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A Novel Control Strategy For Shunt Active Power Filter Using NARX Neural Network

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ABSTRACT
This paper presents a novel control method for shunt Active Power Filter (APF) based on the Nonlinear Auto Regressive with eXogenous neural network (NARX). The proposed series parallel NARX network is trained by using learning algorithm called static backpropagation algorithm for electric loads nonlinearity modelling. Then the well-trained series-parallel architecture NARX network is converted to parallel architecture NARX network and tested with different patterns. The algorithm of the instantaneous reactive power is integrated with the proposed NARX networks to analyze the predominant harmonics. Finally, the control reference signal of the shunt APF is designed. The proposed method is applied on an Electrical Submersible Pump (ESP) rotated by three-phase induction motor which is one of most widely used loads in petroleum industry field. The results show very good behavior of the NARX neural network in harmonic detection and mitigation.

Keywords - NARX neural network, shunt APF, nonlinear loads, instantaneous reactive power algorithm

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I. INTRODUCTION

The rapid increase in electronic device technology causes industrial loads to become nonlinear and consequently results in significant harmonic distortion level. Harmonic current produced from the supply result in a distortion voltage at the Common Coupling Point (PCC) due to the impedance of the system. Harmonics are generally affected badly on utility and consumer equipment. They can cause increase in power losses, line temperature, protection devices malfunction noise and resonance [1].

The shunt APF provided a solution of the problems of power system quality such as harmonic mitigation, harmonic damping and reactive power compensation [2]. According to their topology, The APFs can be classified into series, shunt and unified or hybrid APFs. Shunt APF is considered as the most widely topology of the APFs [3, 4]. The main application of the shunt APF is for compensating the current harmonics of the loads [5]. Series APF is more suitable for voltage sources of harmonics, the main function of this type of the APF is to compensate the negative sequence of voltage and maintain the voltage value in the electrical power system [6]. The Unified Power Flow Conditioner (UPFC) composes of both series and shunt APFs and its prupose is to isolate the current and the voltage harmonics. This type of active power filter is expensive and complex in control [7]. Hybrid active filter is raised up to minimize the initial cost of filtering. The function of hybrid APF depends on using a passive filter to tune up the most dominant harmonic order and then the output is connected to a series or shunt APF. This will reduce the filter rating and cost in turn [8].

In recent decays there have been a great attention in the improvements, applications and control strategy of APFs. Many control methods were proposed and developed to improve the harmonic mitigation performance of shunt APFs [9-20]. These methods include the instantaneous reactive power method [9-11], the synchronous reference frame algorithm [12-13], nonlinear control method [14], etc. The instantaneous reactive power method and the synchronous reference frame algorithm are the most common methods applied in APFs [9-13]. Linear feedback-feedforward controller technique was proposed in [15]. It is very difficult to satisfy both transient and steady-state efficiencies with the linear control algorithm. Slide mode control method was proposed in [16] to deal with the shunt APF nonlinear characteristics. The steady-state errors are nonzero, because there is no closed loop integral control system in this method. Inverse system technique based on the slide mode controller method was designed for the shunt hybrid APF in [17] to investigate the harmonic cancelation performance. The Lyapunov function-based controller method was investigated to generally stabilize the shunt APF by [18]. But it facing a difficulty in calculating the ripples produced from the DC-link (capacitor voltage). A prediction controller method based on the pre-sampled information from the pre-fundamental cycle of the APF was proposed by [19]. Its reference current was determined by the predicted values of the currents. P. Cheng et al. [20] proposed systems that obtain harmonic isolation at a predominant harmonic frequency for rectifier consisted of six pulses by using inverters.

Different Artificial Neura1 Networks (ANNs) were applied for controlling the APF including Radial-Basis-Function (RBF) neural network, Feed Forward Neural Network (FFNN), Recurrent Neural Network (RNN), Adaptive linear neuron (ADALINE) and Echo State Network [21-25]. The NARX neural network is a perfect tool in modeling and simulating the complex nonlinear systems due to its computational power and long term-dependencies [26]. It can be considered as an RNN with global feedback. It is embedded with a memory to model the nonlinear systems. So, it is treated as a time series neural network [27]. NARX neural network has a flexible structure combining between simplicity (since it is simple to learn using backpropagation algorithms) and time series forecasting. It gives a dynamic responsibility, accurate and fast training response.

