Three-phase Three-level (NPC) Shunt Active Power Filter Performances based on PWM and ANN's Controllers for Harmonic Current Compensation

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Abstract: This paper presents a shunt active power filter performances based on three-level (NPC) inverter using conventional pulse width modulation (PWM) and Ann's controllers to mitigate current harmonics generated by non-linear loads. Shunt APF is the best solution to eliminate harmonics drawn from nonlinear load especially for low power system, the conventional scheme based on the two level inverter controlled by hysteresis controller presents several drawbacks such as high inverse voltage applied to power components, degraded output voltage inverter waveforms, etc. Today three-level (NPC) inverter and intelligent controllers are widely used in different industrial applications. To take advantages of these inverter topology and artificial intelligent controller performance a novel control scheme based on Ann's current controller is proposed in this work. The control strategy adopted is the synchronous current detection method, it is easy to implement and permits a good extraction of reference currents compensation. The numerical simulation is performed using MATLAB-Simulink and SimPowerSystem Toolbox. The simulation results obtained in steady and transit states show the effectiveness and the superiority of Ann systems compared to PWM controller.

Keywords: Shunt active power filter, intelligent controller, Ann's, Three-level (NPC) inverter, Harmonic currents compensation, power quality improvement.

1. Introduction

With the proliferation of nonlinear power electronics loads, the problem of harmonic is severity, which influences the quality of power grid. Harmonic currents produced by nonlinear loads, such as rectifiers, power electronics converters, controllers for adjustable-speed motor drives, electronic power supplies, DC motor drives, battery chargers, electronic ballasts are responsible for the rise in PQ related problems [1]. Passive power filter is a traditional harmonic restraint method, this solution have been used to eliminate current harmonics and to increase the power factor, which are simple and low cost. However, the use of passive filter has many disadvantages, such as large size, series or parallel resonance with the system impedance. [2]. One of the most popular active filters is the Shunt Active Power Filter; Shunt APF have been researched and developed, that they have gradually been recognized as a feasible solution to the problems created by non-linear loads. Active filter is used, these last years, to improve power quality on the load side from the grid by injecting compensating currents.

The performance of any active filter mainly depends on the reference current generation strategy, hysteresis or pulse width modulation signals, topology of the power converter, etc... Instantaneous power theory [3] and synchronous reference frame detection method [4] are widely used in different research work, these techniques provide good results under different voltage source conditions but present some drawbacks such as a much calculations number, necessitate complex mathematical transformation and difficult implementation in practice [5]. Synchronous current detection method is another interesting method; it is concise and requires less computational calculation compared the two other methods. In this work, this technique is adopted to use with three-level (NPC) inverter after several modifications.

Received: April 28th, 2013. Accepted: March 14th, 2014

In other side, three-level inverter is one of the most multilevel converters used successfully in medium and high power applications [6], [7]. Their advantages are well known as very low harmonic distortion, smaller common-mode (C-M) portions, and lower switching frequency and power loss. However, the control of a three-level inverter is more complex than that of a two-level inverter because of large numbers of inverter switching states.

The controller is the main part of any active power filter operation and has been a subject of many researches in recent years. 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 centred 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 [8]. To improve the control performances there's a great tendency to use intelligent control techniques, particularly fuzzy logic or artificial neural network controllers [9], [10]. Their principal advantages are robustness, ability to control nonlinear systems, no need accurate mathematical model, etc.

This paper presents the performance of the three-level (NPC) shunt active filter based on PWM and Ann's controllers. The model and numerical simulation in transient and steady states conditions are developed and performed using Matlab-Simulink and SimPowerSystem Toolbox.

2. Shunt active power filter

The basic block diagram including non linear load compensation principle of a shunt active power filters based on three-level (NPC) inverter is shown in Figure 1. It is controlled to draw/supply a compensated current from/to the utility, such that it cancels harmonic currents of the non-linear load and makes the source current in phase with the different waveforms. The current drawn from the power system at the coupling point of the shunt APF will result sinusoidal [11], [12].

