Series Active Power Filter Performances based on Three and Five-Level Neutral Point Clamped Inverter Topologies using Fuzzy Control Scheme

Salim CHENNAI[1]

[1]**CRNB - Algeria**
E-mail:chenaisalimov@yahoo.fr

Abstract - *This paper presents the performances evaluation of series active power filters based on three and five-level (NPC) inverter using instantaneous reactive power theory control strategies. Multilevel inverters are currently being investigated and used in various industrial applications. Today multi-level inverters are widely employed in several industrial applications. Their advantages include the capability to reduce the harmonic content and decrease the voltage or current ratings of the semiconductors. On the other hand intelligent techniques know today a great use, due to the advantages that offers. Fuzzy logic is an interesting alternative compared to conventional techniques. To benefit of all these advantages a novel control schemes for three and five-level series APF using this techniques are proposed in this work. The adopted control strategy uses instantaneous reactive power theory, it is easy to implement and achieves good performance for all load voltage disturbances. The numerical simulation is carried with MATLAB-Simulink and SimPowerSystem Toolbox. The obtained results show the superiority of five-level topologies compared to three-level configuration in terms of reduction of total harmonics distortion.*

Keywords **–** Three and Five-level (npc) inverters, Fuzzy logic, Voltage disturbance compensation, Power quality improvement, Total Harmonic Distortion (THD)

I. INTRODUCTION

The nonlinear electronic loads generate harmonic, reactive and negative sequence currents which lead to low power factor, low efficiency and harmful electromagnetic interference to the distribution systems [1],[2]. To improve the power quality, some solutions have been proposed by several authors. Among them the shunt and series active power filters [3] have proven as an important and flexible alternative to compensate most important voltage and current related power quality problems in the distribution system [3], [4]. In this case, the shunt APF should operate as a current source, and inject the compensation current into power system to cancel the harmonic current produced by the non-linear load. On the other side, the series active power filters have been proposed as an interesting and high performance solution to compensate most important voltage disturbances [4]. The series active power filter (Series APF) is especially used to compensate unbalances, sags, swells and harmonics [5]; it is inserted in series between the load and the source voltage and injects a compensating voltage. To perform the series connection, three single phase transformers are used to inject the compensating voltage to the line. Several multilevel inverter topologies are being used for shunt or series active filter applications, but some practical problems like power circuit packaging, switching circuit complexity and dynamic voltage stress have restricted the number of inverter levels to 3 or 5 [6], [7]. The controller is the main part of any active power filter and has been a subject of many researches in recent years [8], [9]; to improve the Series APF performances there's a great tendency to use intelligent control techniques, particularly Ann's and Fuzzy logic [10], [11]. Fuzzy logic control (FLC) is one of the significant tools in control design originated by Zadh. The advantages of FLC over conventional controllers are high robustness, insensitivity to parameters variations, handling of non-linearity and independent on mathematical models.

The investigation in this paper concentrates on the fuzzy control approaches for series APF using

three and five-level Neutral Point Clamped (NPC) inverters to compensate all voltage disturbances using instantaneous reactive power theory [12]. The performances of the both series APF systems are evaluated using Matlab-Simulink and SimPowerSystem Toolbox under different voltage disturbances.

II. SERIES ACTIVE POWER FILTER

Fig. 1 shows the proposed series APF, it is inserted between the disturbance voltage source and a sensitive load. Lf and Cf are inductance and capacitance of passive filter used to suppress switching ripples and the three transformers to inject the compensating voltage.

