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Harmonic Current Compensation based on Three-phase Three-level Shunt Active Filter using Fuzzy Logic Current Controller

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Abstract – A three-phase three-level shunt active filter controlled by fuzzy logic current controller which can compensate current harmonics generated by nonlinear loads is presented. Three-level inverters and fuzzy controllers have been successfully employed in several power electronic applications these past years. To improve the conventional pwm controller performance, a new control scheme based on fuzzy current controller is adopted for three-level (NPC) shunt active filter. The scheme is designed to improve compensation capability of APF by adjusting the current error using a fuzzy rule. The inverter current reference signals required to compensate harmonic currents use the synchronous reference detection method. This technique is easy to implement and achieves good results. To maintain the dc voltage across capacitor constant and reduce inverter losses, a proportional integral voltage controller is used. The simulation of global system control and power circuits is performed using Matlab-Simulink and SimPowerSystem toolbox. The results obtained in transient and steady states under various operating conditions show the effectiveness of the proposed shunt active filter based on fuzzy current controller compared to the conventional scheme.

Keywords: Fuzzy logic current controller, Harmonic current compensation, Power quality, Shunt active filter, Three-level (NPC) inverter

1. Introduction

Power pollution drawn from nonlinear loads such as switching mode power supplies, commercial lighting, ovens, and adjustable speed drives results in the degradation of power quality in the distribution system. The non-sinusoidal balanced or unbalanced currents generate harmonics, reactive power, and excessive neutral current. Conventionally, passive filters have been used to eliminate current harmonics and increase the power factor. However, the use of passive filter has many disadvantages. Recently, active power filters [1] have been widely studied for the compensation of harmonic and reactive currents in power systems. Shunt active power filters are operated as an ideal current source which can provide a dynamic and adjustable solution for eliminating the harmonic currents and compensating the reactive power by injection of compensation currents [2], [3]. The most powerful converter used has been the two-level voltage source inverter [4], [5]. However, due to power handling capabilities of power semiconductors, these inverters are limited for low power applications. Three-level inverters have been successfully employed in medium and high power applications in the past years [6], [7]. The advantages of these inverters are lower voltage harmonics on the ac side, smaller filter size, lower switching losses, lower electromagnetic interference, lower voltage stress of power semiconductors, and lower acoustic noise. These advantages can reduce the construction cost of active filter in the medium and high voltage applications [8]-[13].

The controller is the core of the active power filter operation and has been the subject of numerous research in recent years [9], [10].The conventional control scheme to generate pulses, which is based on hysteresis or pwm logic control, presents several drawbacks. To improve the active power filter performance, the tendency has been to use intelligent control techniques, particularly fuzzy logic controllers. Recently, the use of fuzzy logic controllers in power electronics applications has generated considerable interest [5], [6]. The principal advantages of these controllers are robustness, ability to control nonlinear systems, absence of the need for accurate mathematical model, etc.

In the present paper, the three-phase three-level shunt active filter based on fuzzy logic current controller is proposed to compensate current harmonics. The new controller is designed to improve compensation capability of APF by adjusting the current error using a fuzzy rule. The reference current signals required to compensate current harmonics use the synchronous reference detection method. The performances of the proposed SAFs are evaluated through computer simulations for transient and steady-state conditions with various nonlinear loads using Matlab-Simulink program and SimPowerSystem toolbox.

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2. Shunt active filter

The circuit configuration of the studied active filter is shown in Fig. 1. The configuration is controlled to cancel current harmonics on the AC side and make the source current in phase with the voltage source. The source current, after compensation, becomes sinusoidal and in phase with the voltage source [11], [12].

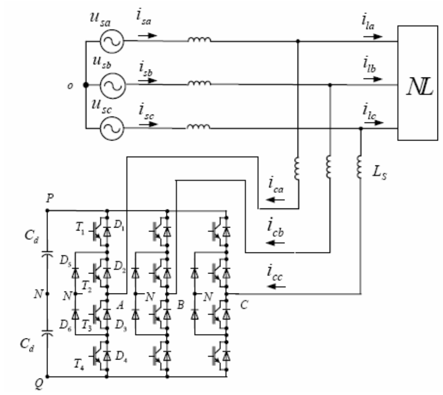

Fig. 1. Three-level shunt active filter

3. Three-level (NPC) inverter

Multilevel inverters are currently being investigated. Recently, these are being used in various industrial applications. Three-level inverter is one of the most popular converters employed in medium and high power applications. Their advantages include the capability to reduce the harmonic content and decrease the voltage or current ratings of the semiconductors [13]. Fig. 2 shows the power circuit of the three-level neutral point clamped inverter based on the six main switches (T11, T21, T31, T14, T24, T34) of the traditional two-level inverter, with six auxiliary switches (T12, T13, T22, T23, T32, T33) and two neutral clamped diodes added on each bridge arm. 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, three output voltage levels can be obtained, namely, Ud/2, 0, and -Ud/2 corresponding to three switching states A, 0, and B. As a result, 27 states of switching output exist in the three-phase three-level inverter [14], [15].