Figure 1. Three-level (NPC) Shunt active filter

Figure 2. Circuit topology of three-level (NPC) inverter

Table 1. Switching states of three-level (NPC) inverter

Switching states	Voltage output	T11	T12	T13	T14
A	Udc/2	ON	ON	OFF	OFF
0	0	OFF	ON	ON	OFF
B	-Udc/2	OFF	OFF	ON	ON

3. Control strategies

The strategy control used is the synchronous reference current detection method is shown in Figure 2. It's concise and requires less computational efforts than many others method control [12], [13]. 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.

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

In order to compensate 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:

$$P_s = \frac{3}{2} V_{sm} \cdot I_{smp}^* = P_{Lav} \tag{2}$$

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

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

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, these unity signals can be obtained from equation (5):

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

Figure 3. Synchronous current detection method control

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

$$\begin{aligned} i_{sa}^*(t) &= I_{sm}^* \cdot i_{ua} \\ i_{sb}^*(t) &= I_{sm}^* \cdot i_{ub} \\ i_{sc}^*(t) &= I_{sm}^* \cdot i_{uc} \end{aligned} \quad (6)$$

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

$$\begin{aligned} i_{ca}^*(t) &= i_{sa}^*(t) - i_{La}^*(t) \\ i_{cb}^*(t) &= i_{sb}^*(t) - i_{Lb}^*(t) \\ i_{cc}^*(t) &= i_{sc}^*(t) - i_{Lc}^*(t) \end{aligned} \quad (7)$$

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 ($U_{dc}=U_{dc1}+U_{dc2}$) with the reference voltage U_{dc-ref} and $\Delta U_{dc}=U_{dc-ref}-U_{dc}$. The loop generates corresponding current I_{smd}^* as given by:

$$I_{smd}^* = K_p \cdot \Delta U_{dc} + K_i \int \Delta U_{dc} dt \quad (8)$$

4. Shunt APF Control

A. PWM current controller

The main component of any active filter is the controller; the conventional scheme is based on hysteresis controller, it is very complicated and requires many calculations for its implementation [15]. To replace the conventional hysteresis control scheme a novel logic controller to use with three-level (NPC) inverter given by Figure (4) is proposed. The difference between the injected current and the reference current determines the reference signal (e). This signal is compared with two triangular-carrying identical waves shifted from one to the other by a half-period of chopping and generating the switching pulses. The control of inverter is summarized in the two following stages:

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

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

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 $T_{i1}=0, T_{i2}=0, T_{i3}=1, T_{i4}=1$.

The bloc diagram of the three-level (NPC) shunt active power filter based on conventional current controller is shown in Figure (5).

Figure 4. Three-level (NPC) inverter PWM logic control

Figure 5. Three-level (NPC) shunt APF block diagram based on conventional controller

B. Ann's current controller

Artificial Neural Networks have provided an alternative modeling approach for power system applications. It is essentially a cluster of suitably interconnected non-linear elements of very simple form that possess the ability of learning and adaptation. These networks are characterized by their topology, the way in which they communicate with their environment, the manner in which they are trained and their ability to process information. The MLPNNs is one of the most popular topologies in use today [16], the structure model of this topology is shown in Figure 6. It consists of input layer, output layer and hidden layer, each layer has many neurons; choosing appropriate number of neurons of the hidden layer and activation function and threshold value of neurons, and determining the weight of connections between neurons through learning and training, it can realize approximation of any non-linear object with small error [17].

Figure 6. Three-layer neural network topology structure

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, 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) [18]. 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.