In this paper, the NARX neural network is selected and designed to model the nonlinear loads and to determine the actual harmonic currents generated from these loads then, a shunt APF will be designed to mitigate the harmonic distortion current. The main issue of the shunt APF is to design an appropriate control method to determine the compensation reference current with minimal errors. In addition, the control strategy produces the control reference signals, then carries out the control method. The control reference signal of shunt APF is proposed using NARX neural network with backpropagation training algorithm. The instantaneous reactive power algorithm is integrated with the NARX network to decompose the predominant harmonics.

II. NARX NEURAL NETWORK FOR LOAD NONLINEARITY MODELING

The NARX neural network based harmonic identifier is used to isolate the predominant harmonics of a load. These isolated harmonics will be used with the instantaneous reactive power algorithm to mitigate the harmonics. The NARX neural network architecture and design procedures will be illustrated in the following sections.

A. NARX Neural Network Architecture

The NARX neural networks combine between the advantages of the FFNN and dynamic neural networks. The FFNNs are accurate and the static backpropagation learning algorithm are used for training [28-31]. In this paper a series parallel structure of NARX network is applied to identify the nonlinearity of load current. The simulated and the field measurements data is used to train and test the proposed NARX networks. To increase the speed and accuracy of training process, the PCC voltage and non-linear load currents are used to train the proposed series parallel NARX network as the input -output patterns.

The designed NARX neural network is composed of two hidden layers, but the neurons number in each layer are differ according to the training process and the complexity of the waveforms of the load current. The series-parallel NARX network is then converted to parallel NARX network. The parallel NARX neural network is tested by applying pure sinewave voltage as input and the resultant output is used to evaluate the actual harmonics and nonlinearity of load currents. At the final step, the Fast Fourier Transform (FFT) method is used to decompose the NARX neural network outputs. The Total Harmonic Distortion (THD) of the NARX network outputs and the actual measured current are compared. The NARX output waveform and the pure sinewave voltage are used in instantaneous reactive power method or p-q method. The designed structure of the proposed NARX neural network is illustrated in Fig. 1.

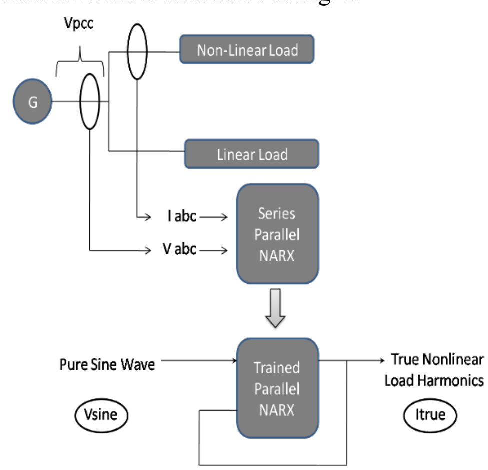


Fig. 1. Block diagram of NARX harmonics extraction

B. Design Procedure of NARX Network

The investigated NARX neural network procedure which is applied to represent the nonlinearity of the electrical loads and to determine their actual harmonic currents can be explained as:

Step 1: Generate the training patterns (PCC voltages and load currents). A power analyzer device is used to measure the PCC voltages and load currents, then transmit them to MATLAB workspace.

Step 2: Select the proposed NARX neural network architecture with the taped delays in in both the output and input layers. The number of first and second hidden layer neurons are configured with N and M neurons respectively.

Step 3: Create the structure of the NARX neural network as a series-parallel architecture and initialize the network biases and weights.

Step 4: Train the created NARX neural network by using the Levenberg Marqurdt backpropagation algorithm. The PCC voltage and the corresponding current are used as input and target respectively.

Step 5: Validate the trained NARX network by comparing the outputs of the NARX neural network and the target load currents. If the difference between NARX neural network output RMS value and the target RMS value are lower than a specified error limit, the process will transmit to the next step, otherwise it will return to step 2 to select another number of hidden layers neurons N and M.