The voltage Uio is linked to Ud through:

$$Uio=Ci.Ud/2 \tag{1}$$

The phase-to-neutral point voltage Uin depends on Uio via (2), (i=a,b,c):

$$Uin = Uio-Uno \tag{2}$$

Assuming that the system is balanced, the sum of Uin is equal to zero:

$$Uan+Ubn+Ucn = 0 \tag{3}$$

By injecting (2) in (3), Eq. (4) is obtained:

$$Uno = (Uao + Ubo +Uco)/3 \tag{4}$$

The instantaneous inverter phase output voltages are obtained by replacing (2) with (4):

$$\begin{bmatrix} Uan \\ Ubn \\ Ucn \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ -1/3 & 2/3 & -1/3 \\ -1/3 & -1/3 & 2/3 \end{bmatrix} \begin{bmatrix} Uao \\ Ubo \\ Uco \end{bmatrix} \tag{5}$$

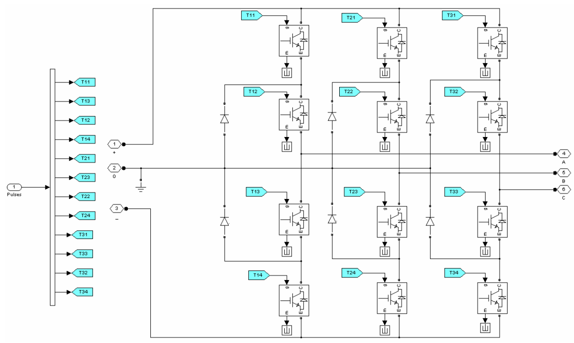

Fig. 2. Three-level NPC inverter

4. Control strategy

The control strategy used in the present work to determine the reference compensating currents for the three-level shunt active filters is based on the synchronous reference frame detection method. The principle of this technique is described below [16], [17]. The three-phase currents iLa, iLb, and iLc are transformed from three-phase (abc) reference frame to two phase- (α–β) stationary reference frame currents iα and iβ using:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{6}$$

The current expressions iα and iβ in (d-q) reference frame are given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{7}$$

The DC quantities and all other harmonics are transformed to non-DC quantities using a low pass filter:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ \bar{i}_q + \tilde{i}_q \end{bmatrix} \quad (8)$$

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

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ i_q \end{bmatrix} \quad (10)$$

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

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \quad (11)$$

The control strategy based on the synchronous reference detection method is shown in Fig. 3.

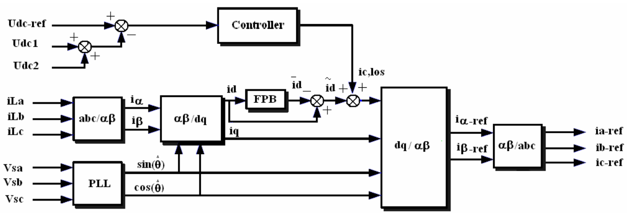

Fig. 3. Control strategy

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 [18], [19]. The loop generates corresponding current Ic,los as given by:

$$I_{c,los} = K_p.\Delta U_{dc} + K_i \int \Delta U_{dc}.dt \quad (12)$$

5. Fuzzy logic current controller

The main component of an active filter is the current controller. The conventional scheme, on the other hand, is based on hysteresis or pwm controllers. The principle of the control technique in the case of the three-level inverter is described below [8].

The three-phase source voltages are given as:

$$\begin{aligned} V_{sa} &= V.\sin(\omega t) \\ V_{sb} &= V.\sin(\omega t - \frac{2\pi}{3}) \\ V_{sc} &= V.\sin(\omega t + \frac{2\pi}{3}) \end{aligned} \quad (13)$$

where V is the peak value of phase voltage in the phases a, b, and c respectively. Hysteresis current controller is used to track the compensated current references. The relationship between the input and output of the hysteresis comparator is expressed as:

$$hys(\Delta i_{cx}) = \begin{cases} 1, if\, \Delta i_{cx} > h \\ 0, if\, \Delta i_{cx} < -h \end{cases} \quad (14)$$

