Fuzzy Logic Controller for Three-Level Shunt Active Filter to Mitigate Current Harmonics with Neutral Point Voltage Unbalances Control

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Abstract: *This paper presents a three-phase three-level (NPC) shunt active filter controlled by fuzzy logic current controller to mitigate current harmonics. Shunt active filter is the best solution to eliminate harmonics drawn from nonlinear load especially for low power system. For the medium power applications three-level inverter is more used, their advantages are reduction of the harmonic content and diminution the semiconductors voltage or current ratings. The compensation currents adopted a synchronous reference frame detection method that gives good performances under ideal or non ideal voltage conditions. To maintain dc link voltage constant and compensate the power losses of the inverter a proportional-integral voltage controller is used in the outer control loop. To perform output voltage delivered by the inverter another controller is added in inner control loop for balancing neutral point voltage. The simulation is performed using Matlab-Simulink and Simpowersystem Toolbox. The obtained results show the effectiveness of the proposed controller scheme.*

Key words: *Shunt active filter, Three-level inverter, Fuzzy logic controller, Synchronous reference detection method, current Harmonics compensation, AC-DC converter.*

1. Introduction

A large part of total electrical energy, produced in the world, supplies different types of non-linear loads. The loads such as AC/DC converters, variable frequency drives and electronic ballasts draw current, which does not resemble the grid sinusoidal voltage. This load is said to be non-linear and typically is composed of odd order currents, which are expressed as multiples of the fundamental frequency. The harmonic current cannot contribute to active power and need to be eliminated to enhance the power quality [1]. Active Power Filter (APF) is the popular solution used to eliminate the undesired current components by injection of compensation currents in opposition to them [2,3]. The most power converter used in APF is the two-level voltage source inverter [4,5], due to power handling capabilities of power semiconductors but these inverter are limited for low power applications. Three-level inverters have been successfully employed in medium and high power applications in the last years [6,7], their advantages are reduction of the harmonic content and diminution of the voltage or current ratings semiconductors.

The controller is the main part of the active power filter operation and has been a subject of many researches in recent years [8,9]. To improve the APF performances there's a great tendency to use intelligent control techniques, particularly fuzzy logic controllers.

In recent years, fuzzy logic controllers have generated a great deal of interest in certain applications [5,6]. These advantages are robustness and no need accurate mathematical model.

In this paper, fuzzy logic current controller is proposed to control the three-phase three-level shunt active filter to mitigate current harmonics. The dc-link voltage is maintained constant using a PI voltage controller and another controller for balancing the neutral point voltage. The performance of the proposed active power filter scheme is evaluated through computer simulations for transient and steady-state conditions using Matlab-simulink program and SimPowerSystem toolbox.

2. Shunt active filter

The circuit configuration of the active filter is shown in Fig.(1), it's controlled to cancel current harmonics on AC side and makes the source current in phase with the source voltage. The source current at the coupling point of the shunt APF will result sinusoidal [10,11].

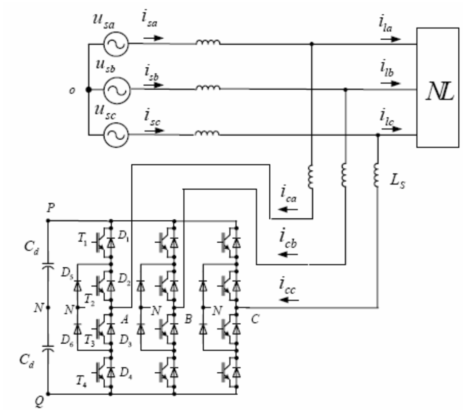

Fig. 1. Three-level shunt active filter

3. Three-level 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 multilevel converters are reduction of the harmonic content and minimization of the voltage or current ratings of the semiconductors [12].

Fig. (2) shows the circuit topology of a diode-clamped three-level inverter 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 0 to obtain Midpoint voltages. Such structure allows the switches to endure larger dc voltage input on the premise of not raising the level of their withstand voltage. Moreover, take phase-A as example, three kinds of voltage level $U_{dc}/2$, 0 and $-U_{dc}/2$ can be output corresponding to three kinds of switching states A, 0, B, As a result, there exist 27 kinds of switching output from the three-phase three-level [13,14].