Step 6: Convert the series-parallel NARX network to a parallel architecture network by removing the delays and converting it to a closed loop configuration.

Step 7: Test the parallel NARX neural network by repeating step 5. If the error is greater than the prescribed error limit, then the procedures will be go back to step 4 and repeat the training process.

Step 8: Compare between the THD of the parallel NARX neural network outputs and THD of load currents. If the difference between them is greater than the prescribed error limit, then the process will go back to step 2 to vary the number of neurons in hidden layers, N and M.

Step 9: Obtain the actual load harmonic current by injecting the NARX neural network with pure sinewave voltage to determine the true current harmonic by excluding the effect of the PCC voltage distortion on load current harmonic.

III. INSTANTANEOUS REACTIVE POWER METHOD

The instantaneous reactive power method or the p–q method was applied to APF by Akagi [2]. The system currents and voltages and can be converted into the αβ0 system as follows [2]:

$$[i_{\alpha\beta 0}] = \sqrt{\frac{2}{3}} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} [i_{abc}] \quad (1)$$

$$[v_{\alpha\beta 0}] = \sqrt{\frac{2}{3}} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} [v_{abc}] \quad (2)$$

where v_{abc} is the three-phase instantaneous voltages vector, i_{abc} is the three-phase instantaneous currents vector, $v_{\alpha\beta 0}$ is the instantaneous voltages on the αβ0 axis vector and $i_{\alpha\beta 0}$ is the instantaneous currents on the αβ0 axis vector.

Based on the p-q theory, the reactive and active power (p and q) are calculated as:

$$p = v_0 i_0 + v_a i_a + v_b i_b \quad (3)$$

$$q = v_a i_a - v_b i_b \quad (4)$$

When the electric power system is a balanced three-phase power system, the active and reactive power are expressed as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha v_\beta \\ -v_\beta \quad v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

The reactive and active power can be extracted into two items: AC and DC part. The AC part is generated from the harmonic components. The DC part is generated from multiply the fundamental voltage and current components and they can be represented as:

$$p = \overline{p} + \tilde{p} \quad (6)$$

$$q = \overline{q} + \tilde{q} \quad (7)$$

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha v_\beta \\ -v_\beta \, v_\alpha \end{bmatrix} \begin{bmatrix} \overline{p} + \tilde{p} \\ q \end{bmatrix} \quad (8)$$

where * represents the value of the reference. i_α^* and i_β^* are the values of the source current reference. Therefore, the source current reference values of the active filter (AF) are expressed as:

$$i_{\alpha AF}^* = i_\alpha^* - i_{L\alpha} \quad (9)$$

$$i_{\beta AF}^* = i_\beta^* - i_{L\beta} \quad (10)$$

Hence, the AF phase reference values are represented by:

$$\begin{bmatrix} i_{aAF}^* \\ i_{bAF}^* \\ i_{cAF}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} \\ -\frac{1}{\sqrt{2}} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (11)$$

IV. NARX CONTROL REFERENCE BASED METHOD FOR SHUNT APF

The previous NARX neural network-based nonlinearity identifier is used to separate the dominant harmonics from the current spectrum of a load. These isolated current harmonics are used to determine the instantaneous reactive power algorithm. Figure 2 shows the evaluation of instantaneous p and q using a pure sine waveform (V_{sine}) and a NARX output current waveform (I_{true}). The instantaneous p and q are used to evaluate I_α , I_β which represent the final step before evaluating reference current as illustrated in Fig. 3. The reference currents are used to switch pulses to the power electronic elements GTO/Diodes to impose the power converter to act as a current source to follow the changes of the reference current.