$$\Delta i_{cx} = i^{*}_{cx} - i_{cx}; x = a, b, c$$

Three valid switching states in each phase are used to generate three different voltage levels on the ac side of the inverter. One high voltage level and one low voltage level are present in the positive and negative phase voltages. In the positive phase voltage, two voltage levels, 0 and Ud/2, are generated on the voltages Uao, Ubo, and Uco. Voltage level Ud/2 is selected to decrease the compensated current. Voltage level 0 is used to increase the compensated current in the positive supply voltage. In the negative half-cycle of phase voltage, Voltage levels –Ud/2 and 0 are generated on the ac side voltage of the inverter. Voltage level –Ud/2 is produced to increase the compensated current. On the other hand, high level 0 is generated to decrease the compensated current in the negative phase voltage. Thus, the low voltage level is selected to increase the compensated current and high voltage level is employed to decrease the compensated current in each half-cycle of phase voltage.

Based on the above description, the switching signals of power switches are expressed as [1]-[8]:

$$T_{a1} = sign(Vsa)[1 - hys(\Delta i_{ca})] \quad (15)$$

$$T_{a2} = [1 - sign(Vsa)]hys(\Delta i_{ca}) \quad (16)$$

$$S_a = sign(Vsa).hys(\Delta i_{ca}) + [1 - sig(Vsa)].[1 - hys(\Delta i_{ca})] \quad (17)$$

$$T_{b1} = sign(Vsb)[1 - hys(\Delta i_{cb})] \quad (18)$$

$$T_{a2} = [1 - sign(Vsb)]hys(\Delta i_{cb}) \quad (19)$$

$$S_b = sign(Vsb).hys(\Delta i_{cb}) + [1 - sig(Vsb)].[1 - hys(\Delta i_{cb})] \quad (20)$$

$$T_{c1} = sign(Vsc)[1 - hys(\Delta i_{cc})] \quad (21)$$

$$T_{c2} = [1 - sign(Vsc)]hys(\Delta i_{cc}) \quad (22)$$

$$S_c = sign(Vsc).hys(\Delta i_{cc}) + [1 - sig(Vsc)].[1 - hys(\Delta i_{cc})] \quad (23)$$

where sign (Vsx) = 1 if Vsx>0; or 0 if Vsx<0 and x = a, b, c.

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 [20], [21]. To benefit from these advantages, a new fuzzy logic current controller is proposed for use in the three-level (NPC) inverter. The new controller is designed to improve compensation capability of APF by adjusting the current 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 shunt active filter are determined according to the error between the compensation currents and reference currents. In this case, the fuzzy logic current controller has two inputs, error e and change of error de and one output s [22]. To convert inputs into linguistic variable, three fuzzy sets are used: N (Negative), ZE (Zero), and P (Positive). Fig. 4 shows the membership functions used in fuzzification.

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

- 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.

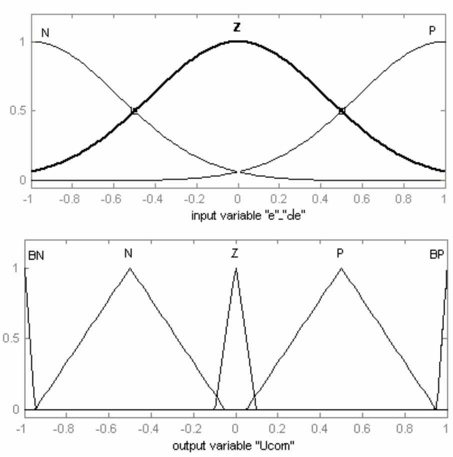

Fig. 4. Membership function for the input and output variables

(1) If error is Negative and error rate is Negative, Then output is Big Negative,
(2) If error is Zero and error rate is Negative, Then output is Positive,
(3) If error is Positive and error rate is Negative, Then output is Big Positive,
(4) If error is Negative and error rate is Zero, Then output in Big Negative,
(5) If error is Zero and error rate is Zero, Then output is Zero,
(6) If error is Positive and error rate is Zero, Then output is Big Positive,
(7) If error is Negative and error rate is Positive ,Then output is Big Negative,
(8) If error is Zero and error rate is Positive, Then output is Negative,
(9) If error is Positive and error rate is Positive, Then output is Big Positive.

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, 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. The switching signals are generated by comparing a two-carrier signal with the output of the fuzzy logic controllers. The Simulink model of the fuzzy logic switching signal generation is given in Fig. 5.

