Periodica Polytechnica
Electrical Engineering
and Computer Science

60(2), pp. 135-142, 2016
DOI: 10.3311/PPee.9015

RESEARCH ARTICLE

Efficient Control Scheme for Five-level (NPC) Shunt Active Power Filters Based on Fuzzy Control Approaches

Salim Chennai[1*]

Received 13 January 2016; accepted after revision 21 March 2016

Abstract
This paper present simple fuzzy control approaches for shunt active power filter based on five-level (NPC) inverter which can mitigate current harmonics generated by nonlinear loads and compensate reactive power. Today, five-level inverter is strongly used in the medium and high voltage applications; these advantages are low harmonic distortions, low switching losses, low electromagnetic interference and low acoustic noise. Second, fuzzy logic techniques have been successfully employed in several power electronic applications. To benefit from these advantages a novel control scheme based on fuzzy current controller is adopted; it is designed to improve compensation capability by adjusting the current error using a fuzzy rule. The reference current signals required to compensate harmonic currents use the synchronous current 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 five-level (NPC) inverter using fuzzy control.

Keywords
Five-level (NPC) inverter, Shunt active power filter, Fuzzy logic control, Power quality improvement

[1]Department of Electrical Engineering
Birine Research Nuclear Center,
BP. 180 Ain-Ouessera, Algeria
[*]Corresponding author, e-mail: chenaisalimov@yahoo.fr

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 power applications in the past years [6, 7]. The five level (NPC) are used in high power applications, Their advantages 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].

The controller is the main part of any active power filter operation and has been a subject of many researches in recent years [9, 10]. Among the various current control techniques, hysteresis current control is the most extensively used technique. It is easy to realize with high accuracy and fast response. In the hysteresis control technique the error function is centered in a preset hysteresis band. When the error exceeds the upper or lower hysteresis limit the hysteretic controller makes an appropriate switching decision to control the error within the preset band. However, variable switching frequency and high ripple content are the main disadvantages of hysteresis current control. To improve the control 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 [11, 12].

In this paper, five-level (NPC) shunt active filter using synchronous current detection method based on fuzzy logic control approach's is proposed to mitigate current harmonics and compensate reactive power. The performances of the proposed Shunt APF are evaluated through computer simulations for transient and steady-state conditions using Matlab-Simulink program and SimPowerSystem toolbox.

2 Shunt AP filter

Power 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 [13, 14].

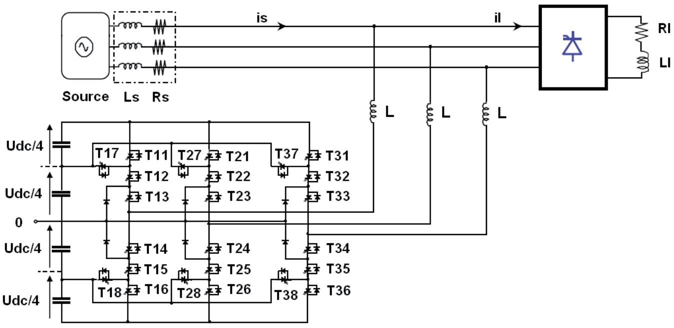

Fig. 1 Five-level (NPC) shunt active power filter

3 Five-level (NPC) inverter

Multilevel inverters are currently being investigated and used in various industrial applications. Five-level inverter is one of the most popular converters employed in high power applications [15]. Their advantages include the capability to reduce the harmonic content and decrease the voltage or current ratings of the semiconductors [16]. The disadvantage is that the devices are needed more and the control algorithm gets more complicated with the increasing of levels and the neutral-point potential fluctuates easily. The power circuit of the five-level neutral point clamped inverter is given by Fig. 2, the DC bus capacitor is split into four, providing a three neutral-point. Each arm of the inverter is made up of eight IGBTs (Insulated Gate Bipolar Transistor) devices, 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, namely, $U_{dc}/2$, $U_{dc}/4$, 0, $-U_{dc}/4$ and $-U_{dc}/2$ corresponding to five switching states A, B, 0, C and D [17, 18]. Table 1 shows the switching states of this inverter [19].

Table 1 Five-level (NPC) witching states

SS*	Switching states								OV**
	Ti3	Ti2	Ti1	Ti4	Ti5	Ti6	Ti7	Ti8	
A	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	$U_{dc1}+U_{dc2}$
B	OFF	ON	ON	OFF	OFF	ON	ON	OFF	U_{dc1}
0	OFF	OFF	ON	ON	OFF	ON	OFF	OFF	0
C	ON	OFF	OFF	ON	ON	OFF	OFF	ON	$-U_{dc3}$
D	OFF	OFF	OFF	ON	ON	ON	OFF	OFF	$-U_{dc3}$ $-U_{dc4}$

