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Neuro-Fuzzy based Controller for a Three-Phase Four-Wire Shunt Active Power Filter

Mridul Jha, S.P. Dubey
Rungta College of Engineering & Technology, Bhilai/ Department of Electrical Engineering
Bhilai, India 0788-6666666/0788-2286480
e-mail: mridul.jha123@gmail.com, spd1020@yahoo.com

Abstract

This paper describes the application of a novel neuro-fuzzy based control strategy which is used in order to improve the Active Power Filter (APF) dynamics to minimize the harmonics for wide range of variations of load current under various conditions. To improve dynamic behavior of a three phase four-wire shunt active power filter and its robustness under range of load variations, adaptive hysteresis band with instantaneous p-q theory is used with the inclusion of neural network filter for reference current generation and fuzzy logic controller for DC voltage control. The proposed control scheme for "split-capacitor" converter topology is simple and also capable of maintaining the compensated line currents balanced, irrespective of unbalancing in the source voltages & deviation in the capacitor voltages. The results presented in MATLAB-SIMULINK software in this paper clearly reflect the effectiveness of the proposed APF to meet the IEEE-519 standard recommendations on harmonic levels.

Keywords*: shunt active power filter, fuzzy logic controller, neural network, P-Q theory*

1. Introduction

The need for effective control and efficient use of electric power has resulted in massive proliferation of power semiconductor processors/converters in almost all areas of electric power such as in utility, industry and commercial applications. This has resulted in serious power quality problems, since most of these nonlinear converters contribute to harmonic injection into the power system, poor power factor, unbalance, reactive power burden etc. The vulnerability of equipments in automated processing industry to poor power quality leads to heavy losses. Conventionally, passive L-C filters were used to eliminate line harmonics. However, the passive filters have the demerits of fixed compensation, bulkiness and occurrence of resonance with other elements. The recent advances in power semiconductor devices have resulted in the development of Active Power Filters (APF) for harmonic suppression [2]. Various topologies of active filters have been proposed for harmonic mitigation [3]. The shunt APF based on Voltage Source Inverter (VSI) structure is an attractive solution to harmonic current problems. The shunt APF is a pulse width modulated (PWM) voltage source inverter that is connected in parallel with the load. It has the capability to inject harmonic current into the ac system with the same amplitude but in opposite phase of the load [4]. The principal function of shunt active filter is compensation of the load harmonic current i.e. it confines the load harmonic current at the load terminals, hindering its penetration into the power system.

The principal components of the APF are the VSI, a DC energy device that in this case is capacitor and the associated control circuits. The performance of an active filter depends mainly on the technique used to compute the reference current and the control method used to inject the desired compensation current into the line. With respect to three phase four wire shunt APF two more things gets added especially with "split capacitor" converter topology that is the control of voltage deviation between the dc capacitors & total DC bus voltage regulation across the capacitors connected to the inverter in order to ensure suitable transit of power to supply the inverter.

In this paper to improve dynamic performance of proposed Shunt APF an ANN controller has been used to facilitate the calculation of reference currents thereby making use of Instantaneous real-reactive (p-q) theory. This theory deals with 3-Φ(a-b-c) to 2-Φ(α-β-0) conversion. Among the various current control techniques available, hysteresis current control is the most popular one for active power filter applications. Hysteresis current control is a method of controlling a voltage source inverter so that the output current is generated which follows a reference current waveform. In this paper a dynamic offset level is added to both limits of the hysteresis band in order to make it more adaptive & to control the voltage deviation. This dynamic offset level is obtained by measurement of DC capacitor voltages. In this work a very simple control circuit is used for generating dynamic offset signal. Also in this work Fuzzy logic controller (FLC) has been used to maintain constant DC voltage across the capacitors connected to the inverter. FLC has been used in place of conventional PI controller because of its various advantages over the latter such as, no need for an accurate mathematical model, facility to work with imprecise inputs, capability to handle non linearity and being more robust than conventional non linear controllers. By using all these techniques neutral current of the load has been compensated.