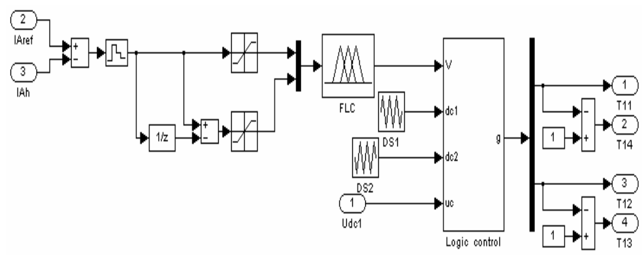

Fig. 5. Three-level inverter switching signal generation

The Simulink model of the logic control designed for the three-level inverter is shown in Fig. 6. The difference between the injected current and the reference current determines the reference voltage (e) and change of error (de). These inputs are injected in fuzzy controller and the fuzzy output is compared with two triangular-carrying identical waves shifted from one to the other by a half-period of chopping and generating of switching pulses. 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.

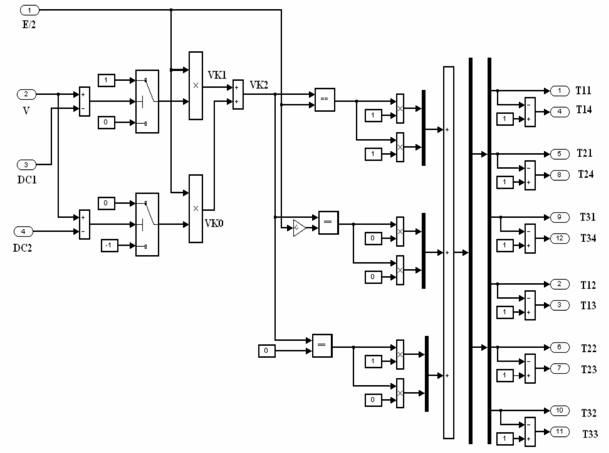

Fig. 6. PWM logic control of the three-level inverter

6. Simulation model

To simulate the proposed shunt active power filter, a model is developed by MATLAB/Simulink and SimPowerSystems Toolbox; it is shown in Fig. 7. The active filter is composed mainly of the three-phase source, three-level (NPC) inverter, a nonlinear load (Rectifier & R,L or R,C), and Fuzzy Logic Controller. The parameters of the simulation are: Lf = 3 mH, C1 = C2=3000 µF, Vs = 220 V/50 Hz, and Udc-ref = 800 V.

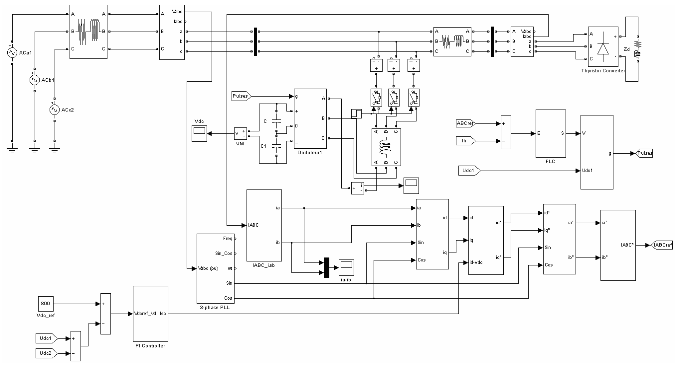

Fig. 7. Three-level shunt active filter based on fuzzy current controller

7. Simulation results and discussion

The simulation results are provided to verify the performance and effectiveness of the proposed control scheme based on fuzzy current controller for the three-level shunt active power filter compared to conventional pwm controller.

7.1 Simulation results using conventional controller

Fig. 8 shows the simulated waveforms of three-phase ac source voltages and source current before compensation. The corresponding harmonic spectrum is shown in Fig. 9. The source current and injected current before and after APF application are shown in Fig. 10 and Fig. 11, respectively. The DC voltage is presented in Fig. 12. The waveforms of source voltage and source current after compensation are simultaneously shown in Fig. 13. The harmonic spectrum of the source current after compensation is shown in Fig. 14.