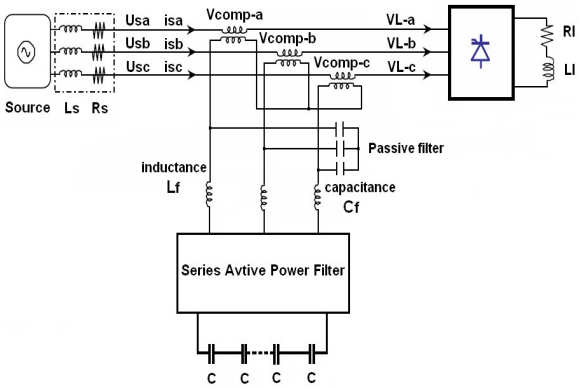


Fig. 1. Series active power filter based on multi-level inverter

III. MULTI-LEVEL INVERTERS

Multilevel inverters are currently being investigated and used in various industrial applications. Three and five-level inverters are the most popular converters employed in medium power applications [13]. Their advantages include the capability to reduce the harmonic content and decrease the voltage or current ratings of the semiconductors. The disadvantage is that more devices are needed and the control algorithm gets more complicated with the increasing of levels and the neutral-point potential fluctuates easily [14].

The power circuits of three-level NPC inverter [15] is given by Fig. 2. based on the six main switches (T11, T21, T31, T14, T24, T34) of the traditional two-level inverter, adding two auxiliary switches (T12, T13, T22, T23, T32, T33) 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. 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. The reason for the inverter to have clamping diodes connected in series is that all diodes can be of the same voltage rating and be able to block the right number of voltage levels. For this structure, three kinds of voltage level Udc/2, 0 and −Udc/2 can be output corresponding to three kinds of switching states A, 0, B [16], listed in (Table 1).

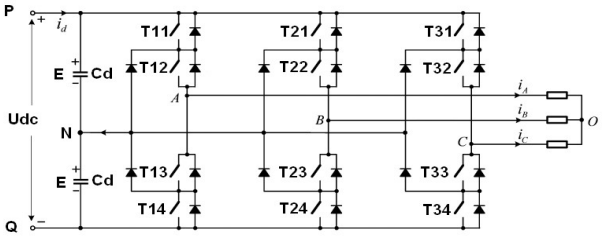


Fig. 2. Three-level NPC inverter

Table 1. Three-level (npc) inverter states

Switching States	Voltage output	T11	T12	T13	T14
A	Udc/2	ON	ON	OFF	OFF
0	0	OFF	ON	ON	OFF
B	−Udc/2	OFF	OFF	ON	ON

When the upper two switches T11, T12 are switched on, the output of this phase is connected to the DC terminal P. When the middle two switches T12, T13 are switched on, the output of this phase is connected to middle point N. Similarly when the lower two switches T13, T14 are switched on, the output of this phase is connected to Q. The allowed logic configurations of NPC switches are able to provide the three different output voltage values furnished by each NPC inverter phase. The states of T11, T12, T13 and T14 are complementary. The two switches of each phase of the NPC inverter are closed, whilst the other two are opened at every time instant [17], [18].

The second configuration of multilevel inverters studded in this research work is the five-level NPC inverter given by Fig. 3. In this structure the DC bus capacitor is split into four, providing a three neutral-point. Each arm of the inverter is made up of eight switches 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 [19], [20], namely, Udc/2, Udc/4, 0, -Udc/4 and -Udc/2 corresponding to five switching states given by Table (2).

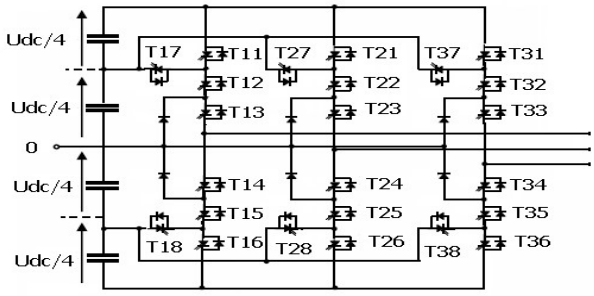


Fig. 3. Five-level NPC inverter

Table 2. Five-level (NPC) inverter states

	Switch	A	B	0	C	D
Switch -ing States	S1	1	1	1	1	0
	S2	1	1	0	0	0
	S3	1	0	0	0	0
	S4	0	0	1	1	1
	S5	0	0	0	1	1
	S6	0	1	1	0	1
	S7	0	1	0	0	0
	S8	0	0	0	1	0
Output voltages		Udc1 + Udc2	Udc1	0	- Udc3	- (Udc3 + Udc4)