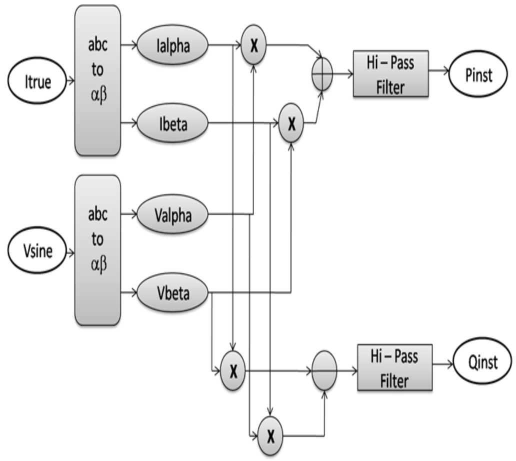


Fig. 2. Instantaneous P and Q determination using pure sine wave and corresponding NARX output block diagram

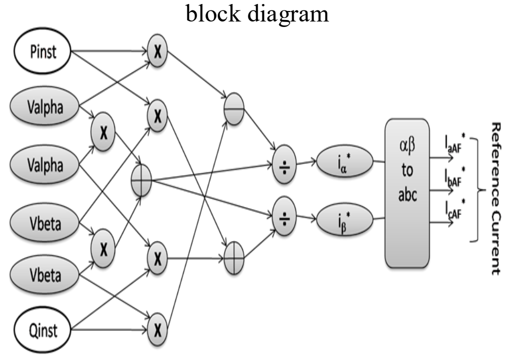


Fig. 3. Reference current determination block diagram

V. RESULT AND DISCUSSION

The tested system (shown in Fig. 4) consists of 50 Hz, 200 V, voltage source connected to nonlinear load 6-pusle converter system through (Y-Δ) transformer and 400 V dc, 5 Ω, 5.4 mH, 0.1μF active filter through 20 KVA (Y-Y) transformer. The system is modeled and implemented using MATLAB/Simulink environments illustrated in Fig. 5. The nonlinear load current waveform is shown in Fig. 6.

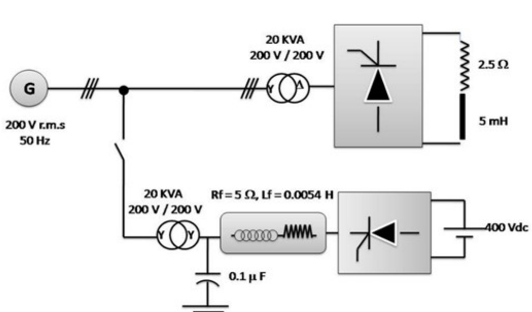


Fig. 4. Single line diagram of the tested system

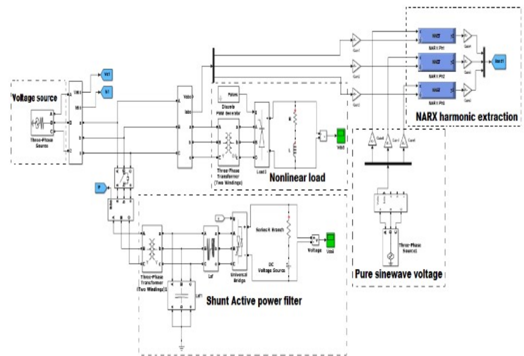


Fig. 5. The Simulink model of the designed system

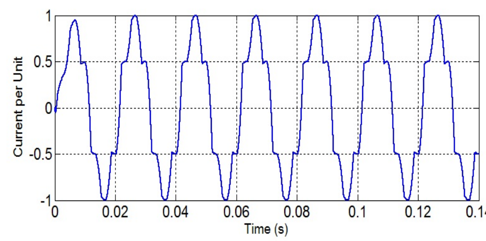


Fig.6. Nonlinear load current waveform

Figure 7 illustrates the analysis of the FFT of the load current waveform which illustrates that the THD is 17.12%. The PCC voltage waveform and load current are used to train the three NARX networks using 1005 samples per cycle. The training performance for the three phases are summarized in the Fig. 8.