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:

$$x_j^h = f \left(\sum_{i=1}^{ni} (x_i w_{i,j}^h) + b_j^h w_{ni+1,j}^h \right) \quad (9)$$

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:

$$f(x) = \frac{1}{1 + e^{-x}} \quad (10)$$

3. Calculate the output layer outputs as:

$$x_k^0 = f \left(\sum_{j=1}^{nk} (x_j^h w_{j,k}^0) + b_k^0 w_{nk+1,k}^0 \right) \quad (11)$$

Where x_k^0 is the output of the output node k , $w_{j,k}^0$ is the weight connecting the hidden node j with output node k , b_k^0 is the input bias to the output node k (normally $b_k^0=1$), $w_{nk+1,k}^0$ is the weight connecting the bias to the output node k and nk is the number of hidden nodes.

4. Calculate δ_k^0 of each of the output nodes as:

$$\delta_k^0 = x_k^0 (1 - x_k^0) (x_k^T - x_k^0) \quad (12)$$

Where δ_k^0 , 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:

$$\delta_j^h = x_j^h (1 - x_j^h) \sum_{k=1}^{no} \delta_k^0 w_{j,k}^0 \quad (13)$$

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

6. Adapt the weights of the output layer as:

$$w_{j,k}^0(t+1) = w_{j,k}^0(t) + \eta \delta_k^0 x_j^h + \alpha \Delta w_{j,k}^0(t) \quad (14)$$

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

$$\Delta w_{j,k}^0(t) = w_{j,k}^0(t) - w_{j,k}^0(t-1) \quad (15)$$

7. Adapt the weights of the hidden layer as:

$$w_{i,j}^h(t+1) = w_{i,j}^h(t) + \eta \delta_j^h x_i + \alpha \Delta w_{i,j}^h(t) \quad (16)$$

Where,

$$\Delta w_{i,j}^h(t) = w_{i,j}^h(t) - w_{i,j}^h(t-1) \quad (17)$$

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

$$e = \sum_{k=1}^{no} (x_k^T - x_k^0)^2 \quad (18)$$

The flow chart for training ANN controller is given by Figure (7).

Figure 7. Flow chart for training Ann's controller

For the three-level (NPC) inverter, the proposed Ann's current controller is shown in Figure 8. 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}^*) [9], [10] and [14]. Whereas the outputs values are the switching states T11, T12, T21, T22, T31 and T32. The hidden layer contains 12 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.

Figure 8. Ann's current controller

The bloc diagram of the three-level (NPC) shunt APF based on Ann's current controller is shown in Figure (9).

Figure 9. Three-level (NPC) shunt APF block diagram based on Ann's current controller

Figure (10) shows the Matlab-Simulink simulation block diagram of the proposed Shunt APF based on artificial neural network current controller.

Figure 10. Three-level (NPC) shunt APF simulation model based on Ann's current controller

5. Simulation results and discussion

The simulation results are provided to verify the performance and effectiveness the three-level (NPC) shunt active power using PWM and Ann's current controllers. The active filter is composed mainly of the three-phase source, three-level (NPC) inverter, nonlinear load (Rectifier & R,L). The parameters of the simulation are: $L_f = 3$ mH, $C_1 = C_2 = 3000$ μ F, $V_s = 220$ V/50 Hz and $U_{dc-ref} = 800$ V.

A. Simulation results using conventional controller

Figure (11) shows the simulated waveforms of the source current before compensation. The corresponding harmonic spectrum is shown in Figure 12. The source current and injected current before and after APF application are shown in Figures 13 and 14, respectively. The DC voltage is presented in Figure 15. The waveforms of source voltage and source current after compensation are simultaneously shown in Figure 16. The harmonic spectrum of the source current after compensation is shown in Figure 17.