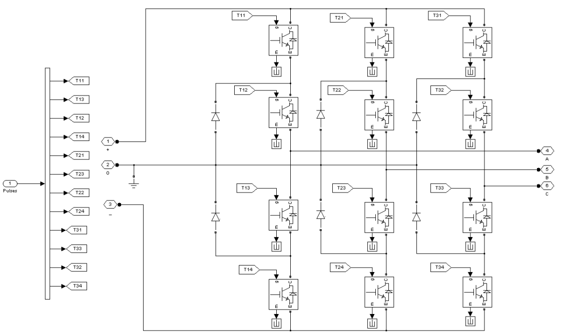
Fig. 2. Circuit topology of three-level NPC inverter

4. Control strategy

The control strategy used in this work is based on the synchronous reference frame detection method. The principle of this technique is described below [15,16]. The three phase currents i_a, i_b and i_c are transformed from three phase (abc) reference frame to two phase's (α-β) stationary reference frame currents i_α and i_β using:

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

Using a PLL (Phase Locked Loop), we can generate $\cos(\theta_{est})$ and $\sin(\theta_{est})$ from the phase voltage source v_{sa}, v_{sb}, v_{sc}.

The currents expression i_α and i_β in (d-q) reference frame are given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

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

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ \bar{i}_q + \tilde{i}_q \end{bmatrix} \quad (3)$$

The expression of the reference current $i_{\alpha\text{-}ref}$ and $i_{\beta\text{-}ref}$ are given by:

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & -\cos(\theta_{est}) \\ \cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix}^{-1} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} = \begin{bmatrix} \sin(\theta_{est}) & \cos(\theta_{est}) \\ -\cos(\theta_{est}) & \sin(\theta_{est}) \end{bmatrix} \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ i_q \end{bmatrix} \quad (5)$$

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

$$\begin{bmatrix} i_{a-ref} \\ i_{b-ref} \\ i_{c-ref} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{\alpha-ref} \\ i_{\beta-ref} \end{bmatrix} \quad (6)$$

The control strategy scheme based on synchronous reference frame detection method is shown in Fig.(3)

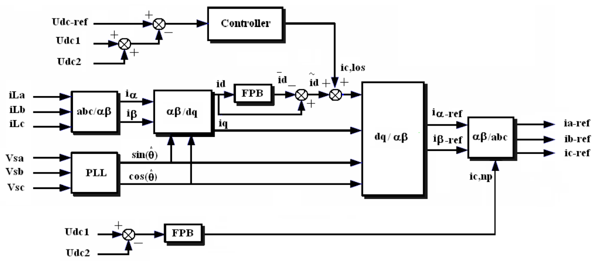

Fig. 3. Control strategy

5. DC voltage controller

To compensate the inverter losses and regulate the DC link voltage Udc, a proportional integral voltage controller is used in outer loop to determine the line current Ic,los. The control loop consists of the comparison of the measured voltage (Udc1+Udc2) with the reference voltage Udc-ref [17,18]:

$$I_{c,los} = K_p.\Delta U_{dc} + K_i \int \Delta U_{dc}.dt \qquad (7)$$

The compensation of the neutral-point voltage is required in the multilevel converter to avoid an unbalanced AC voltage waveform on the AC terminals. To compensate the neutral-point voltage a proportional controller is adopted in the inner control loop. If the average voltage across capacitor C1 is greater than the average voltage across capacitor C2, a small negative DC term current is added to the line current so that in the next source period the charged voltage in capacitor C1 is less than the charged voltage in capacitor C2. If the average voltage Udc1 is less than Udc2, a small positive DC current can be added to the line current in order to increase the capacitor voltage Udc1 in the next period. Therefore, the additional compensated current for the neutral-point voltage balance is given as:

$$i_{npc} = LPF(U_{dc2} - U_{dc1}).K \qquad (8)$$

K is a small gain of the neutral-point voltage compensator.

6. Fuzzy logic controller

The main component of an active filter is the current controller. Recently, fuzzy logic controllers (FLCs) have been interest a good alternative in more application. The fuzzy control system does not need an accurate mathematical model, can work with imprecise inputs, can handle non-linearity, and are more robust than conventional controllers [19]. Fuzzy logic control is the evaluation of a set of simple linguistic rules to determine the control action. To develop the rules of the fuzzy logic, we need good understand of the process to be controlled. The proposed fuzzy current controller has two inputs, error named *e* and change of error *de* and one output named *s* [20]. To convert it into linguistic variable, we use three fuzzy sets: N (Negative), ZE (Zero) and P (Positive). Fig. (4) shows the membership functions used in fuzzification and defuzzification. Error is the difference between filter current and compensate current for each phase [21].

