SHUNT ACTIVE FILTER USING INTELLIGENT CONTROLLERS BASED ON THREE-LEVEL (NPC) INVERTER TO COMPENSATE CURRENT HARMONICS

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Abstract: *Shunt active power filter or power-line conditioner is fundamental equipment used to compensate reactive power and suppress harmonics generated by non-linear loads. The conventional scheme is based on the two level inverter controlled by hysteresis controller. This configuration presents some drawbacks particularly high inverse voltage applied to power components, degraded quality of the output voltage inverter waveforms in addition this configuration is limited to low power applications. Today three-level (NPC) inverter represents a good alternative for several industrial applications, secondly artificial neural networks and fuzzy logic Controllers are increasingly used for power electronic converters control. To take advantages of three-level inverter topology and intelligent techniques performance a new scheme of shunt active filter system based on these controllers is proposed in this work. The control strategy adopted is the synchronous reference currents detection method which gives excellent performance. To compensate losses inverter and maintain the dc voltage across capacitors constant a proportional integral controller is used. The numerical simulation is developed and performed using MATLAB-Simulink and SimPowerSystem Toolbox. The obtained results in transient and steady states show the effectiveness of the proposed shunt active filter configuration based on these intelligent current controllers.*

Key words: *Intelligent controller, Shunt active filter, Three-level (NPC) inverter, Synchronous reference current detection method, Harmonics compensation.*

1. Introduction

A large part of total electrical energy, produced in the world, supplies different types of non-linear loads. The loads such as 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]. Conventionally, passive filters have been used to eliminate current harmonics and to increase the power factor. However, the use of passive filter has many disadvantages [2]. Active Power Filter (APF) is the modern solution used to eliminate the undesired current components by injection compensation currents in opposition to them [3].The universal power converter topology used is the two-level voltage source inverter [4],[5],[6]. Due to power handling capabilities of power semiconductors, these converters are limited to low power applications. Principally, the design of any SAF system pass through three essentials criteria: power inverter topology, current controller and strategy control. Today three-level inverter is one of the most multilevel converter used successfully in medium and high power applications [7],[8], these advantages motivates us to use it for the proposed APF System. Instantaneous power theory [9] and synchronous reference frame detection method [10] are widely used in different research work, these techniques provide good results under different voltage source conditions but present some drawbacks such us a much calculations number, necessitate complex mathematical transformation and difficult implementation in practice [11]. Synchronous current detection method is another interesting method; it is concise and requires less computational calculation compared to the two other methods. In this work, this technique is adopted to use with three-level (NPC) inverter after some necessary modifications.

The controller is the main part of any active power filter operation and has been a subject of many researches in recent years [12],[13]. 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 artificial neural network and 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. 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 [14],[15],[16].

This paper presents two new control schemes for three-level (NPC) shunt active filter based on intelligent controllers. The models and numerical simulation for transient and steady-state conditions are developed and performed using Matlab-Simulink program and SimPowerSystem Toolbox. The simulations results show the effectiveness of these intelligent current controllers used for controlling the proposed shunt active filter system.

2. Shunt active filter

The basic compensation principle of a shunt active power filter is shown in Fig.1. It is controlled to cancel current harmonics on AC side and makes the source current in phase with the voltage source. The source current after compensation becomes sinusoidal at the coupling point of the shunt APF [17],[18].

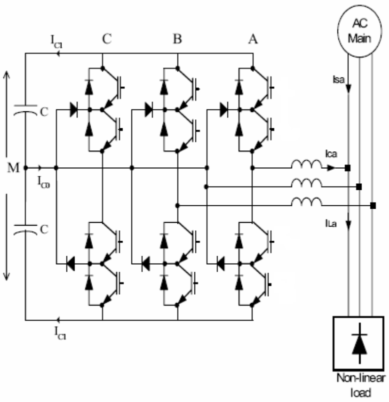

Fig. 1. Three-level shunt active filter

2.1Three-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. These advantages are reduction of the harmonic content generated by the active filter and decrease the voltage or current ratings of the semiconductors [19]. Fig. 2, shows the circuit topology of a diode-clamped three-level inverter based on the six main switches (T_{11}, T_{21}, T_{31}, T_{14}, T_{24}, T_{34}) of the traditional two-level inverter, adding two auxiliary switches (T_{12}, T_{13}, T_{22}, T_{23}, T_{32}, T_{33}) and two neutral clamped diodes on each bridge arm respectively, the diodes are used to make the connection with the point of reference to obtain Midpoint voltages. 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 $-U_{dc}/2$ [20],[21].