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2. Proposed Topology of Shunt Active Power Filter

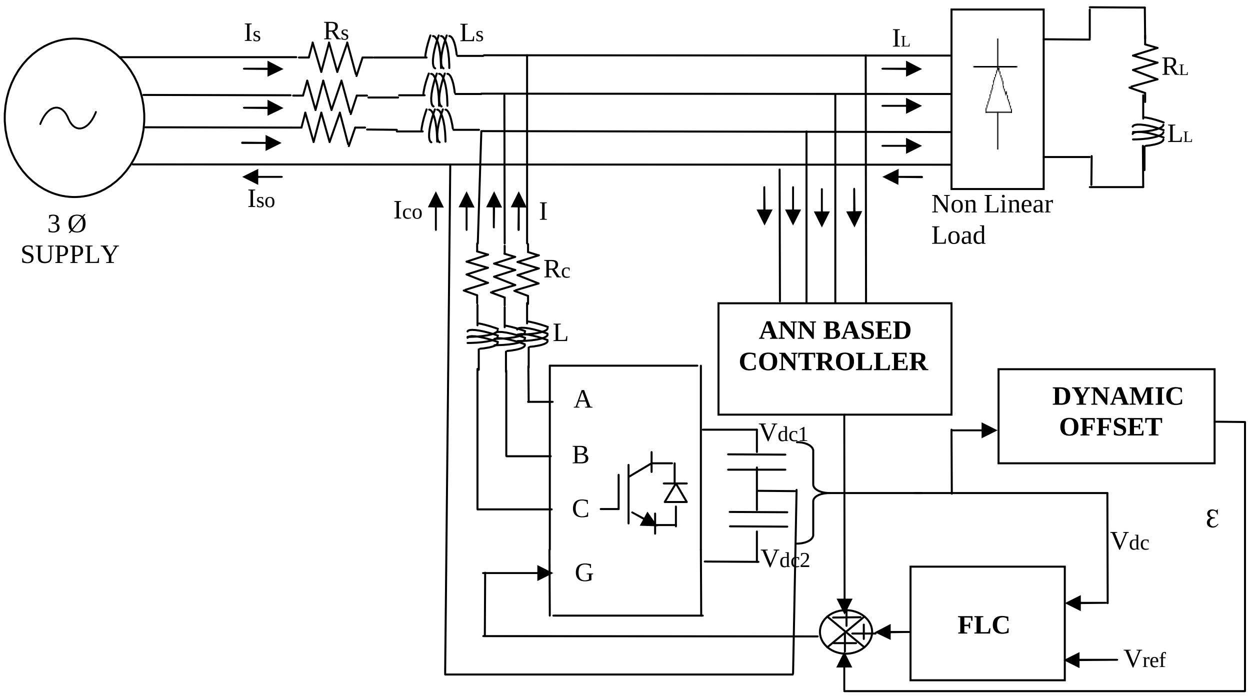


Fig. 1. Proposed topology of shunt active power filter

A system with nonlinear three phase load supplied by a voltage source is considered as shown in Fig. 1. A shunt active power filter is used to generate the compensation currents. The target is to get a source current without harmonic and reactive components. The APF power circuit proposed is a three phase IGBTs bridge inverter with a "split-capacitor" converter topology in the DC side to compensate for three phase four wire unbalanced nonlinear loads. The APF control circuit consists of a NEURO-FUZZY controller in which neural network controller accounts for the reference current generation and fuzzy controller along with dynamic offset block accounts for the DC voltage control. The proper functioning of these three blocks result in the generation of gate signals for three phase inverter which in turn is responsible for generating compensating currents. These compensating currents on injection through the three phase inverter results in harmonic compensation of source currents and load neutral current thereby leading to improvement of power quality on the connected power system [4-5].