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

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

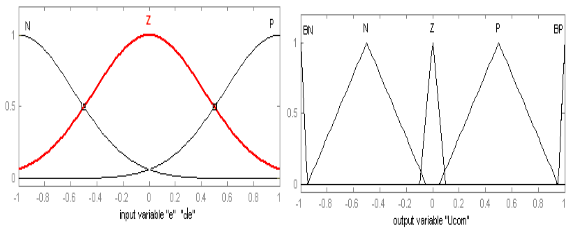

Fig. 4. Membership function for the inputs and output variables

The fuzzy rules are given by Table (1).

e / de/dt	N	Z	P
N	BN	P	BP
Z	BN	Z	BP
P	BN	N	BP

Table (1) Fuzzy rules

The simulink model of the generated switching signals is shown in Fig.(5).

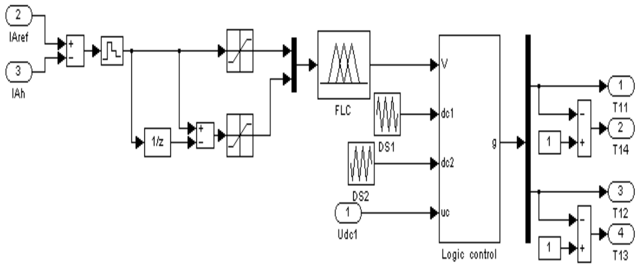

Fig. 5. Process of generation switching signals

7. Simulation results and discussion

To simulate the proposed shunt active power filter, a model is developed using MATLAB/Simulink and SimPowerSystems Toolbox. 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.

Simulation results are given to illustrate the system performance based on the proposed fuzzy logic current controller. Fig.(6) shows the simulated waveforms of three-phase ac source voltages and source current before compensation.

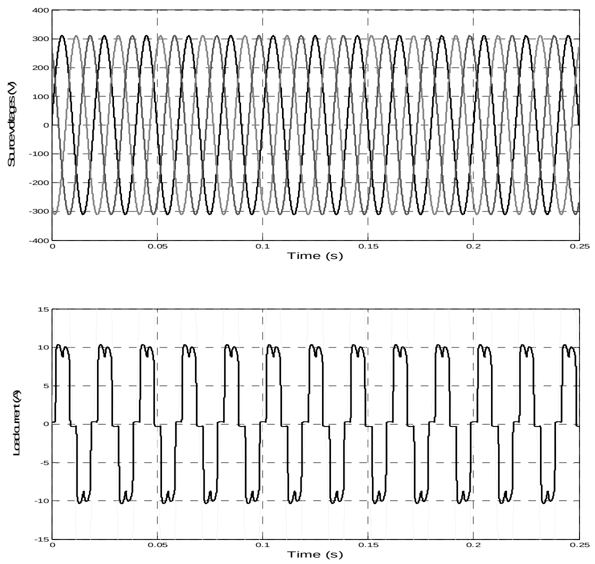

Fig. 6. Source voltage and line current before active filter operation

The harmonic spectrum of the source current without APF is shown in Fig.(7).

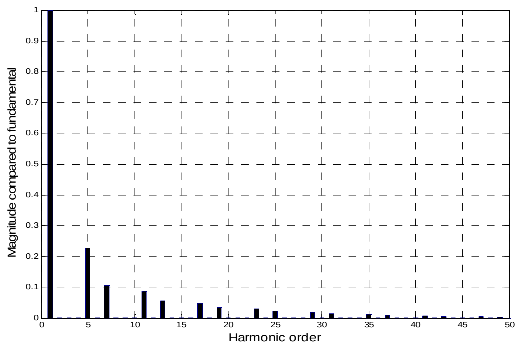

Fig. 7. Spectrum of source current without APF (THD=28.16)

This current is highly distorted and rich on harmonics; its THD is equal to 28.16%.

Fig.(8), shows the source current and injected current before and after filter operation. The corresponding harmonic spectrum is shown in Fig.(9).