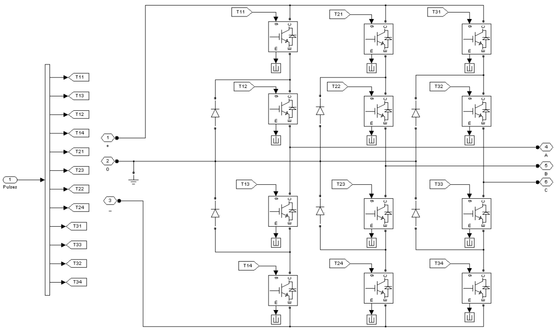

Fig. 2. Circuit topology of three-level NPC inverter

2.2 PWM logic controller

To control the shunt active filter a PWM logic controller is developed. The difference between the injected current and the reference current determine the modulation wave of the reference voltage. This voltage is compared with two carrying triangular identical waves shifted one from other by a half period of chopping and generate switching pulses [22]. The control of inverter is summarized in the two following stages:

Determination of the intermediate signals V_{i1} and V_{i2}:

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

Where V_{i1} and V_{i2} are intermediate voltage, E_c is the difference between injected and reference currents.

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

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

Fig.(3) shows the three-level PWM logic control.

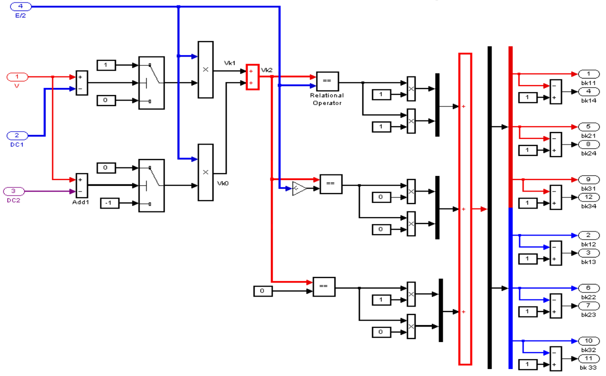

Fig. 3. Three-level PWM logic control

3. Control strategy

The strategy control used in this work is the synchronous reference current detection method. It's concise and requires less computational efforts than many others method control [23],[24]. 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:

$$\begin{aligned} v_{sa}(t) &= V_{sm}.\sin(\omega t) \\ v_{sb}(t) &= V_{sm}.\sin(\omega t - \frac{2\pi}{3}) \\ v_{sa}(t) &= V_{sm}.\sin(\omega t - \frac{4\pi}{3}) \end{aligned} \tag{1}$$

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 :

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

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

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

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:

$$I^*_{sm} = I^*_{smp} + I^*_{smd} \tag{4}$$

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 equation (5):

$$\begin{aligned} i_{ua}(t) &= v_{sa} / V_{sm} \\ i_{ub}(t) &= v_{sb} / V_{sm} \\ i_{uc}(t) &= v_{sc} / V_{sm} \end{aligned} \tag{5}$$

The desired source side currents can be obtained from equation (6):

$$\begin{aligned} i^*_{sa}(t) &= I^*_{sm}.i_{ua} \\ i^*_{sb}(t) &= I^*_{sm}.i_{ub} \\ i^*_{sc}(t) &= I^*_{sm}.i_{uc} \end{aligned} \tag{6}$$

Finally, the reference currents of AF can be obtained from (7):

$$\begin{aligned} i^*_{ca} &= i^*_{sa} - i_{La} \\ i^*_{cb} &= i^*_{sb} - i_{Lb} \\ i^*_{cc} &= i^*_{sc} - i_{Lc} \end{aligned} \tag{7}$$

The principle control scheme of the three-level inverter based on the synchronous reference current detection method is given by Fig.4.

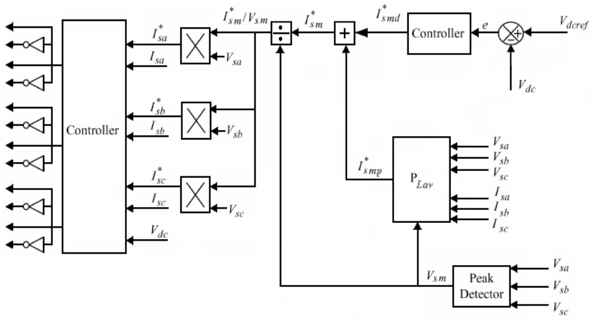

Fig. 4. Control strategy principle

4. DC voltage control

To compensate the inverter losses and maintain the dc-link voltage U_{dc} constant, a proportional integral controller is used to obtain the compensation current I^*_{smd}. The control loop compares the measured voltage U_{dc} with the reference voltage $U_{dc\text{-}ref}$ and generates corresponding current I^*_{smd} given by [25],[26]:

$$I^*_{smd} = K_p.\Delta U_{dc} + K_i \int \Delta U_{dc}.dt \tag{8}$$

Where k_p and k_i are the proportional and integral gains of the PI controller and $EU_{dc} = (U_{dc\text{-}ref} - U_{dc})$ is the DC bus voltage error. The overall closed-loop transfer function of the voltage controller can be expressed as:

$$\frac{U_{dc}}{U_{dc-ref}} = \frac{(K_p+(K_i/s))(K_1/(K_2 s+1))}{1+K(K_p+(K_i/s))(K_1/(K_2 s+1))}$$
$$\frac{U_{dc}}{U_{dc-ref}} = \frac{as+b}{s^2+2\xi\omega_n s+\omega_n^2} \tag{9}$$

Where $k_1/(K_2.s+1)$ is the transfer function of the simplified inverter, K is the voltage feedback scaling gain, ζ and ω_n are respectively the damping factor and natural angular frequency of the voltage response. From (9) we can obtain $K_p = (2.\zeta.\ \omega_n - 1/K_1K)$ and $K_i = \omega_n^2 K_2/K_1K$.

5. Intelligent controllers

5.1 MLPNN current controller

Artificial Neural Networks have provided an alternative modeling approach for power system applications. The MLPN is one of the most popular topologies in use today. This network consists of a set of input neurons, output neurons and one or more hidden layers of intermediate neurons. Data flows into the network through the input layer, passes through the hidden layers and finally flows out of the network through the output layer. The network thus has a simple interpretation as a form of input-output model, with network weights as free parameters. The training cycle has two distinct paths [27], the first one is Forward propagation (it is the passing of inputs through the neural network structure to its output), the second one is the error back-propagation (it is the passing of the output error to the input in order to estimate the individual contribution of each weight in the network to the final output error). The weights are then modified so as to reduce the output error. To train the neural network current controller, the Quasi-Newton Levenberg-Marquardt Training algorithm is used, it is efficient, easy to implement and is not time consuming.

The computations of the algorithm proceed as follows:

1) Initialize the interconnection weights and the biases of the nodes randomly,

2) Calculate the hidden layer outputs as:

$$x_j^h = f\left(\sum_{i=1}^{ni}(x_i w_{i,j}^h) + b_j^h w_{ni+1,j}^h\right) \tag{10}$$

Where x_j^h is the output of the hidden node j, x_i is the i'th input, $w_{i,j}^h$ is the weight connecting input node i with hidden node j, b_j^h is the input bias to hidden node j (normally b_j^h =1), $w_{ni+1,j}^h$ is the weight connecting the bias to the hidden node j, ni is the number of input nodes, and f is sigmoid function defined as:

$$f(x) = \frac{1}{1+e^{-x}} \tag{11}$$

3) Calculate the output layer outputs as:

$$x_k^o = f\left(\sum_{j=1}^{nk}(x_j^h w_{j,k}^o) + b_k^o w_{nk+1,k}^o\right) \tag{12}$$

Where x_k^o is the output of the output node k, $w_{j,k}^o$ is the weight connecting the hidden node j with output node k, b_k^o is the input bias to the output node k (normally b_k^o =1), $w_{nk+1,k}^o$ is the weight connecting the bias to the output node k and nk is the number of hidden nodes.

4) Calculate δ_k^o of each of the output nodes as:

$$\delta_k^o = x_k^o(1-x_k^o)(x_k^T - x_k^o) \tag{13}$$

Where δ_k^o , is the error (target-output) at the output of the neuron multiplied by the derivative of f(x), x_k^T is the target output (desired output) of the output node k.

5) Calculate δ_j^h each of the hidden nodes as follows:

$$\delta_j^h = x_j^h(1-x_j^h)\sum_{k=1}^{no}\delta_k^o w_{j,k}^o \tag{14}$$

Where δ_j^h is the derivative of f(x) multiplied by the summation of the weights multiplied by the output delta,

6) Adapt the weights of the output layer as:

$$w_{j,k}^o(t+1) = w_{j,k}^o(t) + \eta\delta_k^o x_j^h + \alpha\Delta w_{j,k}^o(t) \tag{15}$$