3. Control Strategy of Shunt Active Power Filter

For efficient performance of the shunt active filter there are four main tasks for the controller-(i) identify the harmonic contents and to form the synchronized reference (ii) provide close loop control to force the current of the VSI to follow the reference (iii) regulate the voltage deviation between the DC capacitors (iv) regulate the VSI total DC link voltage in the face of power losses in the VSI and the erroneous real power exchanged with the line [5]. In this work first one i.e. to calculate reference current has been achieved by using a neural network controller thereby implementing p-q theory in it. The second task has been achieved by using a hysteresis current control technique. For the third task a dynamic offset signal (Ɛ) created from measurement of DC capacitor voltages has been added to both the limits of hysteresis band. However the last one has been implemented by using a Fuzzy logic controller.

3.1. Reference current calculation

For reference current calculation instantaneous p-q theory has been used [6-16]. Instantenous p-q theory is one of the best methods for calculating the reference currents. According to this theory 3 phase(abc) to 2 phase(α-β-0) conversion(i.e. Clarke's Transformation) takes place for source voltages and line currents and voltage and current components in two phase system are then used to obtain real and imaginary power components which are then to produce reference currents in two phase. These reference currents are then transformed to three phase through inverse Clarke's transformation which are then used to provide the appropriate gating signals to inverter. The inverter thus produces suitable current which are injected back to supply and thus line currents are compensated. In this work a fundamental positive sequence detector is used so as to limit the effects of supply distortion.

