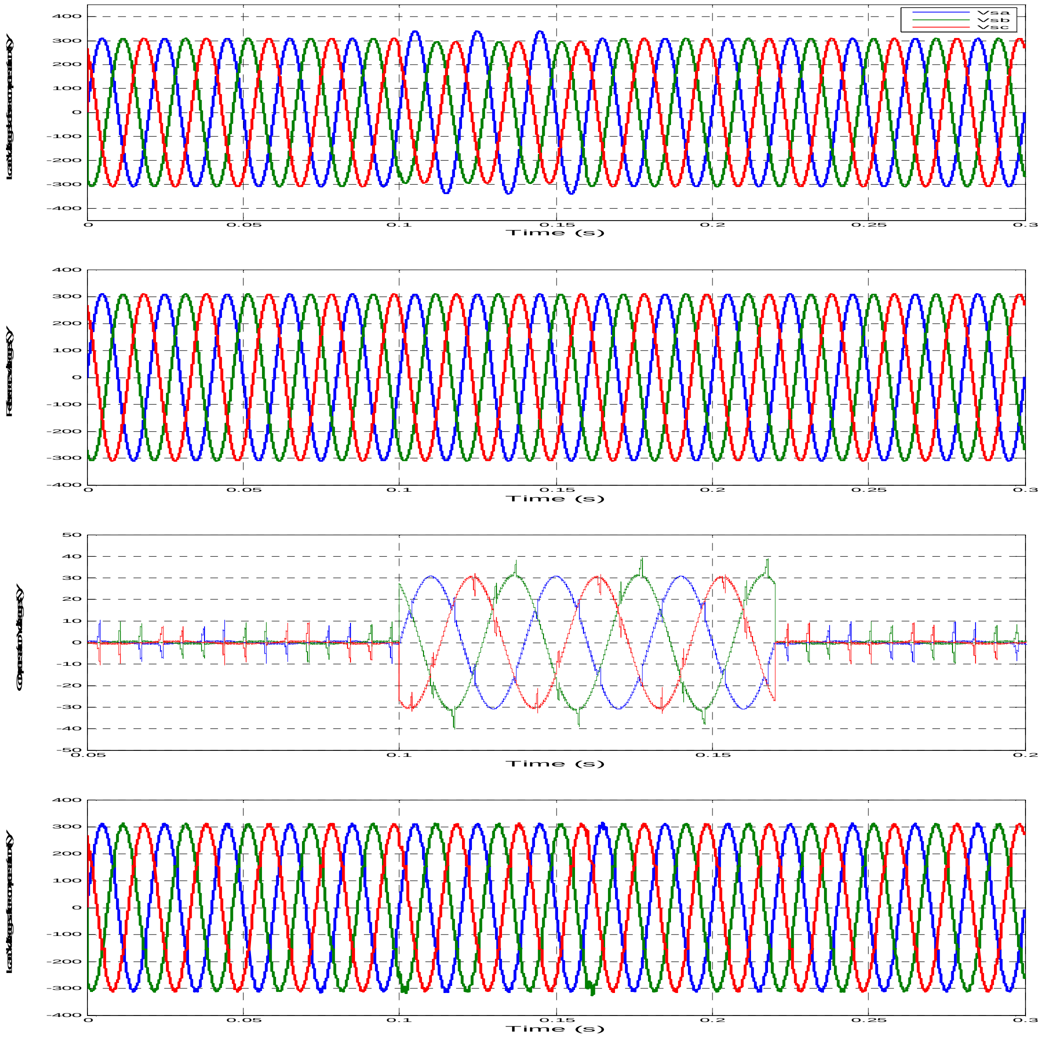

Fig. 10. Three-phase load voltage, three-phase fundamental voltages, three-phase compensating voltage and three-phase load voltage after compensation with unbalance voltage perturbation introduced between t1=0.1s and t2=0.16s

7.3 Voltage sag 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=0.16s. The series APF is put into operation instantly to compensate this perturbation. After time t2=0.16s, 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 Fig.11. The expression of the sag voltage is given by equation (20):

$$v_{sa} = 200\sin(\omega t)$$
$$v_{sb} = 200\sin(\omega t + \frac{4\pi}{3}) \quad (20)$$
$$v_{sc} = 200\sin(\omega t + \frac{2\pi}{3})$$