IV. CONTROL STRATEGIES

The control strategy used for extracting the series APF reference voltages is based on the PQ theory described in [21]. We assume that the three-phase voltage source in the grid is symmetric and distorted:

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

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

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

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

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

Three-phase positive fundamental current template is constructed:

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} \sin(\omega t) \\ \sin\left(\omega t - \frac{2\pi}{3}\right) \\ \sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \quad (4)$$

Te two-phase coordinates source currents $i_{s\alpha}$, $i_{s\beta}$ are obtained by the transformation of equation (4) to (α–β) reference frame:

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = C_{32} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) \\ -\cos(\omega t) \end{bmatrix} \quad (5)$$

According to the instantaneous reactive power theory, then:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} U_{s\alpha} & U_{s\beta} \\ U_{s\beta} & -U_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} \quad (6)$$

Where p and q are the instantaneous active and reactive power:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} & + & \tilde{p} \\ \bar{q} & + & \tilde{q} \end{bmatrix} \quad (7)$$

p and q are passed through low pass filter and DC component $\bar{p}$ and $\bar{q}$ are got:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \sqrt{3} \begin{bmatrix} U_1 \cos(\theta 1) \\ U_1 \sin(\theta 1) \end{bmatrix} \quad (8)$$

$\tilde{p}$ is the AC or harmonic component of active power p, $\tilde{q}$ is the AC or harmonic component of reactive power q and $\bar{p}$, $\bar{q}$ are the DC component of p and q.

According to (7), transformation is made:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} U_{s\alpha} & U_{s\beta} \\ U_{s\beta} & -U_{s\alpha} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \\ i_{s\beta} & -i_{s\alpha} \end{bmatrix} \begin{bmatrix} U_{s\alpha} \\ U_{s\beta} \end{bmatrix} \quad (9)$$

As for DC components of p and q:

$$\begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} U_{s\alpha-f} & U_{s\beta-f} \\ U_{s\beta-f} & -U_{s\alpha-f} \end{bmatrix} \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \\ -i_{s\beta} & i_{s\alpha} \end{bmatrix} \begin{bmatrix} U_{s\alpha-f} \\ U_{s\beta-f} \end{bmatrix} \quad (10)$$

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

$$\begin{bmatrix} U_{s\alpha-f} \\ U_{s\beta-f} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & i_{s\beta} \\ -i_{s\beta} & i_{s\alpha} \end{bmatrix}^{-1} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} & -i_{s\beta} \\ i_{s\beta} & i_{s\alpha} \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \quad (11)$$

The three-phase fundamental voltage is given by:

$$\begin{bmatrix} U_{sa-ref} \\ U_{sb-ref} \\ U_{sc-ref} \end{bmatrix} = C_{23} \begin{bmatrix} U_{s\alpha-f} \\ U_{s\beta-f} \end{bmatrix} = \sqrt{2} U_1 \begin{bmatrix} \sin(\omega t + \theta_1) \\ \sin\left(\omega t + \theta_1 - \frac{2\pi}{3}\right) \\ \sin\left(\omega t + \theta_1 + \frac{2\pi}{3}\right) \end{bmatrix} \quad (12)$$

$$C_{32} = \sqrt{2}/3 \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (13)$$

$$C_{23} = \sqrt{2}/3 \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}^{T} \quad (14)$$

Where C32 is the coordinate's transformation matrix from three-phase system to two-phase system and C23 is the inverse coordinate's transformation matrix from two-phase system to three-phase system. The block diagram of the harmonic voltage identification based on PQ theory is presented in Fig. 4.