Where $0 < \eta < 1$ is the learning constant, $0 < \alpha < 1$ is the momentum constant and,

$$\Delta w_{j,k}^o(t) = w_{j,k}^o(t) - w_{j,k}^o(t-1) \tag{16}$$

7) Adapt the weights of the hidden layer as:

$$w_{i,j}^h(t+1) = w_{i,j}^h(t) + \eta\delta_j^h x_i + \alpha\Delta w_{i,j}^h(t) \tag{17}$$

Where,

$$\Delta w_{i,j}^h(t) = w_{i,j}^h(t) - w_{i,j}^h(t-1) \tag{18}$$

8) Repeat steps 1 to 7 until the error e is less than a prescribed small value ε.

$$\varepsilon = \sum_{k=1}^{no}\left(x_k^T - x_k^o\right)^2 \tag{19}$$

To be able to produce the correct output data, the network was trained with an improved algorithm, during the learning process the error function was minimized with an increasing number of training epochs.

The artificial neural network current controller to use for the three-level inverter shunt active filter is shown in Fig.(5). The input pattern is the error values (E_{ca}, E_{cb} and E_{cc}) between the measured filter currents (i_{fa}, i_{fb} and i_{fc}) and the compensating reference currents (i_{fa}^*, i_{fb}^* and i_{fc}^*) whereas the outputs values are the switching states T_{11}, T_{12}, T_{21}, T_{22}, T_{31} and T_{32}. The hidden layer contains 50 neurons with a sigmoid activation function and the output layer contains six neurons with a linear activation function. The network was trained with 10000 training examples using Levenberg-Marquardt back propagation algorithm [26].

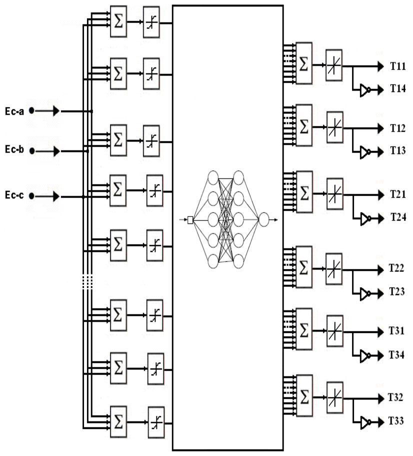

Fig. 5. Artificial neural network current controller

The Matlab-Simulink simulation block diagram of the three-phase three-level shunt active filter based on ANN current controller is shown in Fig.6.

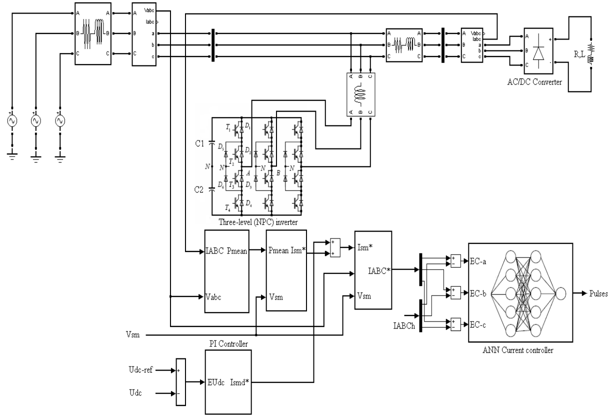

Fig. 6. Block diagram of the three-level (NPC) shunt active filter based on ANN current controller

5.2 Fuzzy current controller

Fuzzy logic controllers (FLCs) have been interest a good alternative in more power electronics application. Their advantages are robustness, not need a mathematical model and accept non-linearity [27],[28]. To benefit of these advantages a new fuzzy logic current controller for three-level inverter is proposed to control SAF system. It is designed to improve compensation capability of APF by adjusting the current error using fuzzy rules. The desired inverter switching signals of the three-level shunt active filter are determined according the error between the compensate 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. To convert it into linguistic variable, we use three fuzzy sets: N (Negative), ZE (Zero) and P (Positive). Fig.(7) shows the membership functions used in fuzzification and defuzzification. The fuzzy controller for every phase is characterized for the following:

- Three fuzzy sets for each input,
- Five fuzzy sets for output,
- Gaussian membership function for the inputs and triangle membership function for the output,
- Implication using the “min” operator,
- Mamdani fuzzy inference mechanism based on fuzzy implication,
- Defuzzification using the “centroid” method.

