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Fuzzy Controlled Shunt Active Power Filter for Power Quality Improvement

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Abstract: This study describes the application of Fuzzy Logic Controller to a three phase Shunt Active Power Filter (SAPF) for the power quality improvement required by a non-linear load. The SAPF controller is based on instantaneous power theory (p-q theory) which is recognized as one of the best methods. The output current of the Voltage Source Inverter (VSI) would track the reference current produced by the p-q algorithm. The Fuzzy Logic Controller (FLC) is used to regulate the DC link capacitor voltage and to control VSI AC output current, respectively. The current control method used in this study is related to Fuzzy Controller based PWM current controller wherein the switching signals are generated by means of comparing a carrier signal with the output of the fuzzy controller. The system is verified by simulation using MATLAB/Simulink simulation package. Experimental results show that the system effectively reduces the Total Harmonic Distortion of the source current below 5% according to IEEE-519 standard.

Key words: Shunt active power filter, p-q theory, fuzzy logic controller, voltage source inverter, output current, India

INTRODUCTION

The Power Quality (PQ) problems in power distribution systems are not new but only recently the effects of these problems have gained public awareness. Advances in semiconductor device technology have fuelled a revolution in power electronics over the past decade and there are indications that this trend will continue. However these power equipments which include Adjustable Speed motor Drives (ASDs), electronic power supplies, Direct Current (DC) motor drives, battery chargers, electronic ballasts are responsible for the rise in related PQ problems. These non-linear loads are constructed by nonlinear devices in which the current is not proportional to the applied voltage. Non-linear loads appear to be prime sources of harmonic distortion in a power distribution system. Harmonic currents produced by non-linear loads are injected back into power distribution systems through the Point of Common Coupling (PCC). These harmonic currents can interact adversely with a wide range of power system equipments, most notably capacitors, transformers and motors causing additional losses, overheating and overloading.

Traditionally, current harmonics caused by non-linear loads have been dealt using passive filters consisting of capacitors, inductors and damping resistors. They provide simple solutions but very often have large size and weight, hence they cannot provide flexible compensation. Moreover, the passive filters are known to cause resonance, thus affecting the stability of the power distribution systems.

The increased severity of harmonic pollution in power networks has attracted the attention of power electronics and power system engineers to develop dynamic and adjustable solutions to the power quality problems. Such equipments, generally known as Active Filters (AFs) are also called Active Power Line Conditioners (APLCs), Instantaneous Reactive Power Compensators (IRPCs), Active Power Filters (APFs) and Active Power Quality Conditioners (APQCs) (Singh *et al*., 1999). The purpose of the active filter is to compensate distorted current drawn by non-linear loads from the utility grid. The active filter and its current control must accurately track the sudden slope variations in the reference current. To obtain efficient active filter performance, it is important to choose both a proper current reference and an adequate current control strategy. One such filter is the Shunt Active Filter which works as a current source when properly designed and controlled produces harmonic currents having opposite phase than those harmonic currents produced by the non-linear loads.

In this study, the method based on instantaneous active and reactive power (p-q) is performed for generating reference current required by the non-linear load (Superti-Furga and Todeschini, 2008; Syed and Ram, 2005).

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In p-q method, the real and imaginary powers are calculated for DC and AC components. The DC component is extracted by means of conventional filters while the AC component is used to generate the reference template of the compensation currents.

Generally a conventional PI controller is used to maintain the magnitude of the dc bus voltage (in VSI) in order to generate the reference current template. The PI controller requires precise linear mathematical models which are difficult to obtain and may not give satisfactory performance under parameter variations, load disturbances, etc. Recently Fuzzy Logic Controllers are replacing the conventional PI controllers due to their following advantages (Hamadi *et al*., 2004; Raviraj and Sen, 1997):

- Do not need an accurate mathematical model
- Can work with imprecise inputs
- Can handle non-linearities and more robust than conventional PI controller

In this study, a TS type of Fuzzy Logic Controller has been implemented for a three-phase shunt active power filter with the objective to (Bhende *et al*., 2006):

- Reduce the settling time of dc capacitor voltage excursion
- Reduce THD

MATERIALS AND METHODS

Control scheme of p-q method: The reference current for the control of the active power filter could be calculated using also the active and reactive power analysis in a stationary α-β frame. The instantaneous real and imaginary powers absorbed by the load are respectively, defined as in Eq. 1:

$$p_l = v_\alpha i_\alpha + v_\beta i_\beta \text{ and } q_l = v_\alpha i_\beta - v_\beta i_\alpha \tag{1}$$