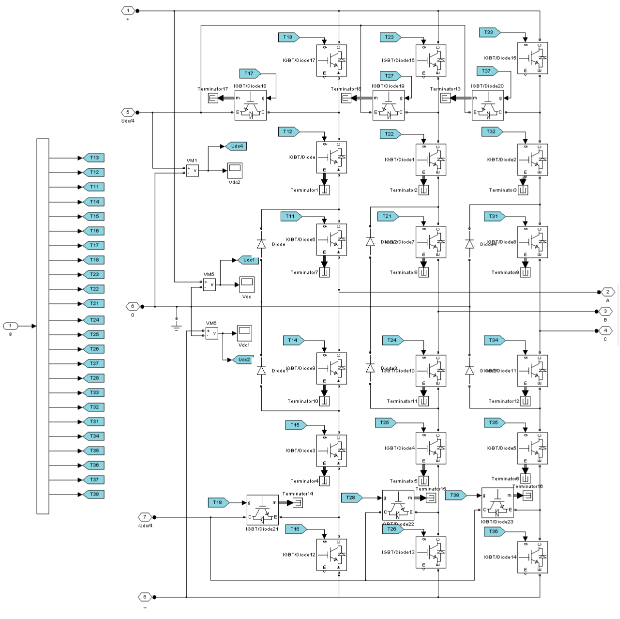

Fig. 2 Five-level (NPC) inverter

The switch connection function F_{ks}, indicates the opened or closed state of the switch T_{ks}:

$$F_{ks}=\begin{cases}1 & \text{if} \quad T_{ks} \quad \text{closed}\\ 0 & \text{if} \quad T_{ks} \quad \text{open}\end{cases} \tag{1}$$

For a leg K of the 3-phase, 5-level NPC voltage source inverter (VSI), several complementary control laws are possible. The optimal control law that allows the obtaining of a 5-level voltage (U_{dc1}, $U_{dc1}+U_{dc2}$, 0, $-U_{dc3}$, $-U_{dc3}-U_{dc4}$) for each leg of this inverter is given below:

$$B_{k1}=\overline{B_{k5}},\quad B_{k2}=\overline{B_{k4}},\quad B_{k3}=\overline{B_{k6}}$$
$$B_{k7}=B_{k1}B_{k2}\overline{B_{k3}},\quad B_{k8}=B_{k4}B_{k5}\overline{B_{k6}} \tag{2}$$

B_{ks} is the control signal of TD_{ks}.

In order to deduce the model of the inverter and using the proposed complementary law, we introduce the connection function F_{ks} of the switch TD_{ks} which describes the state of the switch (1=turned ON and 0=turned OFF) [20]. In this function, k is the number of the arm and s the number of the switch. The voltage of the three phases A, B, C relatively to the middle point M are given by VXM with x = point A, B or C.

$$V_{XM}(V)=\begin{bmatrix}F_{k1}F_{k2}F_{k3}\cdot(U_{dc1}+U_{dc2})\\+F_{k1}F_{k2}\overline{F_{k3}}\cdot(U_{dc1})\end{bmatrix}-\begin{bmatrix}F_{k4}F_{k5}F_{k6}\cdot(U_{dc3}+U_{dc4})\\+F_{k4}F_{k5}\overline{F_{k6}}\cdot(U_{dc3})\end{bmatrix} \tag{3}$$

Consider now, the connection function F_{km}^{b} which describes the state of a half arm with k the number of the arm and m the number of the half arm (1=upper half arm and 0=lower half arm). The expression of the half arm connection function using the switch connection functions has the following form:

$$\begin{matrix}F_{k1}^{b}=F_{k1}F_{k2}F_{k3}\\F_{k0}^{b}=F_{k4}F_{k5}F_{k6}\end{matrix}\quad \&\quad \begin{matrix}F_{k1}^{b'}=F_{k1}F_{k2}\overline{F_{k3}}\\F_{k0}^{b'}=F_{k4}F_{k5}\overline{F_{k6}}\end{matrix} \tag{4}$$

The voltage equation using the half arm connection functions will have the following form:

$$V_{XM}(V)=\begin{bmatrix}F_{k1}^{b}(U_{dc1}+U_{dc2})+F_{k7}\cdot(U_{dc1})\\-F_{k0}^{b}(U_{dc3}+U_{dc4})+F_{k8}\cdot(U_{dc3})\end{bmatrix} \tag{5}$$

The output voltages of the inverter relative to point N of the load using the connection functions are given as follows:

$$\begin{aligned}\begin{bmatrix}V_A\\V_B\\V_C\end{bmatrix}=&\frac{1}{3}\begin{bmatrix}2&-1&-1\\-1&2&-1\\-1&-1&2\end{bmatrix}\left(\begin{bmatrix}F_{17}+F_{11}^{b}\\F_{27}+F_{21}^{b}\\F_{37}+F_{31}^{b}\end{bmatrix}U_{dc1}+\begin{bmatrix}F_{11}^{b}\\F_{21}^{b}\\F_{31}^{b}\end{bmatrix}U_{dc2}\right)\\&-\frac{1}{3}\begin{bmatrix}2&-1&-1\\-1&2&-1\\-1&-1&2\end{bmatrix}\left(\begin{bmatrix}F_{18}+F_{10}^{b}\\F_{28}+F_{20}^{b}\\F_{38}+F_{30}^{b}\end{bmatrix}U_{dc3}+\begin{bmatrix}F_{10}^{b}\\F_{20}^{b}\\F_{30}^{b}\end{bmatrix}U_{dc4}\right)\end{aligned} \tag{6}$$