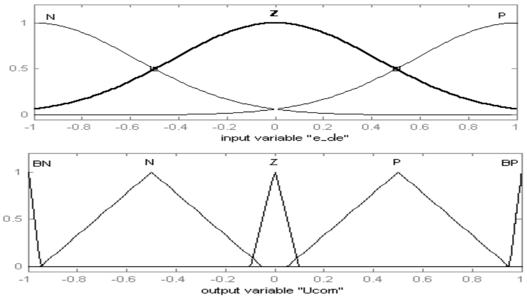

Fig. 7. Membership function for the inputs and output variables

The fuzzy rules are given by Table (I).

Table (I) Fuzzy rules

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

Errors for each phase are discretized by the zero order hold blocks. The error rate is derivative of the error and it is obtained by the use of unit delay block. The saturation block imposes upper and lower bounds on a signal. When the input signal is within the range specified by the lower limit and upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, he signal is clipped to the upper or lower bound. The output of the saturation blocks are inputs to fuzzy logic controllers. The outputs of these fuzzy logic controllers are used in generation of pulses switching signals of the three-level inverter. The switching signals are generated by means of comparing a two carrier signals with the output of the fuzzy logic controllers. The simulink model of the fuzzy logic switching signals generation is given by Fig.(8).

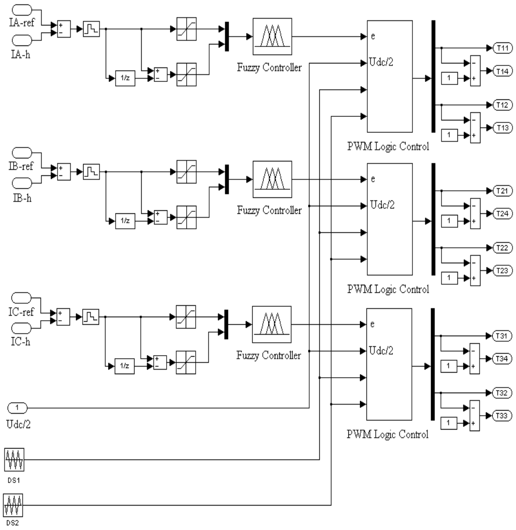

Fig. 8. Switching signals generation for the three-level (NPC) inverter

The Matlab-Simulink simulation block diagram of the three-phase three-level shunt active filter based on Fuzzy logic current controller is shown in Fig.(9).

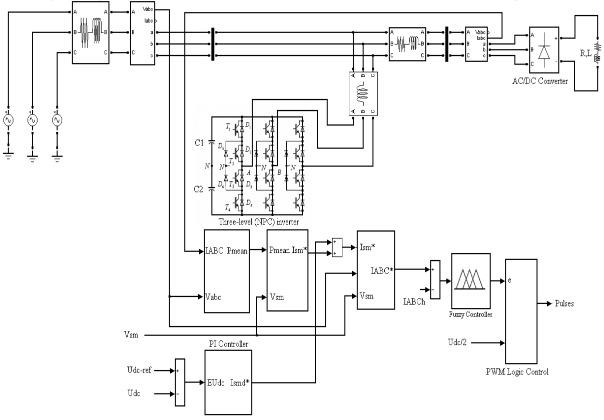

Fig. 9. Block diagram of the three-level (NPC) shunt active based on fuzzy logic current controller

6. Simulation results and discussion

The computer simulation results are provided to verify the effectiveness of the two proposed control scheme based on the ANNs and Fuzzy current controllers. The parameters of the shunt active filter model are: Lf=3mH, C1=C2=300uF, Vs=220V/50Hz, Udc-ref=800V.

6.1 Simulation results using ANN current controller

Figure (10) shows the line voltage and the line current without APF. Figure (11) shows the corresponding source current harmonic spectrum before compensation. The load current, the injected current and the DC voltage across capacitor before and after shunt active filter operation are shown in Fig.(12). Figure 13 shows the harmonic spectrum of the source current after compensation. The output line voltage UAB(V) and output phase voltage UAN(V) when the three-level inverter is connect with the nonlinear load are shown in Fig.(14) and Fig.(15). Finally, the source current and the corresponding source voltage are presented simultaneously in Fig.(16).

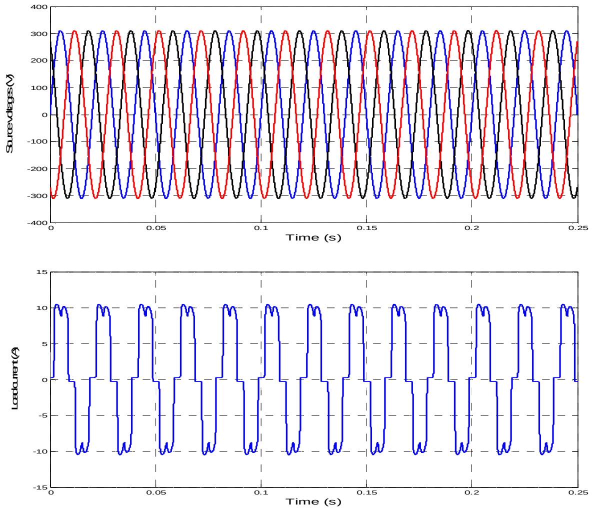

Fig. 10. Source voltages and line current before compensation

The source current is highly distorted and rich on harmonics. It is not in phase with the source voltage, the power factor is poor with high consummation of reactive power.