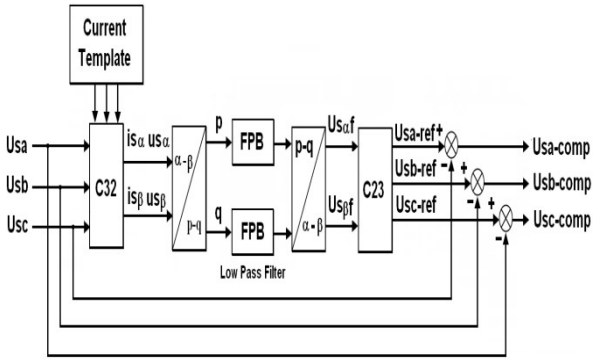


Fig. 4. Reference voltages identification based on instantaneous reactive power theory

V. FUZZY LOGIC CONTROL

Artificial intelligence is one of the key areas to solve such system complexity and make control more robust for transient conditions. Neural network, fuzzy logic, expert system, various other optimization methods are used for the improvement of power quality [22], [23]. Fuzzy logic control is one of the significant tools in control design originated by Zadeh. The advantages of FLC over conventional controllers are high robustness, insensitivity to parameters variations, handling of non-linearity and independent on mathematical models. To benefit of these advantages a FLC is proposed to control the Series APF. It is designed to improve compensation capability by adjusting the voltage error using fuzzy rules stored in the knowledge base. The desired inverter switching signals are determined according to 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 [24], [25]. 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).

Triangles or triangular membership function (TMF) have been frequently used in several applications of FLC. TMF are preferred due to simplicity, easy implementation, symmetrical along the axis. The number of linguistic variables is directly related to the accuracy of approximating function and plays an important role for input-output mapping.

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

- Seven fuzzy sets for each input,
- Seven 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 Inference system is given by Fig. 5.

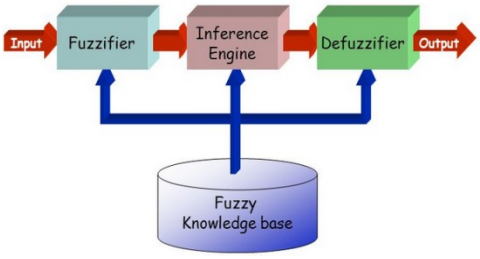


Fig. 5. Fuzzy inference systems

The logic control in case of three-level NPC inverter is shown in Fig. 6.

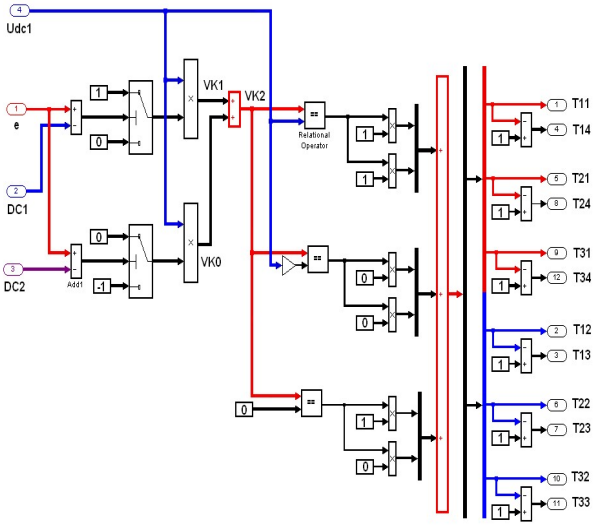


Fig. 6. Three-level NPC inverter logic control

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 [21]. The generation process of switching signals is given by Fig. 7.

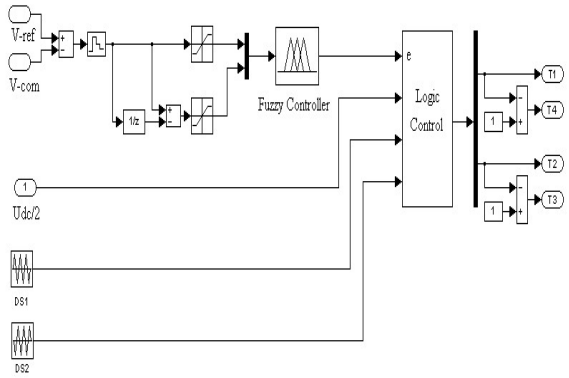


Fig. 7. Three-level NPC inverter fuzzy logic control

In the case of five-level (NPC) inverter, the Simulink logic control is given by Fig. 8.