4 Control strategies

The strategy control used is the synchronous reference current detection method. It's concise and requires less computational efforts than many others method control [21]. The compensating currents of active filter are calculated by sensing the load currents, the current delivered by DC voltage regulator I^{*}_{smd}, peak voltage of AC source (V_{sm}) and zero crossing point of source voltage. The last two parameters are used for calculation of instantaneous voltages of AC source as below:

$$\begin{aligned}V_{sa}(t)&=V_{sm}\cdot\sin(\omega t)\\V_{sb}(t)&=V_{sm}\cdot\sin\left(\omega t-\frac{2\pi}{3}\right)\\V_{sc}(t)&=V_{sm}\cdot\sin\left(\omega t-\frac{4\pi}{3}\right)\end{aligned} \tag{7}$$

In order to compensating the current harmonics, the average active power of AC source must be equal with P_{Lav}, considering the unity power factor of AC source side currents the average active power of AC source can be calculated as bellow:

$$P_s=\frac{3}{2}V_{sm}I^{*}_{smp}=P_{Lav} \tag{8}$$

From this equation, the first component of AC side current can be calculated as bellow:

$$I^{*}_{smp}=\frac{2}{3}\frac{P_{Lav}}{V_{sm}} \tag{9}$$

The second component of AC source current I^{*}_{smd} is obtained from DC capacitor voltage regulator. The desired peak current of AC source can be calculated as bellow:

$$I^{*}_{sm}=I^{*}_{smp}+I^{*}_{smd} \tag{10}$$

The AC source currents must be sinusoidal and in phase with source voltages, theses currents can be calculated with multiplying peak source current to a unity sinusoidal signal, that these unity signals can be obtained from Eq. (10):

$$\begin{aligned}i_{ua}(t)&=v_{sa}/V_{sm}\\i_{ub}(t)&=v_{sb}/V_{sm}\\i_{uc}(t)&=v_{sc}/V_{sm}\end{aligned} \tag{11}$$

The desired source side currents can be obtained from Eq. (11):

$$\begin{aligned}i^{*}_{sa}(t)&=I^{*}_{sm}\cdot i_{ua}\\i^{*}_{sb}(t)&=I^{*}_{sm}\cdot i_{ub}\\i^{*}_{sc}(t)&=I^{*}_{sm}\cdot i_{uc}\end{aligned} \tag{12}$$

Finally, the reference currents of AF can be obtained from (12):

$$\begin{aligned}i^{*}_{ca}(t)&=i^{*}_{sa}(t)-i_{La}(t)\\i^{*}_{cb}(t)&=i^{*}_{sb}(t)-i_{Lb}(t)\\i^{*}_{cc}(t)&=i^{*}_{sc}(t)-i_{Lc}(t)\end{aligned} \tag{13}$$

To compensate the inverter losses and regulate the DC link voltage U_{dc}, a proportional integral voltage controller is used. The control loop consists of the comparison of the measured voltage U_{dc} with the reference voltage $U_{dc\text{-ref}}$. The loop generates corresponding current Ic,los as given by:

$$I_{c,los}=K_p\cdot\Delta U_{dc}+K_i\int\Delta U_{dc}dt \tag{14}$$

The control scheme principle of the Five-level (NPC) shunt active power filter based on the synchronous reference current detection method is given by Fig. 3.

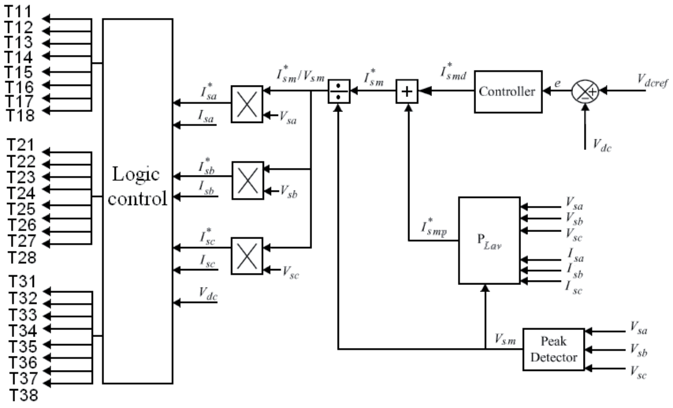

Fig. 3 Five-level (NPC) shunt APF control strategy

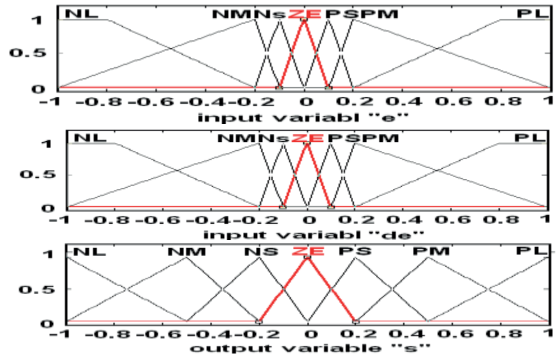

Fig. 4 Membership function (inputs and output variables)

5 Fuzzy shunt APF control

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. 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. There are four main parts for fuzzy logic approach. The first part is 'fuzzification unit' to convert the input variable to the linguistic variable or fuzzy variable. The second part is 'knowledge base' to keep the necessary data for setting the control method by the expert engineer. The 'decision making logic' or the inference engine is the third part to imitate the human decision using rule bases and data bases from the second part. The final part is 'defuzzification unit' to convert the fuzzy variable to easy understanding variable [22, 23].