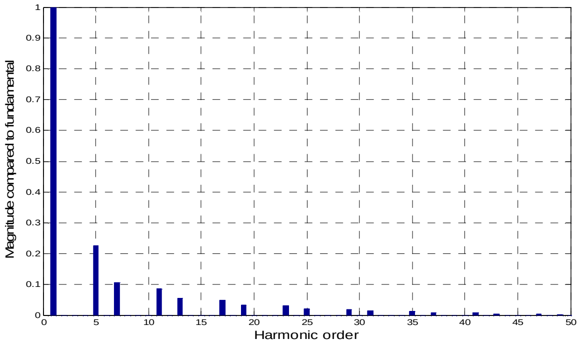

Fig. 11. Spectrum of source current without APF (THD=27.74%)

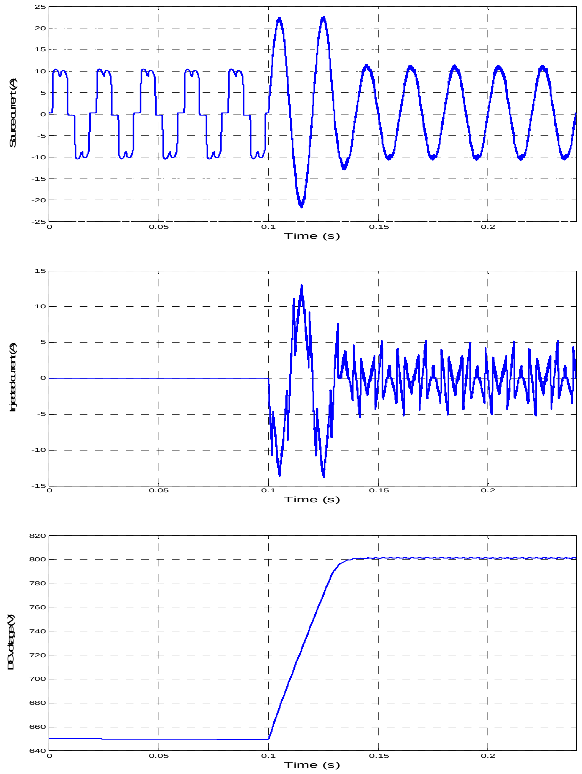

Fig. 12. Line current, injected current and DC voltage before and after compensation using ANN controller

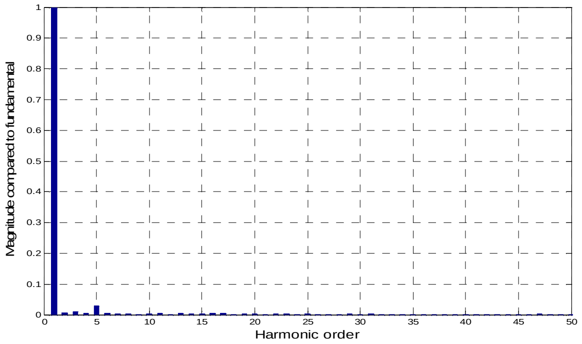

Fig. 13. Spectrum of source current with APF with ANN controller (THD=3.96%)