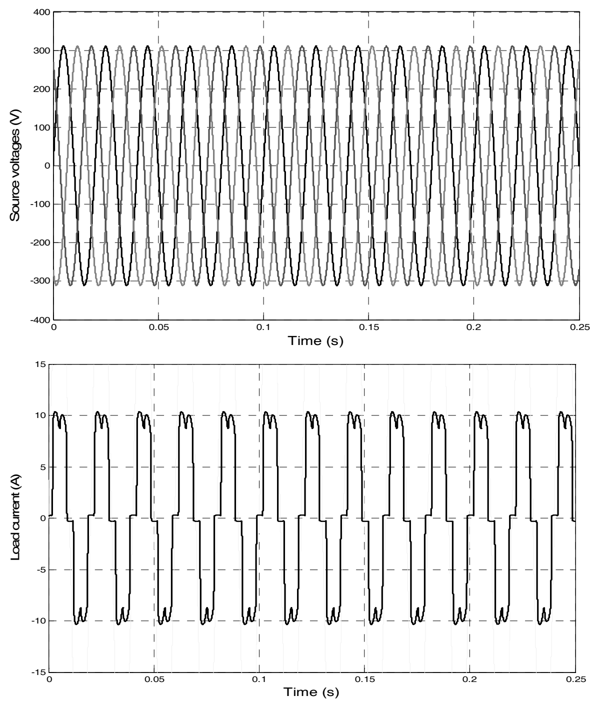

Fig. 8. Source voltages and source current without APF

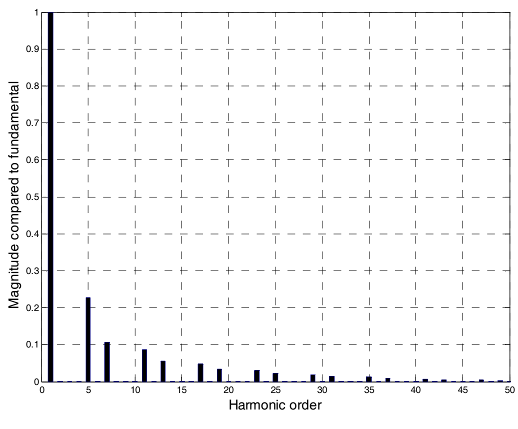

Fig. 9. Source current spectrum without APF (THD 27.74%)

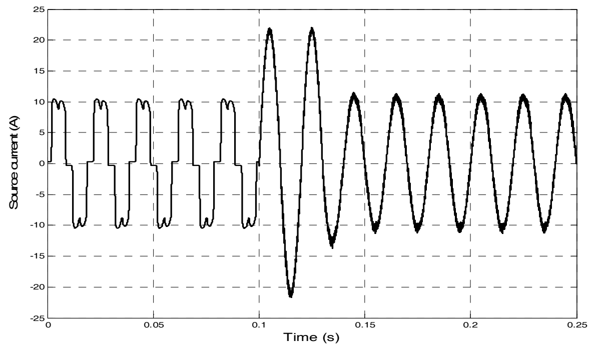

Fig. 10. Source current before and after compensation using conventional controller

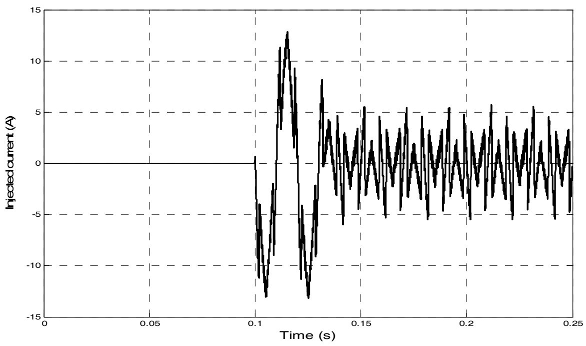

Fig. 11. Injected current

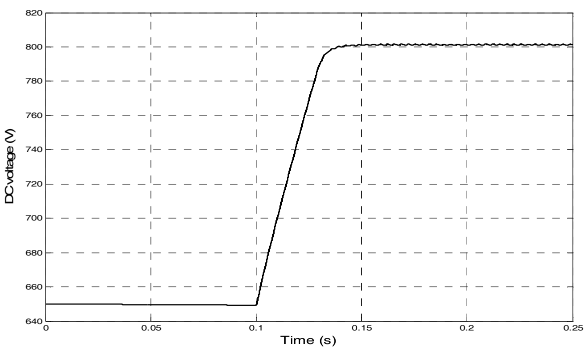

Fig. 12. DC side capacitor voltage

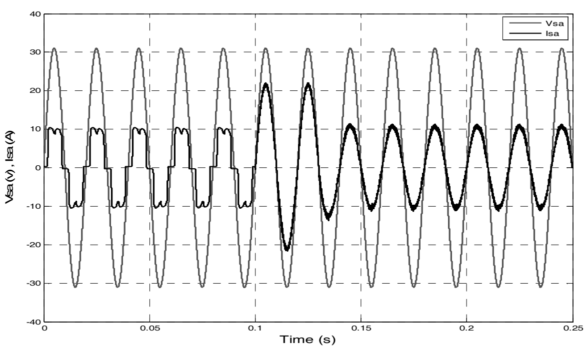

Fig. 13. Current and voltage source before and after compensation (Vsa = 0.1 vsa)