The fuzzy current controller proposed in this paper is designed to improve compensation capability of shunt APF by adjusting the current error using fuzzy rules. The desired inverter switching signals are determined according the error between the injected current and reference current. In this case, the fuzzy logic current 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). Figure 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.

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 [26]. 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 five-level inverter. The switching signals are generated by means of comparing a four carrier signals with the output of the fuzzy logic controllers. The shunt APF control scheme based on five-level (NPC) inverter using fuzzy controllers is given by Fig. 5.

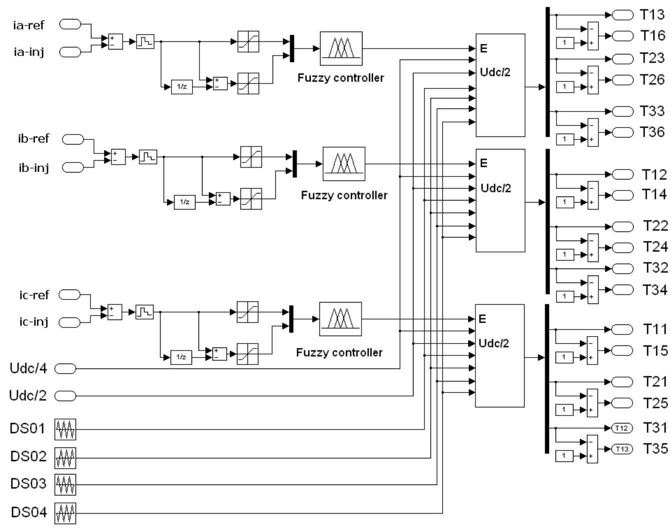

Fig. 5 Five-level (NPC) Shunt APF control scheme

The Simulink model of the logic control designed for the five-level (NPC) inverter is shown in Fig. 6.

6 Simulation results and discussion

The simulation results are provided to verify the performance and effectiveness of the shunt active power filter based on the five-level (NPC) inverter using the proposed control scheme. To simulate the proposed shunt active power filter, a model is developed using MATLAB/Simulink and SimPowerSystem Toolbox; it is shown in Fig. 7. The active filter is composed mainly of the three-phase source, Five-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 = C3 = C4 = 3000 μF, Vs=220 V/50 Hz, and $U_{dc\text{-ref}}$ = 800 V.

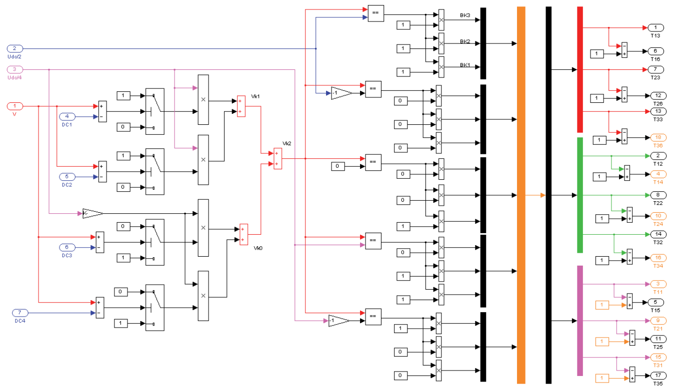

Fig. 6 Five-level (NPC) inverter logic control

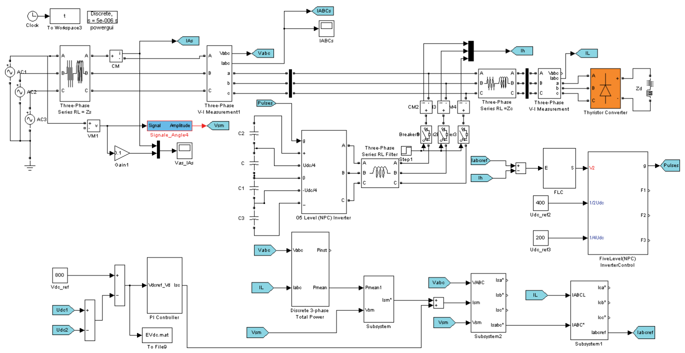

Fig. 7 SimPowerSystem Shunt APF model

6.1 Simulations results using conventional PWM controller

Figure 8 shows the simulated waveforms of the source current and the three-phase ac source voltages before compensation. The corresponding harmonic spectrum is shown in Fig. 9. The harmonic spectrum of the source current after compensation using conventional PWM controller is shown in Fig. 10.

6.2 Simulations results using Fuzzy controller

The source current and injected current after APF application using fuzzy controller are respectively shown in Fig. 11 and Fig. 12. The output DC capacitor voltage is presented in Fig. 13. The waveforms of source voltage with source current after compensation are simultaneously shown in Fig. 14. Lastly, the harmonic spectrum of the source current after compensation is shown in Fig. 15.