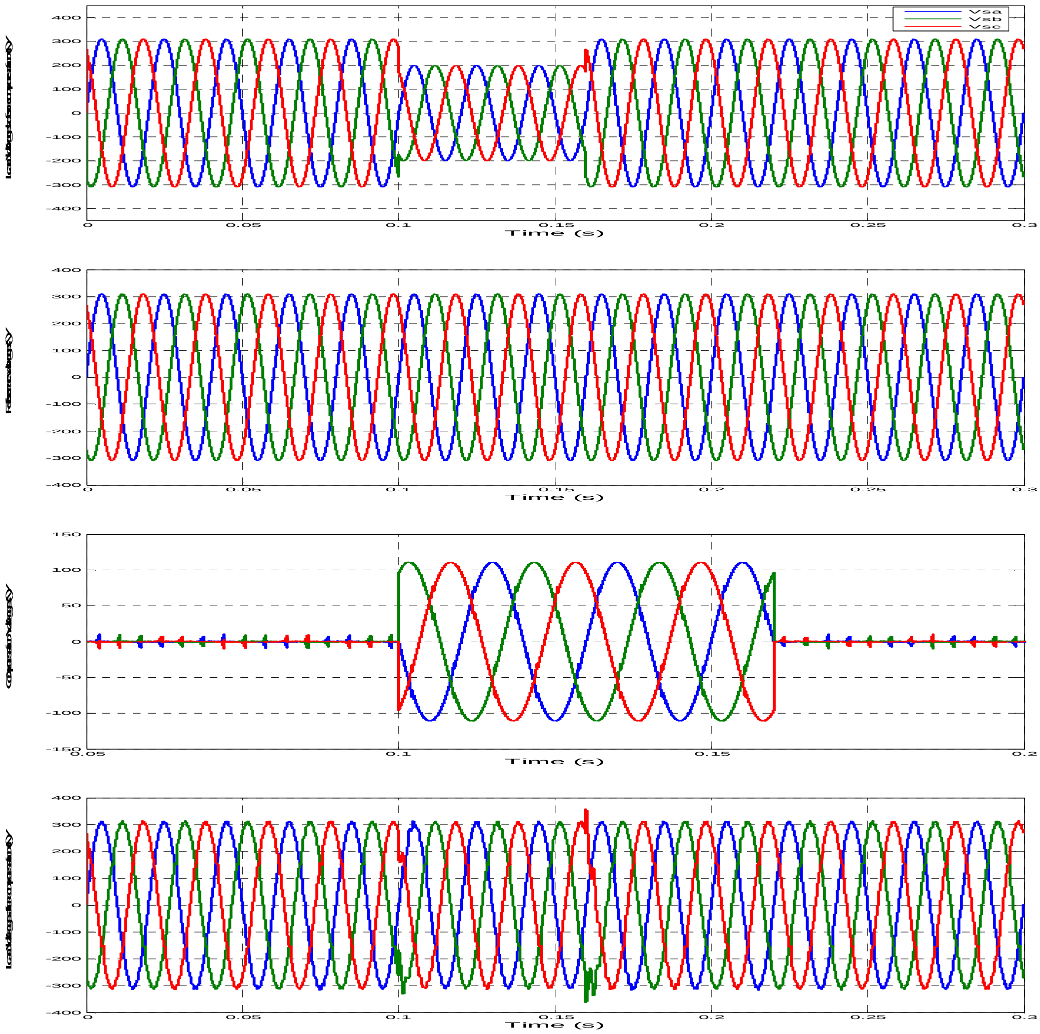

Fig. 11. Three-phase load voltage, three-phase fundamental voltages, three-phase compensating voltage and three-phase load voltage after compensation with voltage sag perturbation introduced between t1=0.1s and t2=0.16s

7.4 Voltage swell compensation

A swell (35%) is now introduced on the system during the time t1=0.1 sec to t2=0.16 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 Fig. 12 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 (21):

$$v_{sa} = 400\sin(\omega t)$$
$$v_{sb} = 400\sin(\omega t + \frac{4\pi}{3}) \quad (21)$$
$$v_{sc} = 400\sin(\omega t + \frac{2\pi}{3})$$