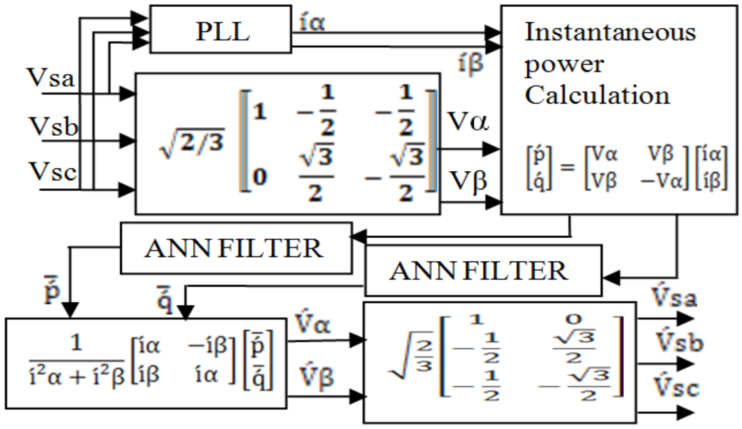


Fig. 2. Fundamental Positive sequence voltage detector

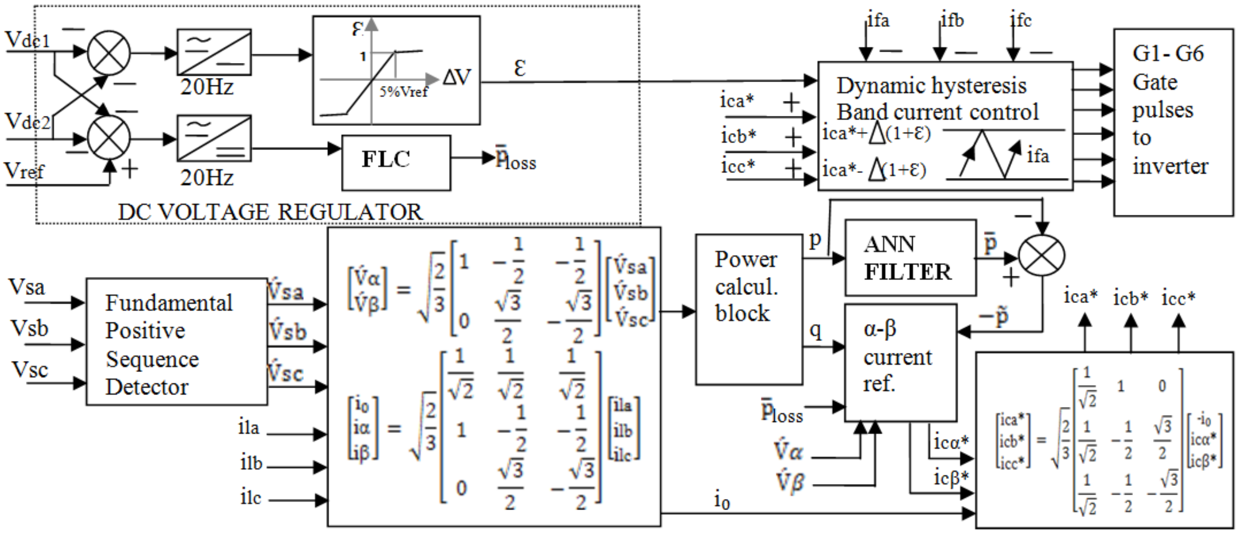


Fig. 3. Contorl block diagram of shunt active power filter

The instantaneous p-q theory is based on “α-β” transformation (or Clarke’s transformation) of voltage and current signals to derive compensating signals. As shown in Fig. 2 first the fundamental positive sequence components of three phase source voltages are attained by using a fundamental positive sequence detector thereby using a ANN based filter. The voltage components and load currents then undergo the “α-β-0” transformation using “Clarke’s transformation”. The transformed voltage and current signals i.e. Vα, Vβ, iα and iβ are then used to calculate instantaneous real and reactive power and can be written as:

$$p=(V\alpha \,.\, i\alpha) + (V\beta \,.\, i\beta). \quad (1)$$

$$q=(V\beta \,.\, i\alpha) + (-V\alpha \,.\, i\beta). \quad (2)$$

where p is the instantaneous real power and q is the instantaneous reactive power. The alternated value of instantaneous real power ($\tilde{p}$) is obtained by using an ANN based filter. This $\tilde{p}$ and q are then used to calculate reference currents in “α-β” coordinates as shown below:

$$\begin{bmatrix} ic\alpha * \\ ic\beta * \end{bmatrix} = \frac{1}{V\alpha^2 + V\beta^2} \begin{bmatrix} V\alpha & V\beta \\ V\beta & -V\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \bar{p}loss \\ -q \end{bmatrix}$$

where icα* and icβ* are the reference compensation currents in the “α-β” coordinates. The reference currents in abc coordinates are then obtained by applying inverse Clarke’s transformation on the “α-β-0” coordinates as shown in Fig. 3. As shown in Fig. 3 dynamic hysteresis current control technique is used to compare the reference currents (ica*) and the filter currents (ifa) so as to generate suitable gate pulses for the inverter. The word “dynamic” comes from the fact that a dynamic offset (Ɛ) is created from the measurement of the DC capacitor voltages and this offset level is added to both limits of hysteresis band so as to control the capacitor voltage difference.

The filtered voltage difference $\Delta V = V_{dc2} - V_{dc1}$ produces Ɛ according to following limit function generator:

$\mathcal{E}=-1 \quad \leftrightarrow \Delta V < -0.05V_{ref};$
$\mathcal{E}=\Delta V / (-0.05V_{ref}) \quad \leftrightarrow -0.05V_{ref} \leq \Delta V \leq 0.05V_{ref};$
$\mathcal{E}=1 \quad \leftrightarrow \Delta V > 0.05V_{ref};$

where V_{ref} is a predefined voltage reference, and $\pm 5\% V_{ref}$ was arbitrarily chosen as an acceptable margin of voltage variation.

3.2. Neural network controller

In this work a neural network controller comprising of an ANN based filter is used to obtain the alternated value of instantaneous real power ($\tilde{p}$) which is used as an input for calculating the reference currents as shown in Fig. 3.