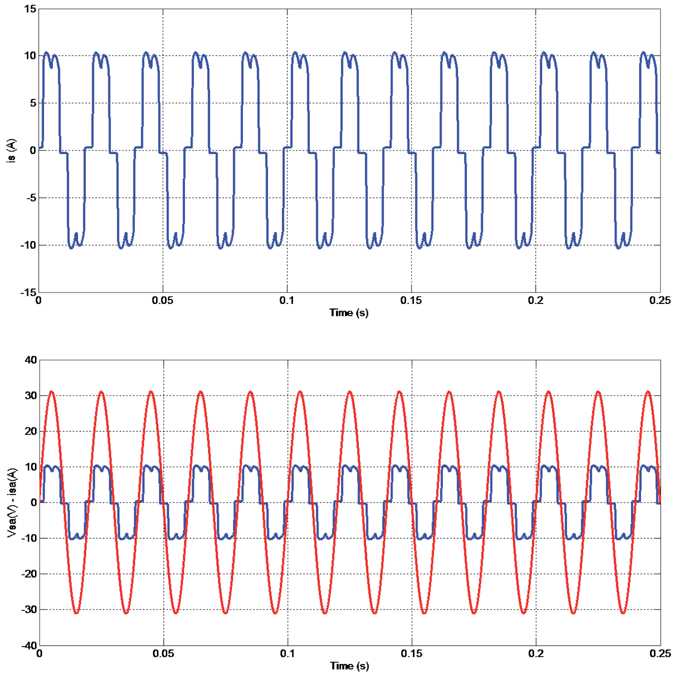

Fig. 8 Source voltage and source current without APF

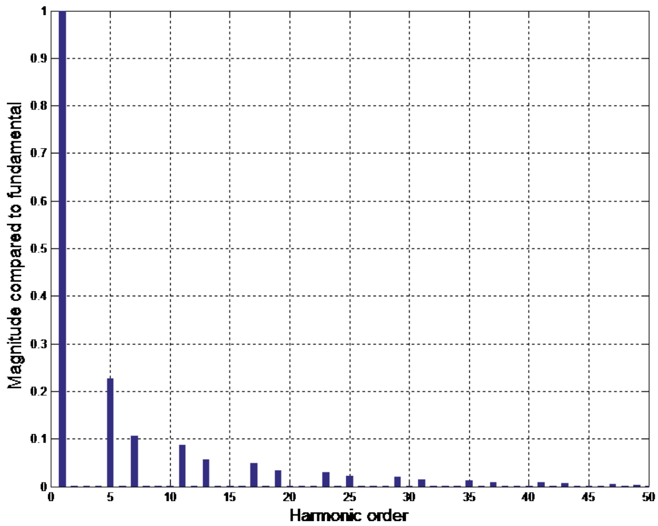

Fig. 9 Source current spectrum without APF (THDi = 28.16 %)

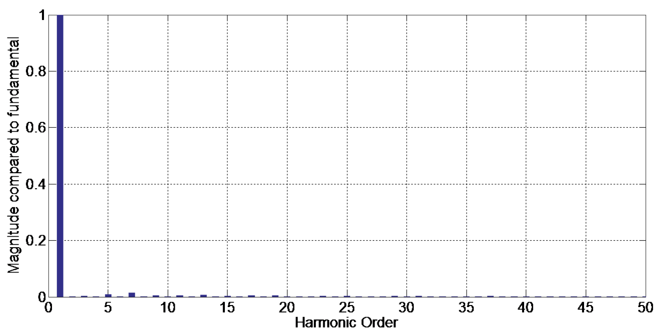

Fig. 10 Source current spectrum after compensation with APF using conventional PWM controller (THDi = 3.64 %)

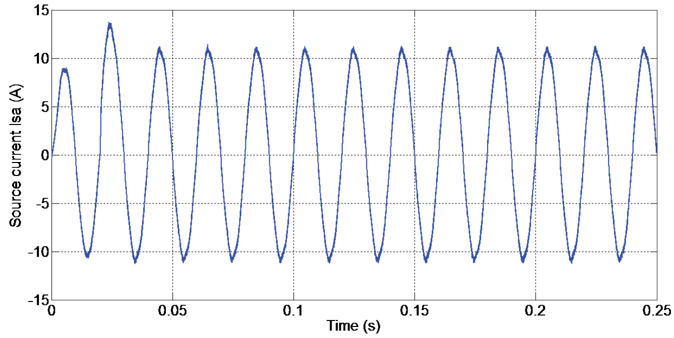

Fig. 11 Source current after compensation using Fuzzy Controller

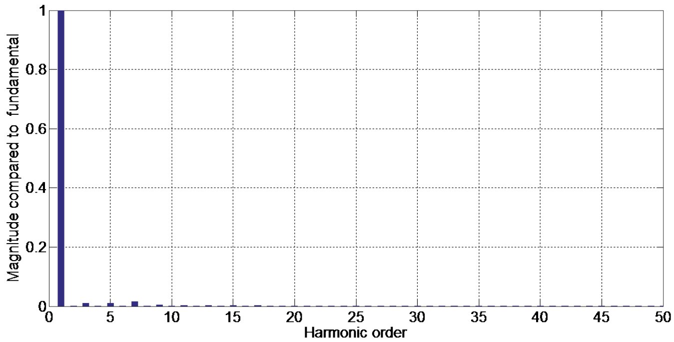

Fig. 15 Source current spectrum with APF using fuzzy controller (THDi = 2.80 %)