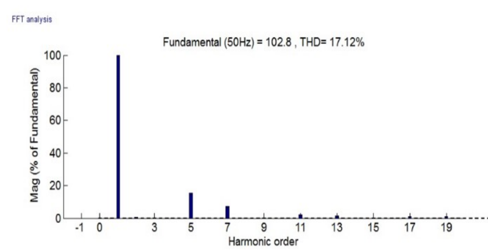
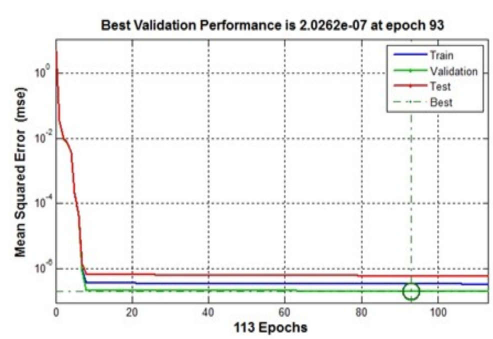
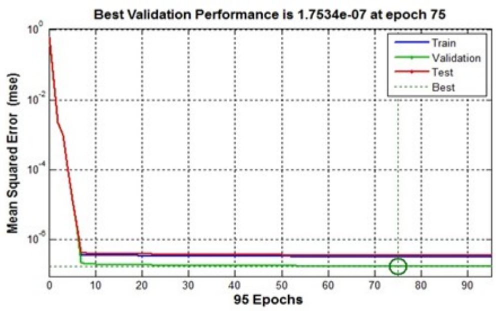


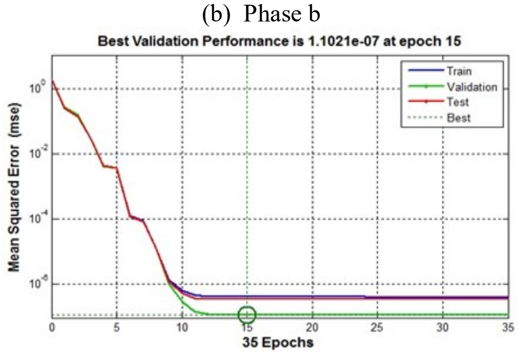
Fig. 7. FFT of nonlinear load current



(a) Phase a



(b) Phase b



(c) Phase c

Fig. 8. Training performance for the three phases NARX neural networks

The training procedure is applied using Levenberg Marqurdt backpropagation algorithm. The performance curves illustrate the advantage of NARX series-parallel network as the best validation is achieved very fast and with mean square error less than 10^{-6}.

The fast convergent of NARX series-parallel network training procedure is suitable for the APF as it has good response for the expected changes in waveforms. A comparison between the target waveform (nonlinear load current) and the NARX output using input voltage waveform explains very close results as shown by Fig. 9.

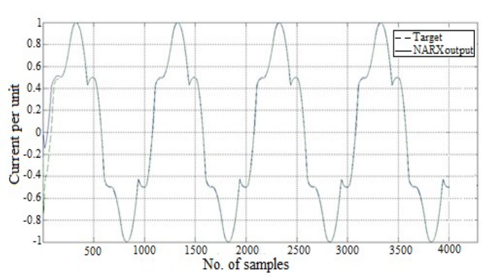


Fig. 9. Comparison between parallel NARX output and target waveforms

In the next step, the NARX network will be injected by sinusoidal waveform which represent a pure voltage source. The NARX output waveform and pure sinusoidal waveforms are used to determine the reference current using instantaneous reactive power technique as explained before. The instantaneous reactive and active power are illustrated in Figs. 10 and 11. These two waveforms are recorded during the operation of shunt APF.

Figure 12 illustrates the reference currents for the three-phases, which is used as an input to 2 kHz PWM used for firing the three-arms six-pulses GTO/Diode to inject the active filter current to the system. The APF current for the three phases are illustrated in Fig. 13, whereas the effect of the APF on the current source is shown in Fig. 14. The APF circuit breaker is closed after 0.1 sec thus it mitigates the effect of harmonics source current. The source current waveform after applying APF is analyzed using FFT. The current harmonic spectrum after using NARX based harmonic extraction filter is illustrated by Fig. 15.