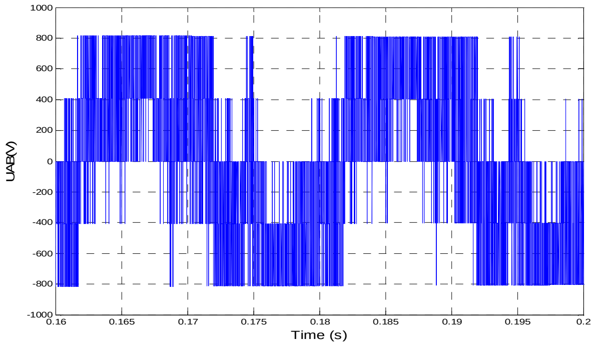

Fig. 14. Output line voltage UAB(V) using ANN controller

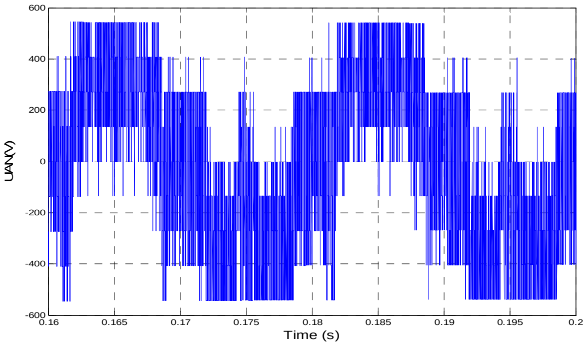

Fig. 15. Output phase voltage UAN(V) using ANN controller

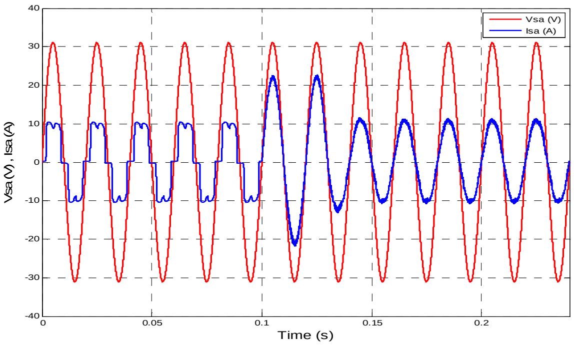

Fig. 16. Current and voltage source after compensation with ANN controller (vsa= Vsa/10)

Using the proposed SAF system controlled by ANN's controller, we can conclude that the source current after compensation is practically sinusoidal and in phase with the corresponding source voltage. The SAF start the compensation process instantly when it is connected to the non-linear load. The system passes through transient period of 0.04s necessary to attain the steady state of the source current and to stabilize the dc voltage to its reference $U_{dc\text{-}ref}$=800V. The source current THD is significantly reduced from 27.74% to 3.96% in conformity with IEEE standard Norms.

6.2 Simulation results using Fuzzy current controller

The load current, the injected current and the DC voltage across capacitor before and after shunt active filter operation are shown in Fig.(17). Figure 18 shows the harmonic spectrum of the source current after compensation. The output line voltage UAB(V) and output phase voltage UAN(V) when the three-level inverter is connect with the nonlinear load are shown in Fig.(19) and Fig.(20). Finally, the source current and the corresponding source voltage are presented simultaneously in Fig.(21).

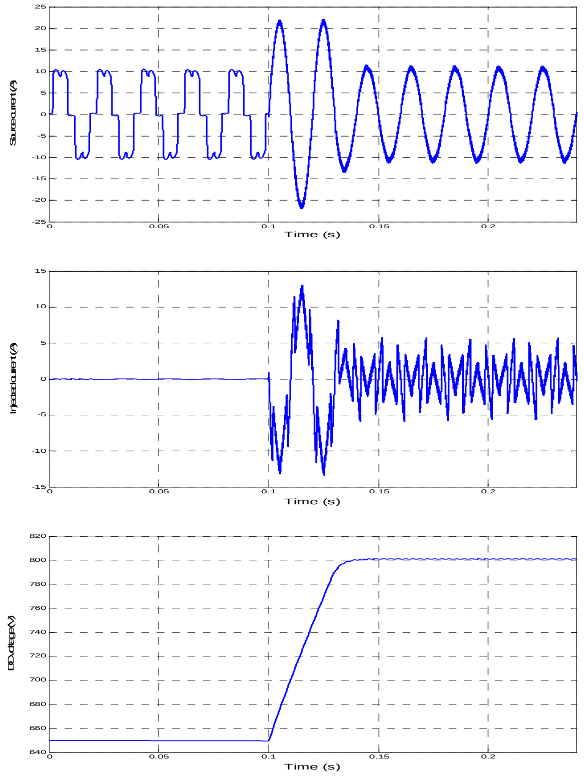

Fig.17. Line current, injected current and DC voltage before and after compensation using Fuzzy current controller

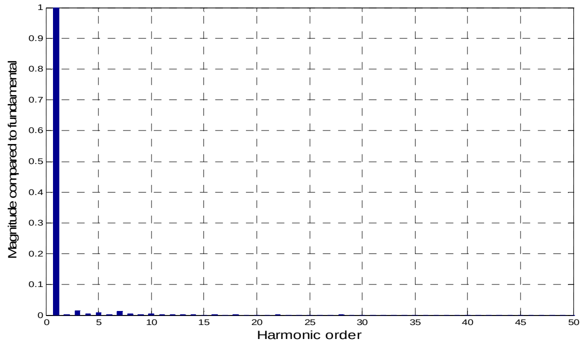

Fig. 18. Spectrum of source current after compensation with Fuzzy controller (THD=1.62%)