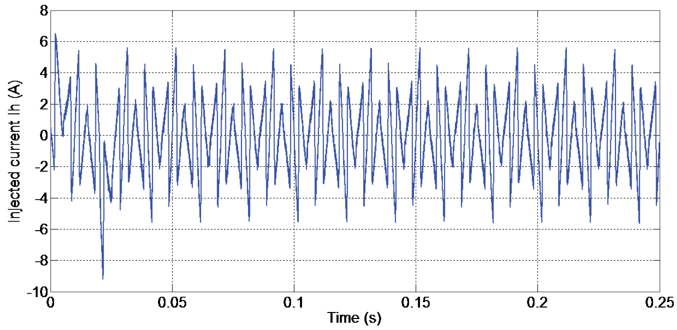

Fig. 12 Injected current

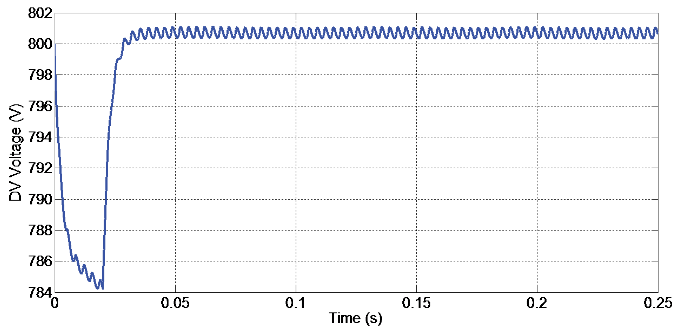

Fig. 13 DC side capacitor voltages

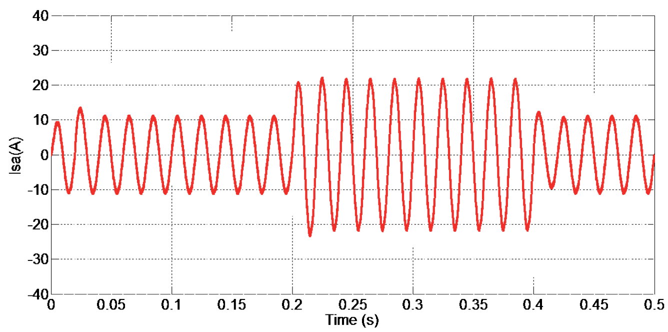

Fig. 14 Current and voltage source after compensation

6.3 Simulations results using Fuzzy controller with step change in the 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 = 0.2 sec and t2 = 0.4 sec. Figures 16 and 17 show the respective waveforms of load current and injected current after compensation with step change in load. The dc side capacitor voltage is shown in Fig. 18. The current and the voltage source waveforms after compensation are simultaneously presented in Fig. 19.

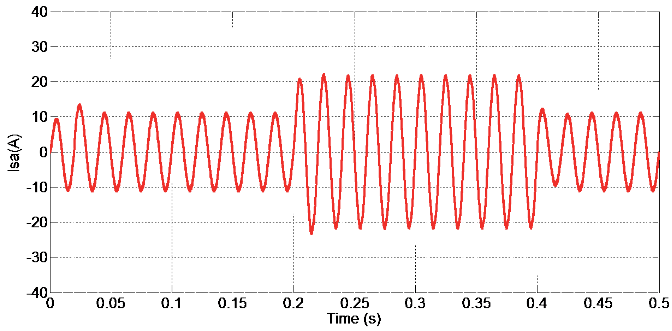

Fig. 16 Load current with step change in load (between t1 = 0.2 sec and t2 = 0.4 sec)

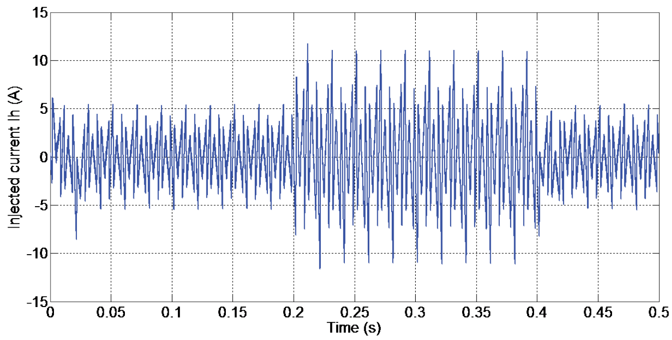

Fig. 17 Injected current with step change in load (between t1 = 0.2 sec and t2 = 0.4 sec)

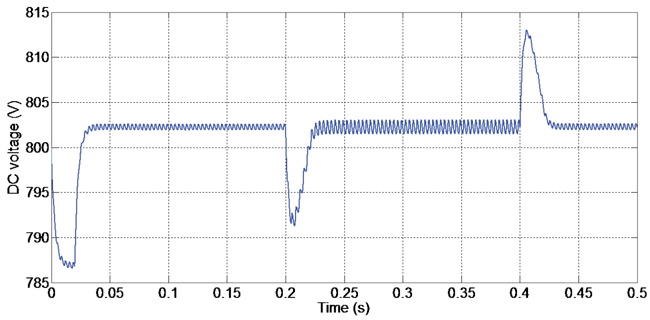

Fig. 18 DC voltage with step change in load (between t1 = 0.2 sec and t2 = 0.4 sec)