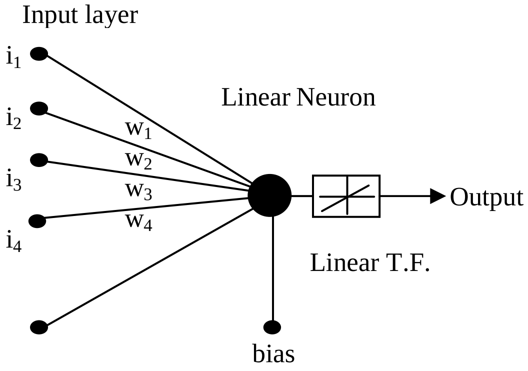


Fig. 4. Internal blocks of proposed neural network

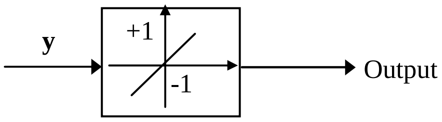


Fig. 5. Input/Output relationship of purelin transfer function

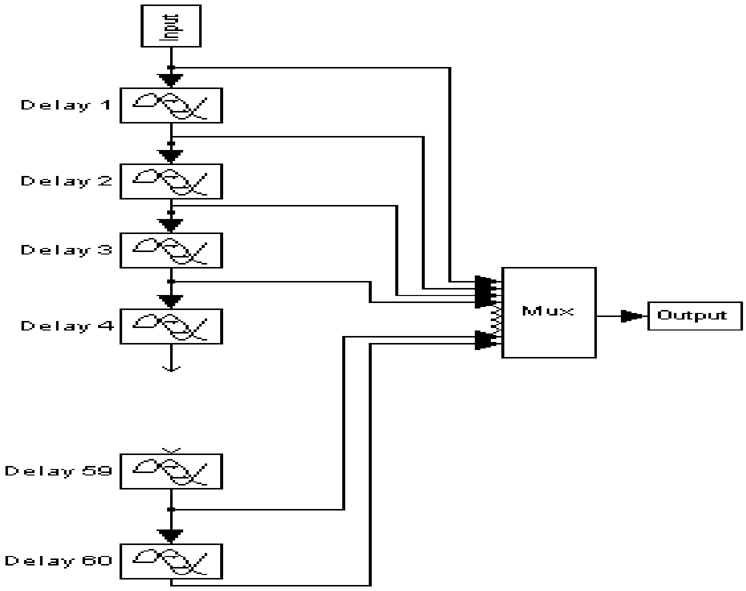


Fig. 6. Internal structure of delay blocks

Fig. 4 shows the architecture of the proposed ADALINE neural network. It is a two layers (input and output) network having n-inputs and a single output. The basic blocks of this network are input signal delay vector, a purelin transfer function, weight matrix and bias.
The input output relationship is expressed as:

$$y = \sum_{n=1}^{61} w_n . i_n + b \tag{3}$$

where 'b' is bias 'w' is weight and 'i' is the input to the NN. This output 'y' is fed to the purelin transfer function, whose input output relationship is shown in Fig. 5. The input to the network is a time delayed series of the signal whose fundamental component is to be extracted. The length of this signal is 61, which has been decided considering expected maximum distortion and unbalance in 3-phase input signal. Fig. 6 shows the internal structure of delay block. The proposed NN receives 61 samples of input signal at a time and produce single output. The input is sampled at 6KHz i.e. 120 samples per fundamental cycle of voltage. Target data ($\bar{p}$) required for training the proposed NN was generated using decomposition technique. The weight adjustment is performed during the training process of ADALINE using Widrow-Hoff delta rule. The mean square error between desired output and actual output is reduced to $3.2e^{-5}$ by repetitive training with a learning rate of 0.0006.

3.3. Fuzzy logic controller

In this section we present the main ideas underlying FLC. Fuzzy logic uses fuzzy set theory, in which a variable is a member of one or more sets, with a specified degree of membership. Fuzzy logic allow us to emulate the human reasoning process in computers, quantify imprecise information, make decision based on vague and incomplete data, yet by applying a defuzzification process, arrive at definite conclusions.