Figure 11. Source current without Shunt APF

Figure 12. Source current spectrum without Shunt APF: THDi (%) = 28.16%

Figure 13. Source current i_{sa} (A) before and after compensation using conventional controller

Figure 14. Injected current i_{ha} (A)

Figure 15. DC side capacitor voltages U_{dc} (V)

Figure 16. Current source isa (A) and voltage source vsa (V) before and after compensation

Figure 17. Source current spectrum with Shunt APF: THDi (%) = 4.32%

B. Simulation results using conventional controller with sudden step change in load

Figure 18. Source current isa (A) with step change in load (between $t_1 = 0.2$ s and $t_2 = 0.4$ s)

To evaluate dynamic responses and test robustness of the proposed shunt active filter a step change in load is introduced between $t_1 = 0.2$ sec and $t_2 = 0.4$ sec. Figures 18 and 19 show the respective waveforms of the source current and injected current before and after compensation. The dc side capacitor voltage is shown in Figure 20. The current and the voltage source waveforms before and after compensation are simultaneously presented in Figure 21.

Figure 19. Injected current i_{ha} (A) with step change in load (between $t_1 = 0.2$ s and $t_2 = 0.4$ s)

Figure 20. DC side capacitor voltage with step change in load (between $t_1 = 0.2$ s and $t_2 = 0.4$ s)

Figure 21. Current and voltage source before and after compensation with step change in load (between $t_1 = 0.2$ s and $t_2 = 0.4$ s)

C. Simulation results using Ann's current controller

The source current and injected current before and after APF application using Ann's controller are respectively shown in Figures 22 and 23. The output DC capacitor voltage is presented in Figure 24. The waveforms of source voltage with source current after compensation are simultaneously shown in Figure 25. The harmonic spectrum of the source current after compensation is shown in Figure 26.

Figure 22. Source current i_{sa} (A) before and after compensation using Ann's controller

Figure 23. Injected current i_{ha} (A)

Figure 24. DC side capacitor voltages U_{dc} (V)

Figure 25. Current source isa (A) and voltage source vsa (V) before and after compensation

Figure 26. Source current spectrum with APF using Ann's current controller:
THDi (%) = 3.96%

Through visualization (Figs. 13, 18, and 22), we are able to conclude that the operation of the proposed three-level shunt APF based on conventional and Ann's current controllers is successful. Before the application of shunt APF, 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 3.96% for Ann's controller and to 4.32% for conventional controller. The dc voltage is maintained at a constant value which is equal to the reference value $U_{dc-ref} = 800$ V by using PI voltage controller. Figures 20 and 21 illustrate the dynamic response of the proposed shunt APF. It is observed that the dc voltage pass through a transitional period of 0.06 s before stabilization and reaches its reference $U_{dc-ref}=800$ V with moderate peak voltage approximately equal to 7 V when a step change in load current is introduced between $t_1= 0.2$ s and $t_2= 0.4$ s. Figures 16, 21, and 25 demonstrate that after active filter application, the current source is sinusoidal and in phase with the voltage source. The performance of the three-level shunt active filter based on Ann's controller in terms of harmonics elimination and reactive power compensation is very satisfactory and better than conventional current controller. The THDi values obtained with the two controllers respect the IEEE standard Norms of $THDi \leq 5\%$.

6. Conclusion

In the present paper, a three-phase three-level (NPC) shunt active power filter with neutral-point diode clamped inverter based on PWM and Ann's current controllers are presented. Use of the filter is aimed at achieving the elimination of harmonics introduced by nonlinear loads. Several simulations with nonlinear loads composed by AC/DC converter with R,L loads under different conditions are performed. The simulation results show the robustness and effectiveness of the proposed Ann's controller in terms of eliminating harmonics compared to conventional current controller. The THDi is significantly reduced from 28.16% to 4.32% using conventional controller and to 3.96% using Ann's controller in conformity with the IEEE standard norms. 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 value ($U_{dc-ref}=800V$). The steady state of the source current is obtained after 0.03 sec in the two cases. The current source after compensation for the two proposed control scheme is sinusoidal and in phase with the line voltage source; the power factor is nearly equal to unity. Hence, the proposed Ann's current controller is excellent candidates to control shunt active filters based on multilevel inverter topology toward eliminating the harmonic currents and improving the power factor compared to conventional current controller.

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