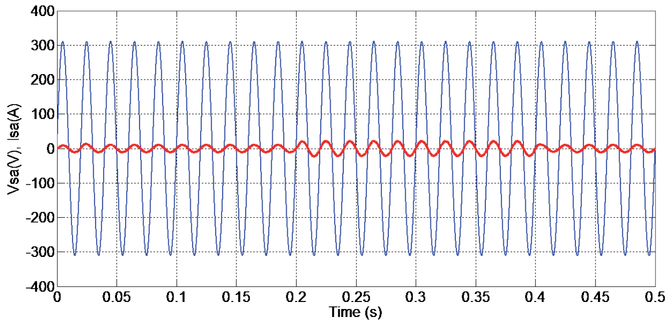

Fig. 19 Current and voltage source before and after compensation with load step change

Through visualization Figs. 11, 14 and 19, we are able to conclude that the operation of the proposed five-level Shunt APF based on fuzzy logic controller is successful. Before the application of SAPF, the source current is equal to non-linear load current; highly distorted and rich in harmonic. After compensation, the THDi is considerably reduced from 28.16 % to 3.64 % using conventional controller and to 2.80 % using proposed fuzzy system. The dc voltage is maintained at a constant value which is equal to the reference value $U_{dc\text{-ref}} = 800$ V by using PI voltage controller. Figures 16 and 18 illustrate the dynamic response of the proposed Shut APF. It is observed that the dc voltage pass through a transitional period of 0.06 sec before stabilization and reaches its reference $U_{dc\text{-ref}} = 800$ V with moderate peak voltage approximately equal to 10 V when a step change in load current is introduced between t1 = 0.2 sec and t2 = 0.4 sec. Figures 14 and 19 demonstrate that after active filter application, the current source is sinusoidal and in phase with the voltage source.

The performances of the proposed five-level (NPC) shunt active filter, in terms of harmonics elimination and reactive power compensation based on fuzzy logic controller are very satisfactory. The THDi values obtained respect the 519 IEEE standard Norms (THDi ≤ 5 %).

7 Conclusion

In the present paper, five-level (NPC) 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 under different conditions are performed using conventional 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 THDi is significantly reduced from 28.16 % to 2.80 % for fuzzy controller (with shunt APF) in conformity with the IEEE standard norms. The current source 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.

References

[1] Aredes, M., Hafner, J., Heumann, K. "Three-phase four-wire shunt active filter control strategies." *IEEE Transactions on Power Electronics*. 12(2), pp. 311-318. 1997. DOI: 10.1109/63.558748

[2] Khruathep, U., Premrudeepreechacharn, S., Kumsuwan, Y. "Implementation of shunt active power filter using source voltage and source current detection." In: 3rd IEEE Conference on Industrial Electronics and Applications, 2008, Singapore, June 3-5, 2008, pp. 2346-2351. DOI: 10.1109/ICIEA.2008.4582937

[3] Zouidi, A., Fnaiech, F., Al-Haddad, K. "Voltage source inverter based three-phase shunt active power filter: Topology, Modeling and control strategies." In: IEEE International Symposium on Industrial Electronics, Montreal, Que., July 9-13, 2006, Vol. 2, pp. 785-790. DOI: 10.1109/ISIE.2006.295734

[4] Bhattacharya, S., Frank, T. M., Divan, D. M., Banerjee, B. "Active filter system implementation." *IEEE Industry Applications Magazine*. 4(5), pp. 47-63. 1998. DOI: 10.1109/2943.715508

[5] Routimo, M., Salo, M., Tuusa, H. "Comparaison of voltage source and current source shunt active power filter." *IEEE Transactions on Power Electronics*. 22(2), pp. 636-643. 2007. DOI: 10.1109/TPEL.2006.890005

[6] Gong, B., Cheng, S., Qin, Y. "Simple three-level neutral point voltage balance control strategy based on SVPWM." *Archives of Electrical Engineering*. 62(1), pp. 15-23. 2013. DOI: 10.2478/aee-2013-0002

[7] Chennai, S., Benchouia, M.-T. "Simplified Control Scheme of Unified Power Quality Conditioner based on Three-phase Three-level (NPC) inverter to Mitigate Current Source Harmonics and Compensate All Voltage Disturbances." *Journal of Electrical Engineering & Technology*. 8(3), pp. 544-558, 2013. DOI: 10.5370/JEET.2013.8.3.544

[8] Lin, B.-R., Huang, Ch.-H., Yang, T.-Y., Lee, Y.-Ch. "Analysis and implementation of shunt active power filter with three-level PWM scheme." In: The Fifth International Conference on Power Electronics and Drive Systems, Nov. 17-20, 2003, Vol. 2, pp. 1580-1585. DOI: 10.1109/PEDS.2003.1283225

[9] Liu, G., Su, S., Peng, P. "Intelligent. Control and Application of All-function Active Power Filter." In: International Conference on Intelligent Computation Technology and Automation (ICICTA), Hunan, Oct. 20-22, 2008, Vol. 1, pp. 1078-1081. DOI: 10.1109/ICICTA.2008.439

[10] Kerrouche, S., Krim, F. "Three-phase active power filter based on fuzzy logic controller." *International Journal of Sciences and techniques of automatic Control & Computer Engineering*. 3(1), pp. 942-955. 2009.