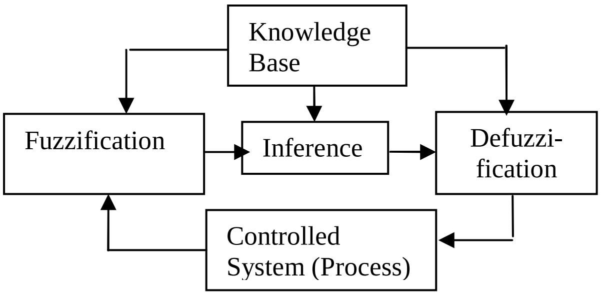


Fig. 7. Basic configuration of Fuzzy logic controller (FLC)

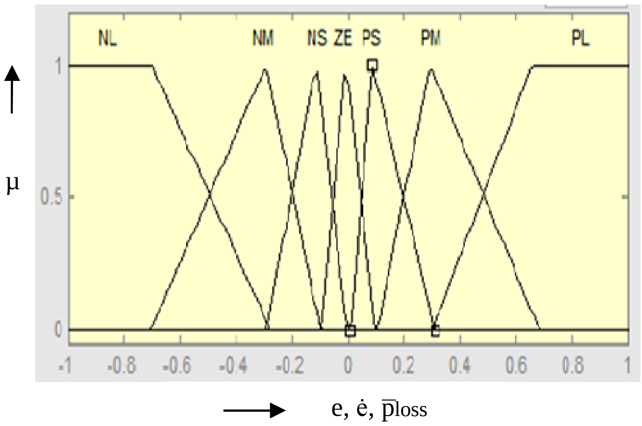


Fig. 8. Membership functions for the input and output variables

A fuzzy logic controller comprises of four principal components: a fuzzification interface, a knowledge base, decision making logic, and a defuzzification interface. The fuzzification interface involves various functions such as it measures the values of input variables, performs a scale mapping that transfers the range of values of input variables into corresponding universe of discourse and performs the function of fuzzification that converts input data into suitable linguistic values which may be viewed as labels of fuzzy sets.The knowledge base comprises a knowledge of the application domain and the attendant control goals. It consists of data base and a linguistic control rule base. While the data base provides necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in an FLC, the rule base characterizes the control goals and control policy of the domain experts by means of a set of linguistic control rules. The inference mechanism uses a collection of linguistic rules to convert the input conditions into the fuzzified output. Finally, defuzzification is used to convert the fuzzy outputs into control signals [17-18].

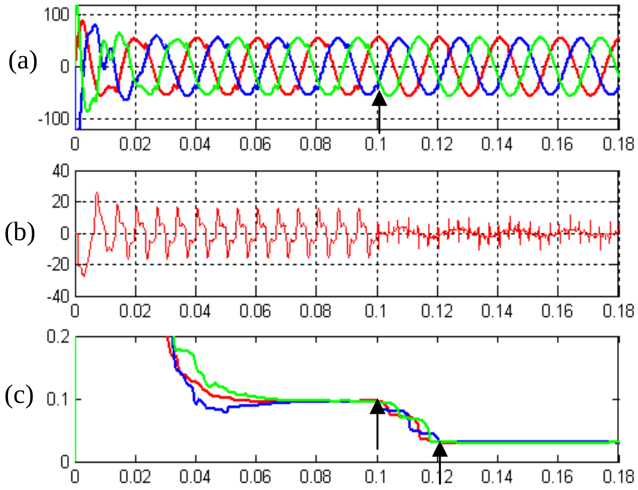
To design the FLC, variables which can represent the dynamic performance of the system to be controlled should be chosen as the inputs to the controller. It is common to use the error (e) and the rate of error (ė) as controller inputs. In the case of the fuzzy logic based DC voltage control, the capacitors total voltage deviation and its derivative are considered as the inputs of the FLC and the very small amount of real power ploss required for voltage regulation is taken as the output of the FLC. The input and output variables are converted into linguistic variables. In this case, seven fuzzy subsets, NL(negative large), NM(negative medium), NS(negative small), ZE(zero), PS(positive small), PM(positive medium) and PL(positive large) have been chosen. Membership functions used for the input and output variables used here are shown in Fig. 8. As both inputs have seven subsets, a fuzzy rule base formulated for the present application is given in Table 1.