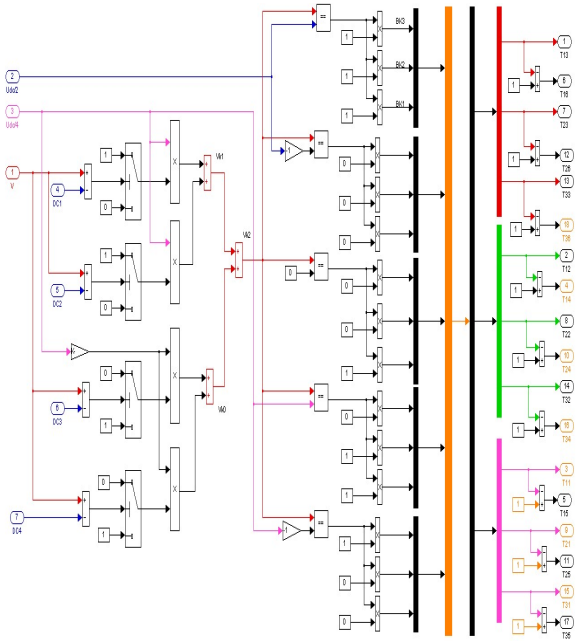


Fig. 8. Five-level NPC inverter logic control

The switching signals generation in this case using fuzzy logic controller is given by Fig. 9.

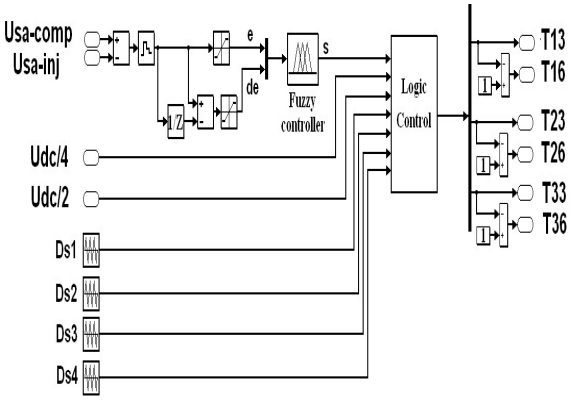


Fig. 9. Five-level NPC inverter fuzzy logic control

The difference between the injected and compensate voltages determines the reference signal control. These signals are compared with four triangular-carrying identical waves shifted from one to the other by a (+Upm, -Upm and -2Upm) and generating of switching pulses [21].

VI. SIMULATION RESULTS AND DISCUSSION

SimPowerSystems is the Toolbox of Matlab Simulink that operates in Simulink environment. It consists of electrical power circuits and electromechanical devices. It is developed to simulate electrical drive, power electronics and electrical power systems.

The first voltage harmonic disturbances is rich on 5 and 7 component harmonics, it is introduced voluntarily at t_1=0.1s to t_2=0.16s. Between t_2=0.16s and t_3=0.2s, the system is again at normal working condition. The second harmonic voltage disturbances is rich on 2, 4 and 5 component harmonics, it is introduced between t_3=0.2s and t_4=0.26s. The series APF starts compensating voltage harmonics instantly. The harmonic spectrum of the load voltage before and after compensation is shown respectively in Fig. 10 to Fig. 13.

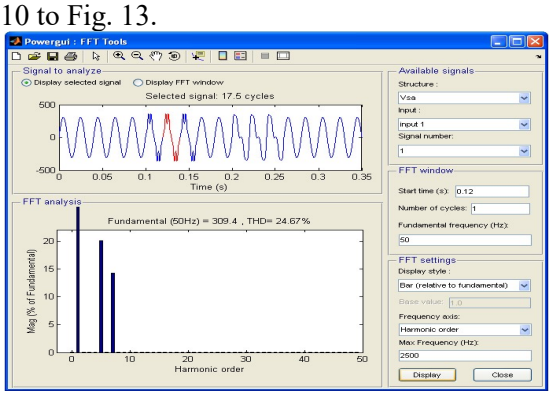


Fig. 10. Load voltage harmonic spectrum without Series APF (THDv=24.67%).