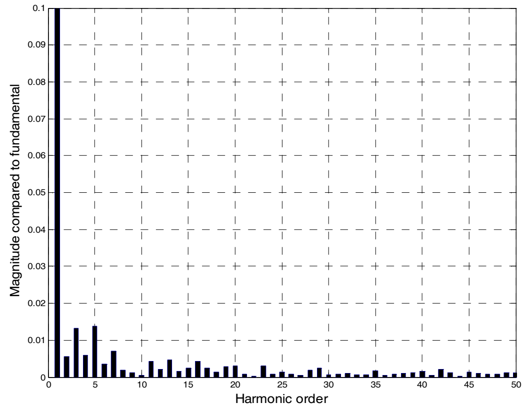

Fig. 14. Source current spectrum with APF (THD = 3.12%)

7.2 Simulation results using fuzzy controller

The source current and injected current before and after APF application using fuzzy controller are respectively shown in Fig. 15 and Fig. 16. The output DC capacitor voltage is presented in Fig. 17. The waveforms of source voltage with source current after compensation are simultaneously shown in Fig. 18. Lastly, the harmonic spectrum of the source current after compensation is shown in Fig. 19.

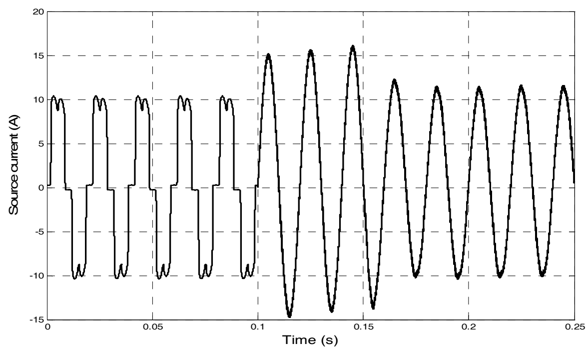

Fig. 15. Source current before and after compensation using Fuzzy controller

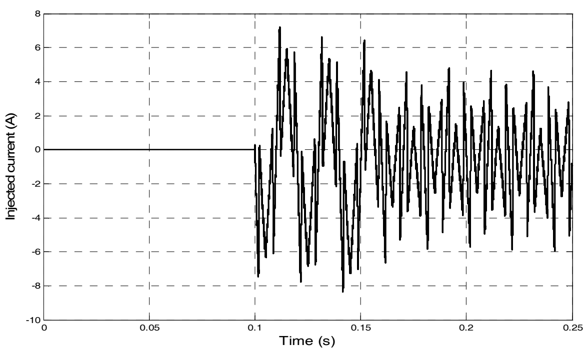

Fig. 16. Injected current

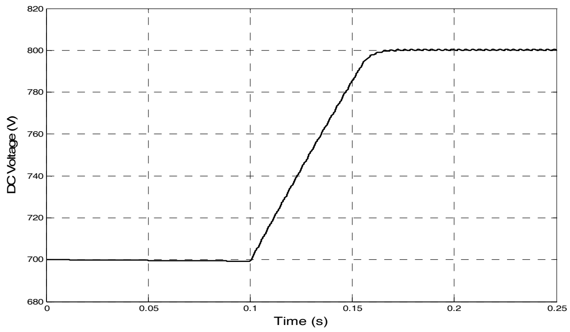

Fig. 17. DC side capacitor voltage

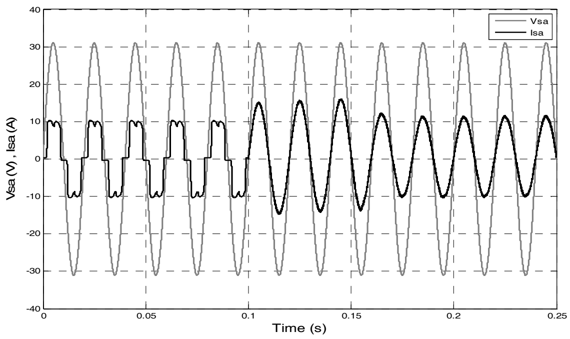

Fig. 18. Current and voltage source before and after compensation (Vsa = 0.1 vsa)