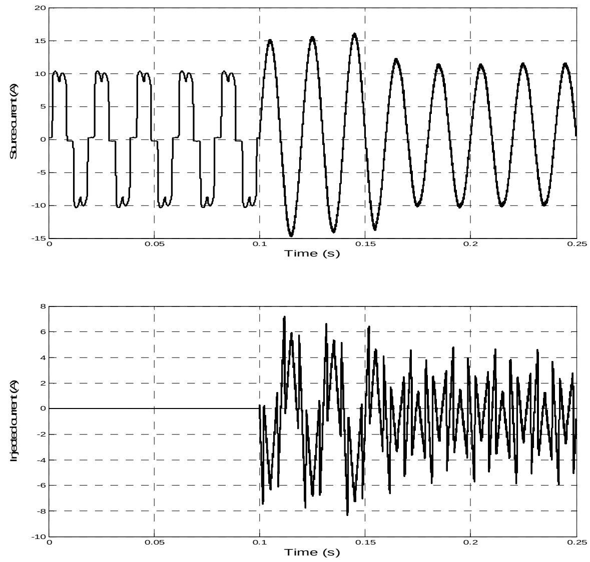

Fig. 8. Source current and compensated current before and after active filter operation

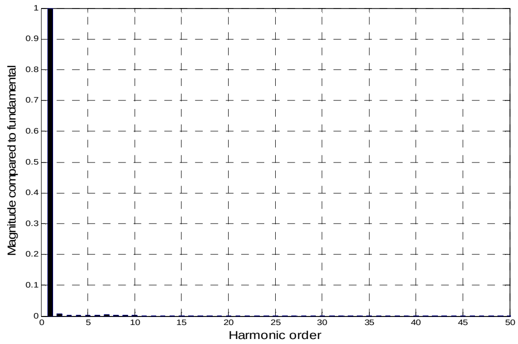

Fig. 9. Spectrum of source current after compensation (THD 1.26%)

Fig.(10) shows simultaneously, the source voltage and corresponding source current before and after compensation.

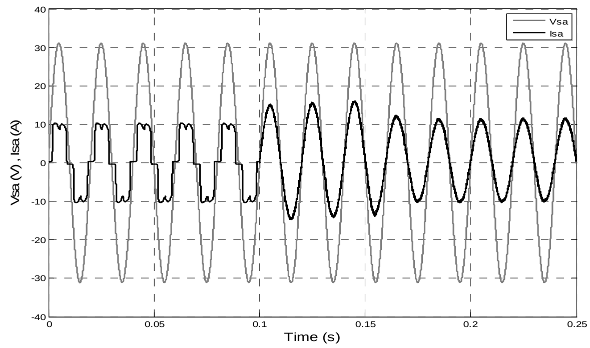

Fig. 10. Current and voltage source before and after compensation

Fig.(11) and Fig.(12), shows the output line voltage U_{AB} (V) and output phase voltage U_{AN}(V) when the three-level inverter is connect with the nonlinear load.

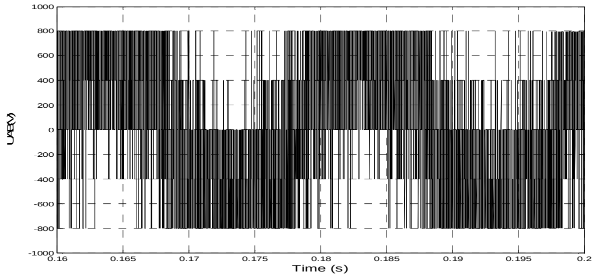

Fig. 11. Output line voltage UAB(V)

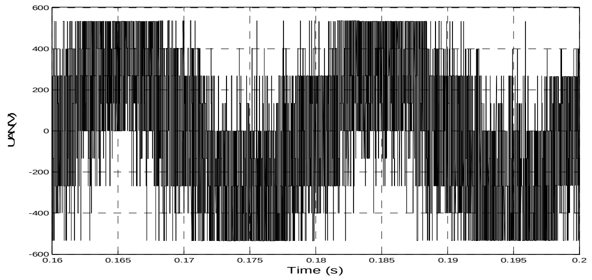

Fig. 12. Output phase voltage UAN(V)

The DC output voltages capacitors U_{dc}, U_{dc1}, U_{dc2} are shown in Fig.(13).