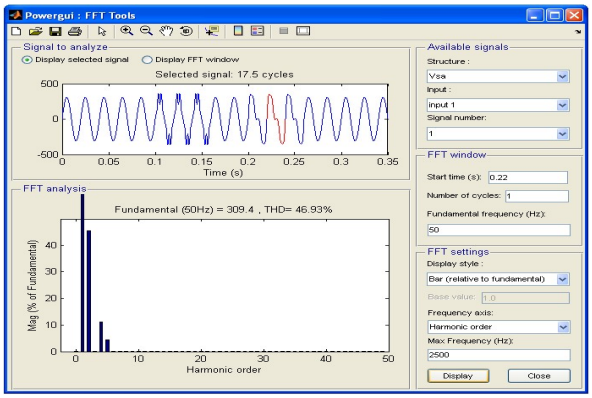
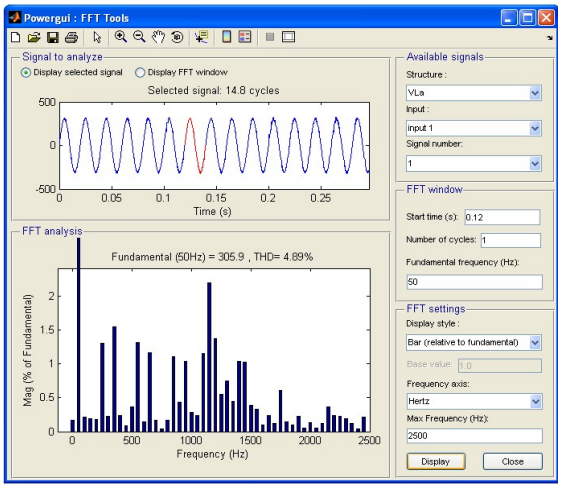
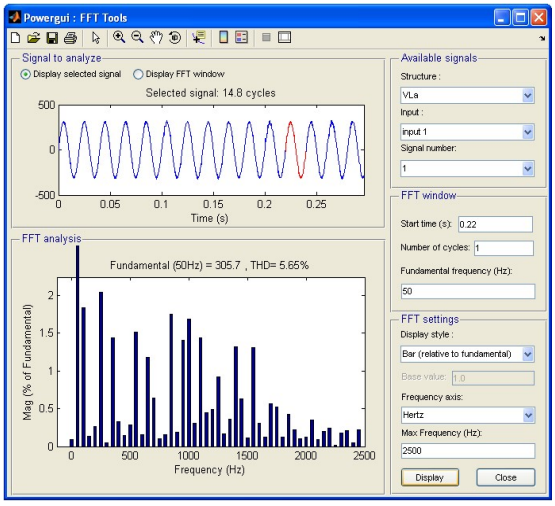


Fig.11. Load voltage harmonic spectrum without Series APF(THDv=46.93%)

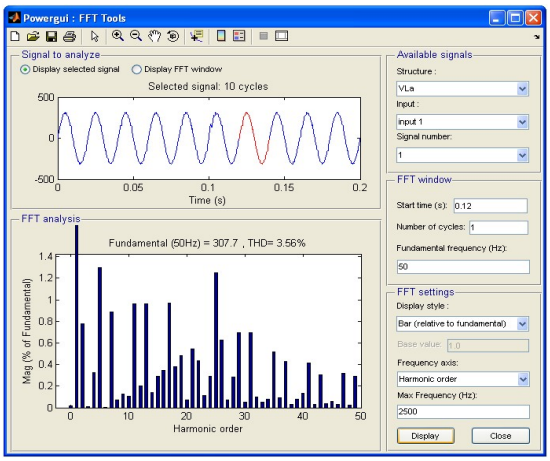


(a) First harmonics (THDv=4.89%)