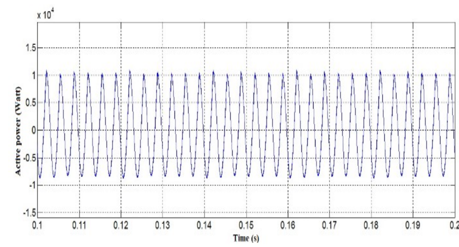


Fig. 10 active power waveform

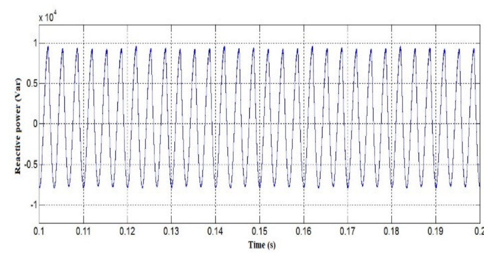


Fig. 11 waveform of the reactive power

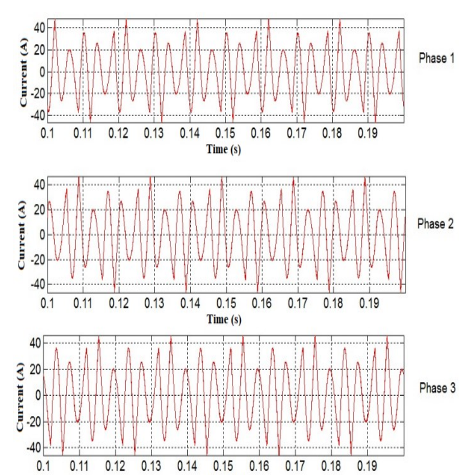


Fig. 12 Three phase reference currents

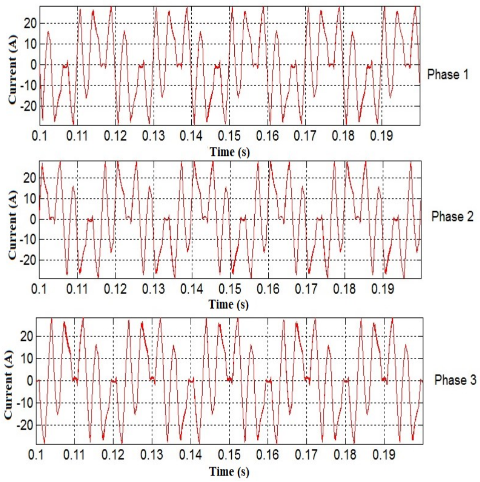


Fig. 13 Three phase APF current

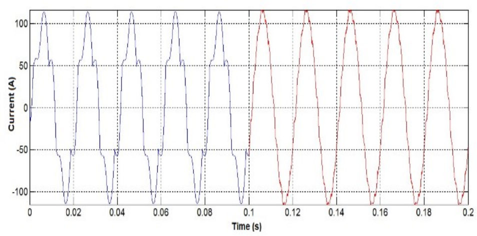


Fig. 14 Effect of the designed APF on source current

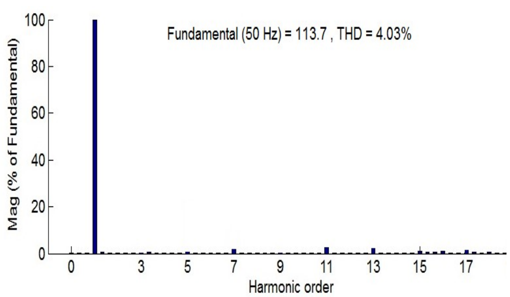


Fig. 15 Harmonic current spectrum after using NARX based harmonic extraction APF

The effect of APF can be summarized in the following impacts:

- The source current THD is decreased from 17.12 % to 4.03 %,
- The 5th harmonic is decreased from 17.35% to 0.76%,
- The 7th harmonic is decreased from 5.67 % to 0.91 % and
- The 11th harmonic is decreased from 2.41 % to 2.1%.

VI. CONCLUSION

This paper presents a novel shunt APF control reference signal using the NARX neural network with backpropagation training algorithm.

The paper proposes a method for calculating the actual harmonics of nonlinear load in distributed electric power system using the NARX network. The NARX network based harmonic identifier is used to isolate the predominant harmonic of a load. It determines the actual current harmonics by excluding the effect of the PCC voltage distortion on load current harmonics. The test results show the effectiveness of the presented method and give a good performance for mitigating the current harmonics, and justifying the accuracy of the proposed NARX neural network. It is suitable for the APF due to its fast convergent and response for the expected changes in waveforms.

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