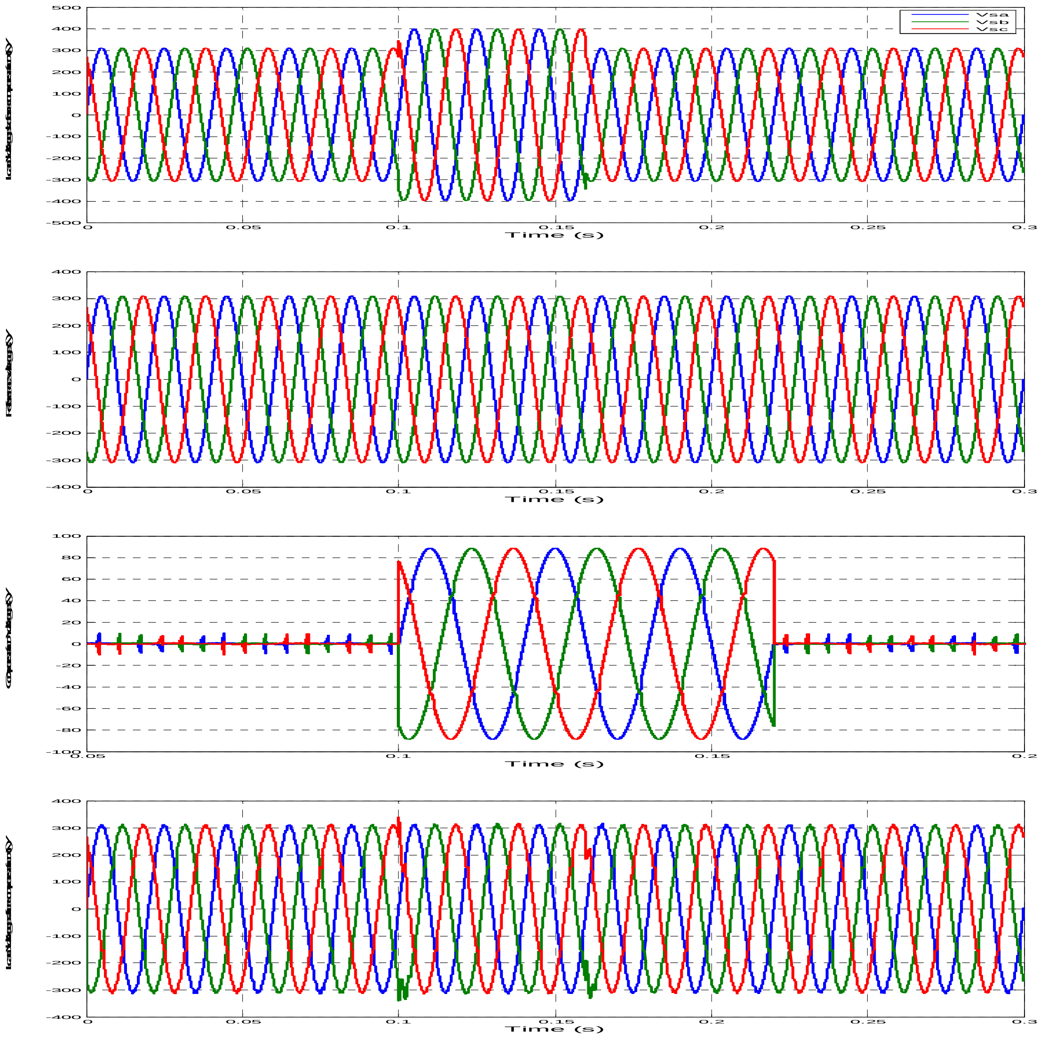

Fig. 12. Three-phase load voltage, three-phase fundamental voltages, three-phase compensating voltage and three-phase load voltage after compensation with swell voltage perturbation introduced between t1=0.1s and t2=0.16s

7.5 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 Fig.13. The voltage swell is introduced voluntarily in the utility voltage (35%) between t1=0.06s and t2=0.12s. And after that, a voltage sags (30%) is introduced between t2=0.12s and t3=0.18s. The voltage harmonics is introduced between t3=0.18s and t4=0.24s. The voltage unbalances is introduced between t4=0.24s and t5=0.30s. After t5=0.30s 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 Fig.13. 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.