Table 1. Fuzzy control rule table

e ė	**NL**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	NL	NM	NS	ZE	PS	PM	PL

4. Results and Analysis

The Active Power Filter and the proposed controller was modeled and simulated in MATLAB/SIMULINK simulation software. The proposed neuro-fuzzy controller simulated with balanced and unbalanced nonlinear loads with sinusoidal/distorted, balanced/unbalanced conditions of source voltages. The system parameters: Load resistance R_L=100Ω, Load inductance L_L=37mH, Supply Phase voltage=240V(rms), Supply line parameters Rs =1Ω, Ls=3mH, Filter coupling inductance Rc=0.5Ω, Lc=3mH, Inverter DC bus capacitor =2200µF, Reference Voltage =250V, Hysteresis band limit =0.5A and Switching frequency =12kHz.



APF STARTS
AT t=0.1sec

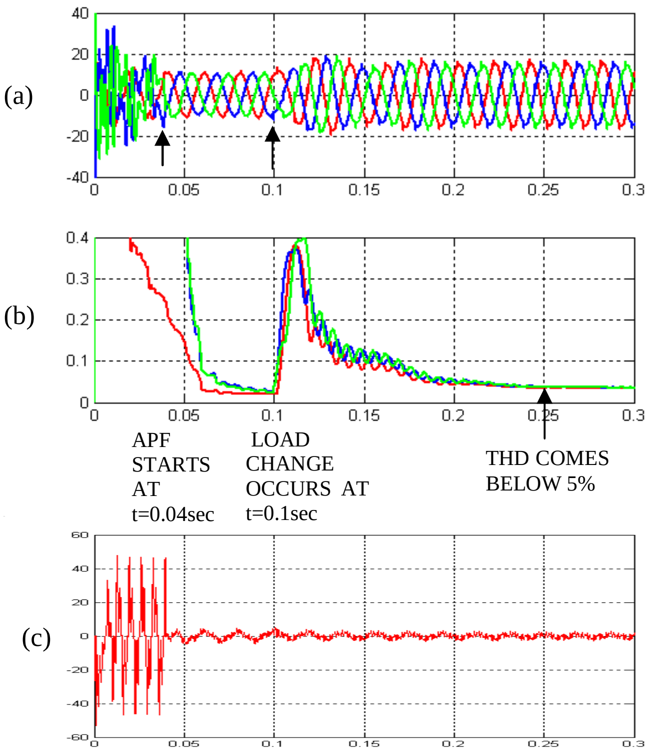
THD COMES
BELOW 5%

Fig. 9. Steady state filtering performance: (a) 3-ph source currents (b) neutral current (c) THD

Fig. 9 (a), (b), (c) shows the source current, neutral current and total harmonic distortion (THD) waveforms respectively before and after the starting of active filter. At t=0 sec. the rectifier load is connected to the AC supply. Initially the source currents are highly distorted and in transient condition. Active filter is started at time t=0.1 sec. It can be seen that source current become sinusoidal immediate after starting the active filter. The neutral current is compensated as shown in Fig. 9 (b). The THD in individual source current after filtering is found to be less than 3% shown in Fig. 9 (c).

Fig. 10 shows the three phase source current when a load is suddenly increased by 40% at the time t=0.1sec. In this case the shunt active power filter starts at t=0.04sec.The waveforms are maintained sinusoidal in spite of such large variation in load as shown in Fig. 10 (a). The THD comes below 5% at t=0.25 sec as shown in Fig. 10 (b). Neutral current compensation is shown in Fig. 10 (c). Fig. 11 shows the filtering performance under unbalance load condition. In this simulation study, a 1- phase rectifier load is connected between phase ‘r’ and ‘b’ in addition to three phase rectifier. This creates an unbalance of 60% in line currents. In this case the APF starts at t=0.1 sec. It can be seen that the proposed neuro-fuzzy controller keeps currents in each phase nearly sinusoidal and THD less than 4% in time t=0.12 sec. As shown in Fig. 11 (a) currents become sinusoidal as soon as the APF starts at t=0.1 sec. The neutral current of the load is also compensated as shown in Fig. 11(b). Inspite of unbalancing the THD comes below 5% in time t=0.12 sec as shown in Fig 11(c).