These powers may be decomposed into oscillatory component (harmonic power) and average component (fundamental active and reactive powers) given by Eq. 2:

$$\begin{bmatrix} p_l \\ q_l \end{bmatrix} = \begin{bmatrix} \bar{p}_l \\ \bar{q}_l \end{bmatrix} + \begin{bmatrix} \tilde{p}_l \\ \tilde{q}_l \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} \tag{2}$$

To obtain a sinusoidal current with unity power factor, the oscillating term of p and all terms of q have to be removed. As a result, only the mean value of the active power is absorbed from the grid. The constraints are:

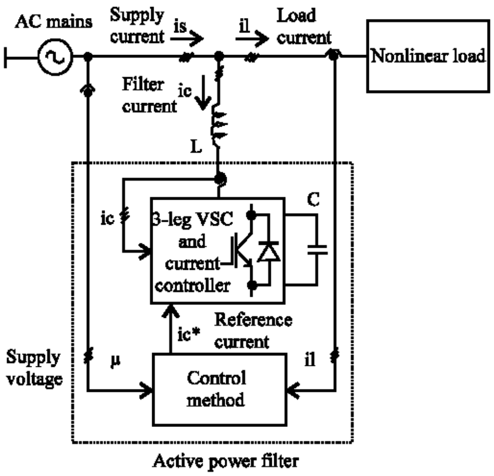

Fig. 1: Basic structure of shunt APF

$$\begin{cases} p(t) = P \\ q(t) = 0 \end{cases} \tag{3}$$

The compensation currents in α-β quantities are:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -p_f^* \\ -q_f^* \end{bmatrix} \tag{4}$$

By performing the inverse transformation, three phase compensation currents are obtained given by Eq. 5:

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \end{bmatrix}^T \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \tag{5}$$

An optimum value for gain K can be computed by the fuzzy inference system applied to control the DC bus voltage which in turn controls the proper amount of active power fed or drawn by the SAPF. The diagram of (p-q) algorithm given in Fig. 1 shows the control circuit of the compensator.

Proposed fuzzy control scheme: The general structure of Fuzzy Logic Controller is shown in Fig. 2. In order to implement the control algorithm of a SAPF in closed loop, the optimum value of K gain is calculated by a fuzzy inference system which receives inputs as the slope of D.C. average bus voltage and D.C. voltage error. Both

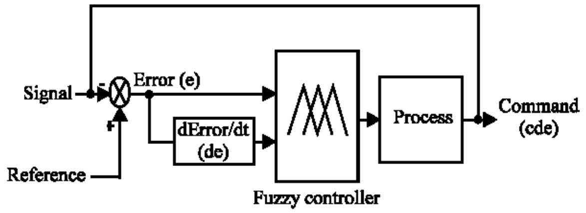

Fig. 2: Structure of fuzzy logic controller

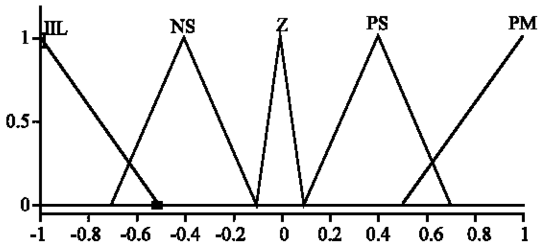

Fig. 3: D.C. voltage error normalized membership function

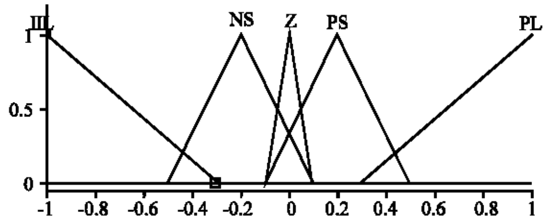

Fig. 4: D.C. voltage slope normalized membership function

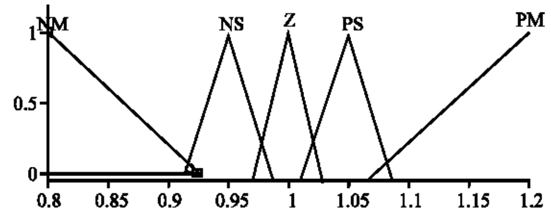

Fig. 5: Output weight membership functions for K gain value

quantities (error and slope of DC voltage) are normalized by suitable values. Thus, each range is between -1 and 1 normalized unity. Taking into account that the value of K is quite near unity, the range of the output weight membership function is considered between 0.6 and 1.4.