[11] Li, Y. F., Lau, C. C. "Development of fuzzy algorithms for servo systems." *IEEE Control System Magazine*. 9(3), pp. 65-72. 1989. DOI: 10.1109/37.24814

[12] Correa, J. M., Hutto, E. D., Farret, F. A., Simoes, M. G. "A fuzzy-controlled pulse density modulation strategy for a series resonant inverter with wide load range." In: IEEE 34th Annual Power Electronics Specialist Conference, Acapulco, Mexico, June 15-19, 2003, Vol. 4, pp. 1650-1655. DOI: 10.1109/PESC.2003.1217705

[13] Mir, S. A., Zinger, D. S., Elbuluk, M. E. "Fuzzy controller for inverter fed induction machines." *IEEE Transactions on Industry Applications*. 30(1), pp. 78-84. 1994. DOI: 10.1109/28.273624

[14] Sarra, M., Djazia, K., Chaoui, A., Krim, F. "Three-phase active power filter with integrator-proportional control." In: Third International Conference on Electrical Engineering-ICEE'09, Algiers, Algeria, May 19-21, 2009.

[15] Zeng, F.-P., Tan, G.-H., Wang, J.-Z., Ji, Y.-C. "Five-level voltage-source inverter for shunt active power filter." In: Applied Power Electronics Conference and Exposition, 2008. APEC 2008. Twenty-Third Annual IEEE, Austin, TX, Feb. 24-28, 2008 , pp. 1618-1622. DOI: 10.1109/APEC.2008.4522941

[16] Sing, B., Haddad, K., Chandra, A. "A new control approach to three-phase active filter for harmonics and reactive power compensation." IEEE Transactions on Power Systems. 13(1), pp. 133-138. 1998. DOI: 10.1109/59.651624

[17] Chaturvedi, P. K, Shailendra, J., Agrawal, P. "A study of Neutral point potential and common mode voltage control in multilevel SPWM technique." In: Fifteenth National Power Systems Conference (NPSC), IIT Bombay, December 2008, pp. 518-523. URL: https://www.ee.iitb.ac.in/~npsc2008/NPSC_CD/Data/Oral/EIC4/p176.pdf

[18] Abdelkrim, T., Berkouk, E. M., Benamrane, K., Benslimane, T. "Study and control of 5-level PWM rectifier-5-level NPC active power filter cascade using feedback control and redundant vectors." *Turkish Journal of Electrical Engineering & Computer Sciences*. 20(5), pp. 655-677. 2012. DOI: 10.3906/elk-1012-931

[19] Chibani, R., Berkouk, E. M., Boucherit, M. S. "Five-Level NPC VSI: Different ways to balance input DC link voltages." *Elektrika*. 11(1), pp. 19-33. 2009.

[20] Ozdemir S., Ozdemir E., Tolbert, L. M., Khomfoi, S. "Elimination of harmonics in a five-level diode-clamped multilevel inverter using fundamental modulation." In: 7th International Conference on Power Electronics and Drive Systems, Bangkok, Nov. 27-30, 2007, pp. 850-854. DOI: 10.1109/PEDS.2007.4487803

[21] Krug, D., Bernet, S., Fazel, S. S., Jalili, K., Malinowski, M. "Comparison of 2.3-kV Medium-Voltage Multilevel Converters for Industrial Medium-Voltage Drives." *IEEE Transactions on Industrial Electronics*. 54(6), pp. 2979-2992. 2007. DOI: 10.1109/TIE.2007.906997

[22] Chennai, S. "Three-level neutral point clamped shunt active power filter performances using intelligent controllers." *Revue Roumaine des Sciences Techniques – Serie Électrotechnique et Énergétique*. 59(3), pp. 303-313. 2014.

[23] Benaissa, A., Rabhi, B., Benkhoris, M. F., Moussi, A., Le Claire, J. C. "Fuzzy logic controller for five-level shunt active power filter under distorted voltage conditions." In: IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, QC, Oct. 25-28, 2012, pp. 4973-4978. DOI: 10.1109/IECON.2012.6388986

[24] Reddy, T. N., Subramanyam, M.V. "Fuzzy Logic Controlled Shunt Active Power Filter for Mitigation of Harmonics with Different Membership Functions." In: Advances in Computing, Control, & Telecommunication Technologies, 2009. ACT '09. International Conference on, Trivandrum, Kerala, Dec. 28-29, 2009 , pp. 616-620. DOI: 10.1109/ACT.2009.157

[25] Tsengenes G., Adamidis G. "Shunt active power filter control using fuzzy logic controllers." In: 2011 IEEE International Symposium on Industrial Electronics, Gdansk, June 27-30, 2011, pp. 365-371. DOI: 10.1109/ISIE.2011.5984186

[26] Chennai, S., Benchouia, M. T., Goléa, A. "Harmonic Current Compensation based on Three-phase Three-level Shunt Active Filter using Fuzzy Logic Current Controller." *Journal of Electrical Engineering & Technology*. 6(5), pp. 595-604. 2011. DOI: 10.5370/JEET.2011.6.5.595