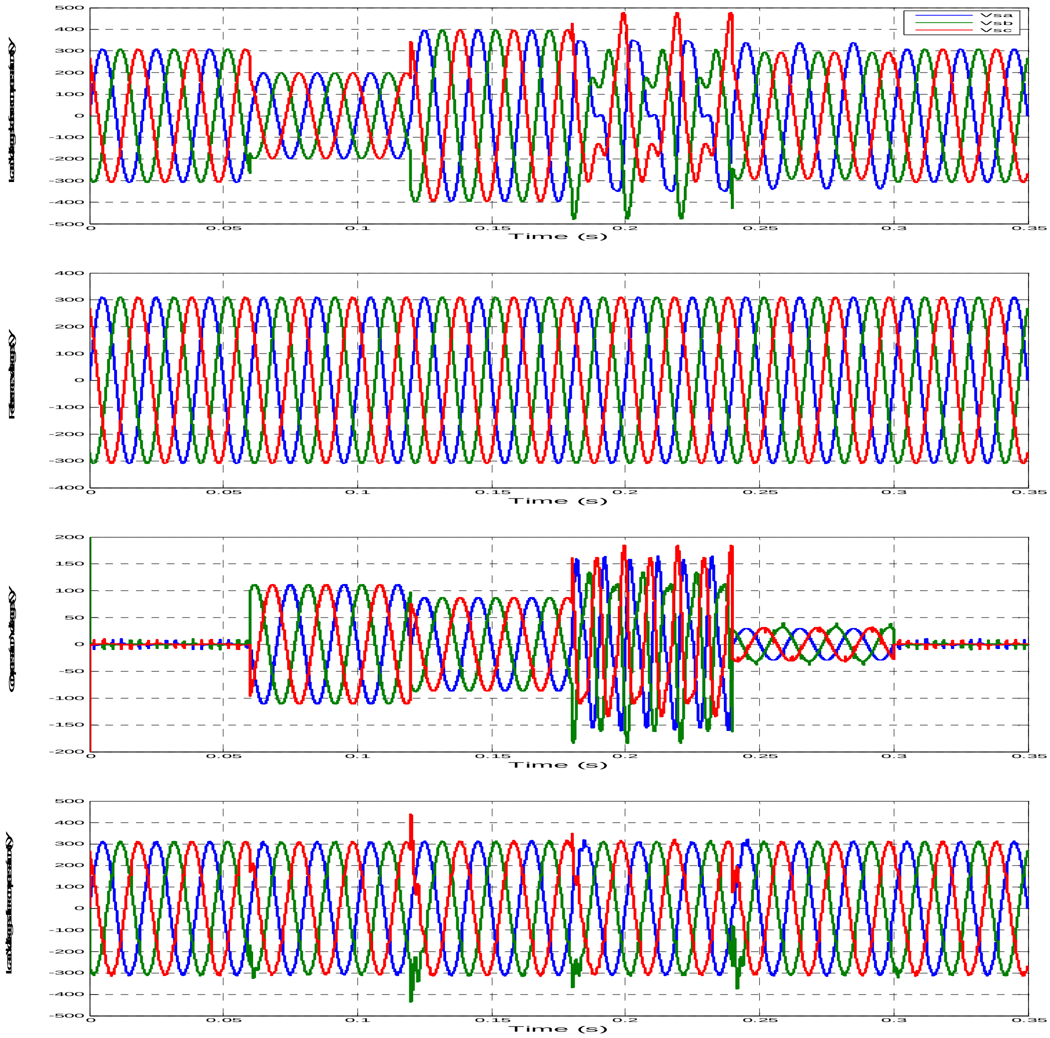

Fig. 13. Three-phase load voltage, three-phase fundamental voltages, three-phase compensating voltage and three-phase load voltage after compensation under all voltage perturbation introduced between t1=0.06s and t5=0.30s

The performance of the proposed series AF system is tested under all voltage perturbations separately and simultaneously: harmonics, swells, sags and unbalances. Fig.(9) and Fig.(10) shows 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 3.66% 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= 0.16s, 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.

8. Conclusion

To enhance the power quality and improve the voltage delivered to sensible and critical loads, a new series active power filter configuration using fuzzy logic 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 configuration. 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 3.66%. 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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