The results shown in Fig. 9-11 demonstrate the excellent steady state and dynamic performance of proposed neuro-fuzzy controller under AC source distortion and unbalance and nonlinear loading conditions. The neutral current of the load is fully compensated in all the cases.

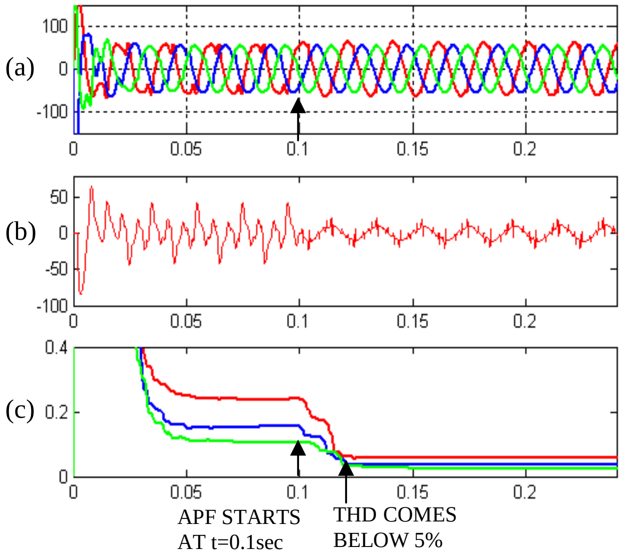


APF STARTS AT t=0.04sec

LOAD CHANGE OCCURS AT t=0.1sec

THD COMES BELOW 5%

Fig. 10. Dynamic performance: 40% step change in load: (a) 3-ph source currents (b) THD (c) neutral current



APF STARTS AT t=0.1sec

THD COMES BELOW 5%

Fig. 11. Filtering performance under unbalance loading: (a) 3-ph source currents (b) neutral current (c) THD

5. Conclusion

In this paper a new control technique based on neuro-fuzzy logic has been presented. The simulated results demonstrate its effectiveness under various operating conditions. Some of the advantages of the proposed controller are: It is independent of the source voltage distortion and unbalance; fast and accurate tracing of fundamental component under balanced and unbalanced nonlinear condition; simple architecture and easy for implementation; and active filter controller compensates the whole neutral current of the load.

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Bibliography of authors

Mridul Jha received his Bachelors in Electrical and Electronics Engineering from Shri Shankaracharya College of Engineering & Technology, Bhilai, India in 2008. Currently he is lecturer in the department of Electrical Engineering, R.C.E.T., Bhilai, India and persuing his Masters in Engineering (Power Electronics) from R.C.E.T., Bhilai, India. His current research interests include power convertres, active filtering, power conditioning, neural network and fuzzy logic based controller design for Electrical drives.

S.P. Dubey received his Bachelors in Electrical Engineering from Govt. Engineering college now National Institute of Technology Raipur, India in 1995. He completed his Masters in Engineering (Power Apparatus and Electrical Drives) from Indian Institute of Technology Roorkee, Roorkee, India in 2000. He obtained Ph.D. degree from Birla Institute of Technology and Science, Pilani, India in 2006. He worked as Lecturer for six years and as Assistant Professor for one year in the Electrical and Electronics Engineering Group at Birla Institute of Technology and Science, Pilani and as an Assistant Professor in the Department of Electrical Engineering Indian Institute of Technology Roorkee, India. Currently he is Professor in the department of Electrical Engineering, R.C.E.T., Bhilai, India. His current research interests include power converters, active filtering, power conditioning, AC and DC drives, neural network and fuzzy logic based controller design for Electrical drives, Genetic Algorithm Optimization technique for LC filter design.