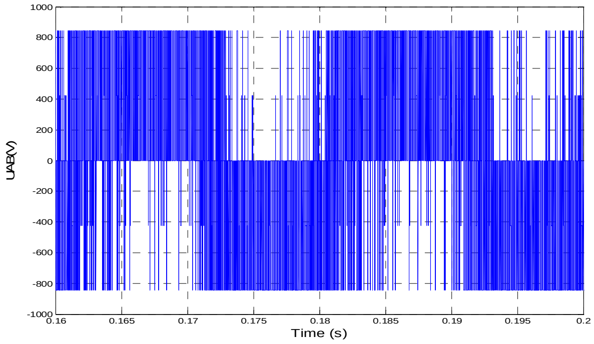

Fig. 19. Output line voltage U_{AB}(V) using fuzzy controller

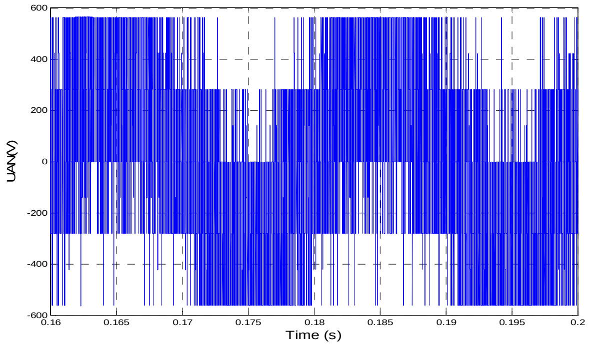

Fig. 20. Output phase voltage U_{AN}(V) using Fuzzy controller

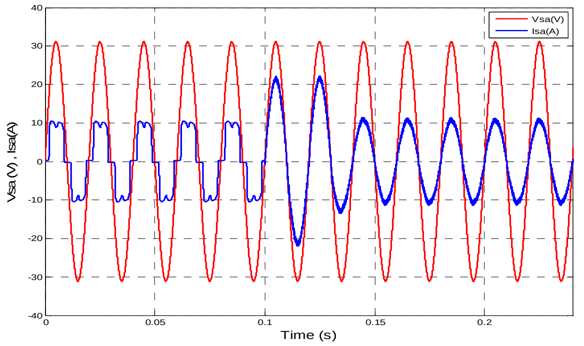

Fig. 21. Current and voltage source after compensation with fuzzy controller (vsa= Vsa/10)

By visualizing Figures (12) and (17), we can conclude the successful simulation of the harmonic currents compensation using the two proposed intelligent current controllers. The performances of the three-level shunt active filter based on FLC controller in terms of eliminating harmonics is better than ANN controller. In the two cases, the THD is widely reduced from 27.74% to 3.96% for ANN and to 1.62% for FLC controllers. The control strategy based on synchronous current detection method permits a good extraction of reference currents compensation. The PI Controller ensures that the dc voltage across capacitor is maintained constant and equal to reference vale ($U_{dc\text{-}ref}$=800V). The steady state of the source current is obtained after 0.03 sec in the two cases. Figures (14) and (19) shows the output line voltage U_{AB}(V), figures 15 and 20 shows the output phase voltage U_{AN}(V), for the two cases, the three-level voltage delivered are 266.66 V, 400V and 533.33V corresponding respectively to $U_{dc}/3$, $U_{dc}/2$ and $2U_{dc}/3$. Figures (16) and 21 shows that the source current is sinusoidal and in phase with the corresponding source voltage. The THD values obtained respect widely the IEEE standards Norms (THD ≤5%).

7. Conclusion

A three-phase three-level shunt active filter with neutral-point diode clamped topology using intelligent current controllers is proposed to suppress current harmonics. The numerical simulation is performed using MATLAB-Simulink and SimPowerSystem Toolbox. For the two configurations synchronous current detection method strategy is adopted to calculate reference signals, it’s concise and requires less computational efforts than many others method control. The harmonic spectrum after compensation shows that the THD is widely reduced for the two controllers in conformity with IEEE Norms (THD<=5%) but the fuzzy is more efficiency than ANNs systems. The DC voltage controller ensures that the voltage across capacitors is maintained constant with fast dynamic response in case of load current variation. The current source after compensation is sinusoidal and in phase with the line voltage source with reduced THD vale.

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