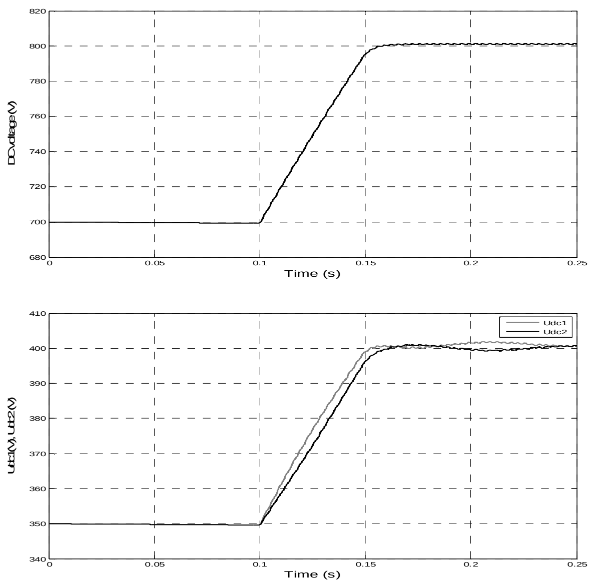

Fig. 13. DC output voltages Udc, Udc1, Udc2

To prove the dynamical response of the PI controller at transient condition, the DC side load is changed from R_{L1} to R_{L2} between t_1=0.2s and t_2=0.3s. It is clear from simulation results shown in Fig.(14) and Fig.(15) that we obtain good transient response for the source current and the DC voltage capacitor.

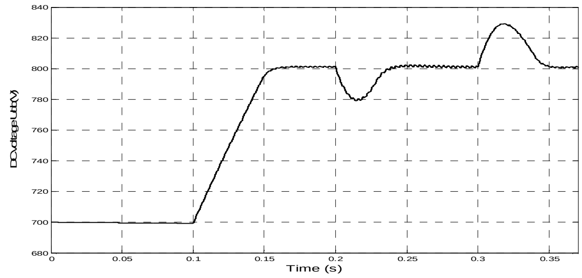

Fig. 14. Load perturbation response of PI dc voltage controller

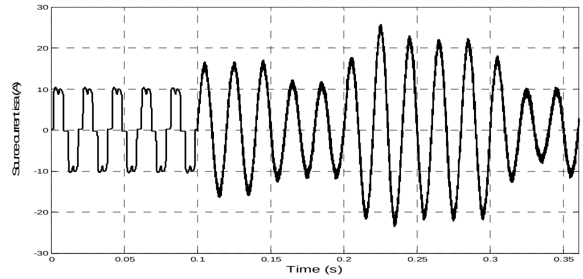

Fig. 15. Current source with variable load

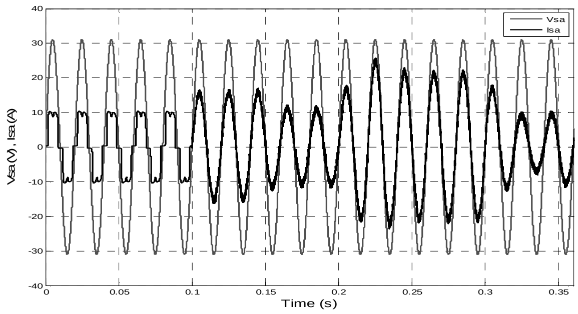

Fig. 16. Current and voltage source with variable load

The source current obtained without active power filter shown in Fig.(7) is high distorted and rich on harmonic. After compensation the THD is widely reduced from 28.16% to 1.26%, it is nearly sinusoidal and in phase with voltage source. The PI voltage controller ensure that the dc voltage capacitor is maintained constant and equal to the reference value U_{dc-ref} equal to 800V after transitional period equal to 0.05sec.

The delivered output line voltage UAB (V) and output phase voltage UAN (V) are shown in Fig. (11) and Fig. (12), the three-level voltages are 266.66V, 400V and 533.33Vcorresponding respectively to $U_{dc}/3$, $U_{dc}/2$ and $2U_{dc}/3$.

The performances of the three-level shunt active filter based on fuzzy logic current controller in terms of eliminating harmonics are very satisfactory. The THD value obtained after compensation respect widely the IEEE standards Norms (THD=1.26% < 5%).

8. Conclusion

In this paper, a three-phase three-level shunt active filter with neutral-point diode clamped topology based on fuzzy logic current controller is adopted to compensate current harmonics introduced by non linear loads such as AC/DC converter. The control strategy used is the synchronous reference frame detection method. It's easy to implement and gives good performances under ideal or non ideal voltages conditions. The paper is focused on new approach's using fuzzy techniques control. The simulation results obtained using MATLAB-Simulink and SimPowerSystem Toolbox shows the efficiency of the proposed fuzzy controller. The source current after compensation is sinusoidal and in phase with line voltage source. The total harmonic spectrum of the source current is widely reduced after compensation and respects the IEEE Norms.

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