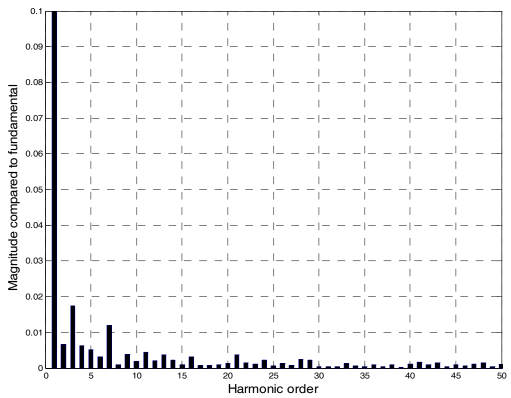

Fig. 19. Source current spectrum with APF using fuzzy controller (THD 1.26%)

7.3 Simulation results using fuzzy controller with step change in load

To evaluate dynamic responses and test robustness of the proposed shunt active filter based on fuzzy logic controller, a step change in load is introduced between t1 = 2 s and t2 = 4 s. Figs. 20 and 21 show the respective waveforms of load current and injected current before and after compensation. The dc side capacitor voltage is shown in Fig. 22. The current and the voltage source waveforms before and after compensation are simultaneously presented in Fig. 23.

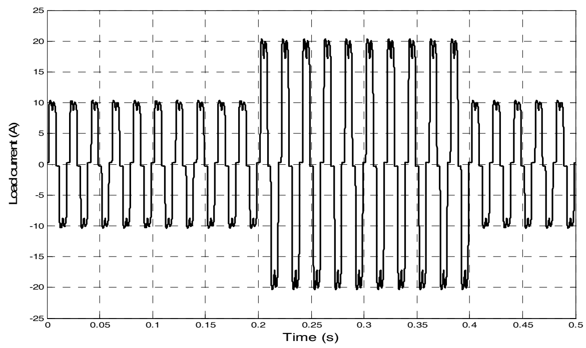

Fig. 20. Load current with step change in load (between t1 = 2 s and t2 = 4 s)

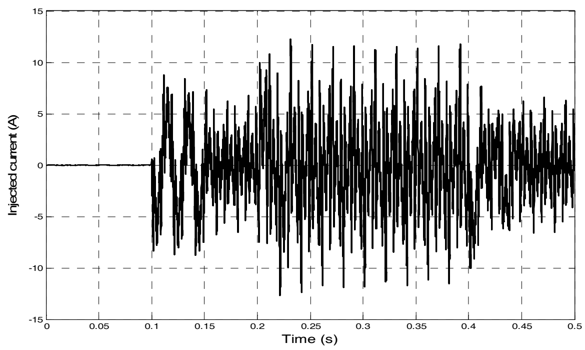

Fig. 21. Injected current with step change in load

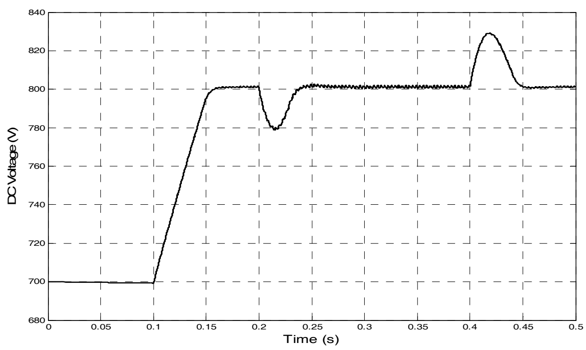

Fig. 22. DC side capacitor voltage with step change in load

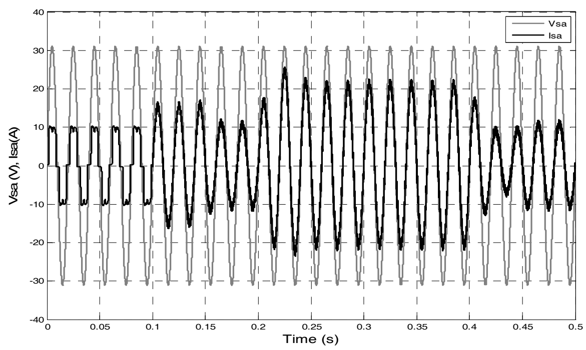

Fig. 23. Current and voltage source before and after compensation with step change in load

7.4 Simulation results using fuzzy controller with capacitive load

In order to test the performance of the proposed three-level shunt active filter with capacitive R,C loads under the same tests conditions, we have performed the following simulations.