(b) Second harmonics (THDv=5.65%)

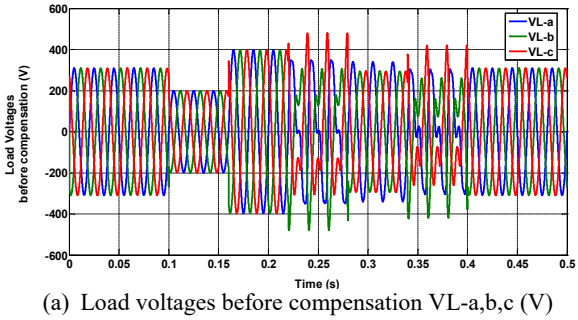
Fig. 12. Load voltage harmonic spectrum with Series AF using fuzzy controller based on three-level NPC inverter



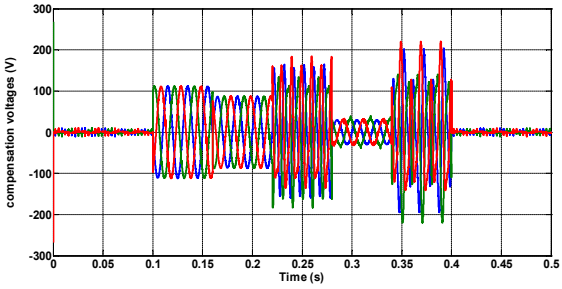
First harmonics (THDv=3.56%)

Fig. 13. Load voltage harmonic spectrum with Series AF using fuzzy controller based on five-level NPC inverter

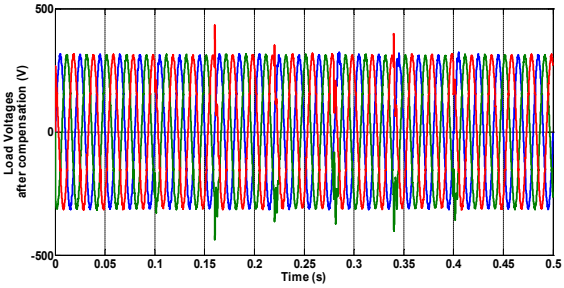
The performance of the proposed Series APF system is also tested under all voltage disturbances introduced simultaneously. The simulation results are shown in Fig. 14.



(a) Load voltages before compensation VL-a,b,c (V)



(b) Compensation voltages Uabc-comp (V)



(c) Load voltages after compensation UL-abc (V)

Fig. 14. Simulation results using Series APF for all voltage disturbances compensation

The performance of the proposed series APF system based on three and five-level NPC inverters is tested under all voltage disturbances introduced simultaneously: harmonics, swells, sags and unbalances. Figs 10 to 13 show respectively the harmonic spectrum of the voltage delivered to sensitive loads before and after application of the proposed series APF. It is observed that the load voltage harmonics are widely reduced in conformity with IEEE standard Norms from 46.93% to 5.65% using three-level NPC inverter and to 3.56% using five-level NPC inverter. It is shown in Fig. 14; that after introducing voluntarily the voltage swell (35%), voltage sag (30%) or unbalances in the supply voltage, 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 disturbance significant effect present in the utility voltages on its compensation capability and the load voltage is maintained constant and sinusoidal under all voltage disturbances.

VII. CONCLUSION

To enhance the power quality and improve the voltage delivered to sensitive loads a series APF based on three and five-level NPC inverter topologies using fuzzy control techniques has been proposed in this paper. The most voltage disturbances studied concern voltage harmonics, sags, swells and unbalances, all these disturbances 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 THDv (%) is significantly reduced from 46.93% to 5.65% using three-level NPC inverter and to 3.56% using five-level NPC inverter based on instantaneous reactive power theory with fuzzy control approach's. The simulation results show that the proposed series APF is efficient and compensates all voltage disturbances instantly and we can notice the superiority of the series APF based on five-level(npc) inverter topologies compared to the three-level(npc) inverter configuration in terms of total harmonic distortion reduction.

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