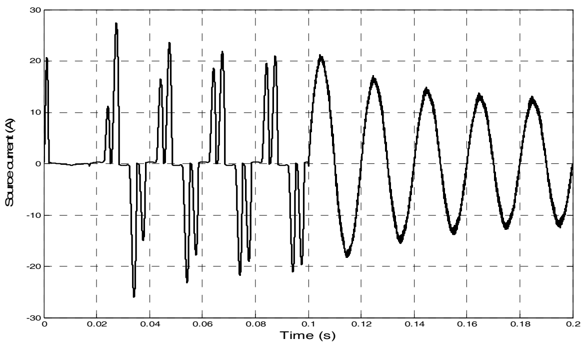

Fig. 24. Source current before and after compensation with capacitive load

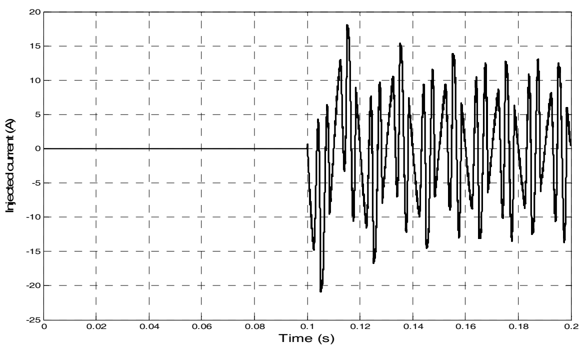

Fig. 25. Injected current before and after compensation

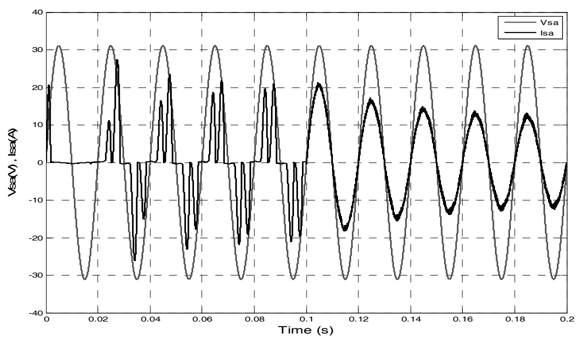

Fig. 26. Voltage and current source before and after compensation

Through visualization (Figs. 18, 23, and 24), we are able to conclude that the operation of the proposed three-level shunt active based on fuzzy logic current controller is successful. Before the application of shunt active power filter, the source current is equal to non-linear load current; highly distorted and rich in harmonic. After compensation, the THD is considerably reduced from 27.74% to 3.12% for the conventional pwm controller and to 1.26% for the fuzzy controller. The dc voltage is maintained at a constant value which is equal to the reference value Udc-ref = 800 V by using PI voltage controller. Figs. 22 and 23 illustrate the dynamic response of the proposed SAF. It is observed that the dc voltage pass through a transitional period of 0.06 s before stabilization and reaches its reference Udc-ref = 800 V with moderate peak voltage approximately equal to 10 V when a step change in load current is introduced between t1 = 0.2 s and t2 = 0.4 s. Figs. 13, 23, and 26 demonstrate that after active filter application, the current source is sinusoidal and in phase with the voltage source. The dynamic performances of the two controllers are summarized in Table 1.

The performance of the three-level shunt active filter, in terms of harmonics elimination and reactive power compensation, based on FLC controller is very satisfactory. The THD values obtained adhere to the IEEE standard of THD≤5%.

Table 1. Dynamic performance

Controller	THD (%) without APF	THD (%) with APF	Ts (s) Udc	Is max (A) during transitional Time Ts	Tps (s) with step in load/Is
Conventional pwm controller	27.74	3.12	0.04	23	0.04
Fuzzy controller	27.74	1.26	0.06	16	0.04

8. Conclusion

In the present paper, a three-phase three-level shunt active filter with neutral-point diode clamped inverter based on fuzzy logic current controller is presented. Use of the filter is aimed at achieving the elimination of harmonics introduced by nonlinear loads. Several simulations with various nonlinear loads (AC/DC converter with R,L or R,C) under different conditions are performed using the conventional pwm and fuzzy current controllers. The results show the superiority and effectiveness of the proposed fuzzy controller in terms of eliminating harmonics, response time, and magnitude of source current during transient period. The THD is significantly reduced from 27.74% to 3.12% by conventional pwm controller and to 1.26% for fuzzy controller (with APF) in conformity with the IEEE standard norms. The current source for the two controllers after compensation is sinusoidal and in phase with the line voltage source; the power factor is nearly equal to unity. Hence, the proposed fuzzy logic current controller is an excellent candidate to control shunt active filters based on multilevel inverter topology toward eliminating the harmonic currents and improving the power factor.

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