To characterize this fuzzy controller seven and five sets are chosen, respectively for the error and slope inputs. The output is defined by seven sets (Bhende *et al.*, 2006). The D.C. voltage error normalized, the D.C. voltage slope normalized and the output weight membership functions are shown in Fig. 3-5.

Table 1: Fuzzy rules for DC voltage control

	D.C voltage error				
D.C voltage slope	NL	NS	Z	PS	PM
NL	NM	NS	NS	PS	PM
NS	-	-	Z	-	-
Z	-	-	Z	-	-
PS	-	-	Z	-	-
PL	-	-	PS	-	-

The linguistic rules for the fuzzy logic controller are chosen, in most cases, depending only of the D.C. voltage error. These fuzzy rules used as the objective to maintain the K gain not too far from unity are resumed in the Table 1. The error e and the change of error ce are used as numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy sets are used: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big). The fuzzy controller is characterized as follows:

- Seven fuzzy sets for each input and output
- Triangular membership functions for simplicity
- Fuzzification using continuous universe of discourse
- Implication using Sugeno type inference system
- Defuzzification using weighted average method

Fuzzy current control: To obtain the desired switching signals according to output inverter currents to follow the reference currents, a current control should be made by fuzzy logic controller.

The inputs variables for the necessary control action of active filter are the error and the rate change of error between the reference signal and the active filter output current.

The current control method used in this study is related to fuzzy controller based PWM current controller. The switching signals are generated by means of comparing a carrier signal with the output of the fuzzy controller.

In this case, to characterize the fuzzy controller, three fuzzy sets for each input and for the output are chosen. Their membership functions are shown in Fig. 6-8.

Simulation: Simulations were performed to show the effectiveness of the APF regulation by means of fuzzy controllers which control the DC bus voltage and the active filter output current to track current reference.

The system parameters considered for the simulation studies are shown in Table 2. The simulation is divided into two cases of different supply condition; a nonlinear

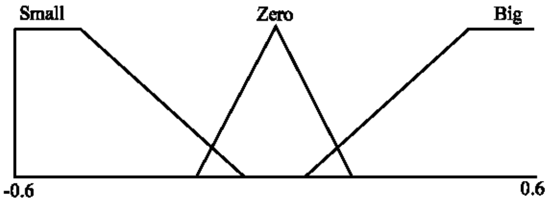

Fig. 6: D.C. voltage error normalized memebership function

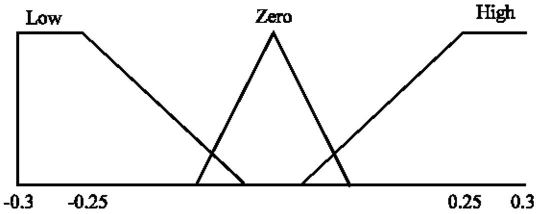

Fig. 7: D.C. voltage slope error normalized membership function

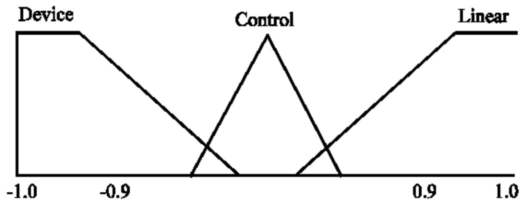

Fig. 8: Output weight membership functions for K gain value

Table 2: Active filter parameters

Active filter parameters	Values
Supply phase voltage	230 V
Supply frequency	50 Hz
Filter inductor	3.35 mH
DC link capacitor	40 mF
PWM carrier frequency	10 kHz

load consisting of a three phase diode based rectifier and a resistive load in its DC side is fed by both balanced and unbalanced sinusoidal voltages.

The normal sinusoidal supply is 230 V_{rms}, 50 Hz and the unbalanced supply for phase B and C with 30° apart.

RESULTS AND DISCUSSION

The simulation result is divided into two cases of different supply source condition; the balanced sinusoidal supply and the unbalanced sinusoidal supply. The waveform of input source current, load current and percentage of THD of the load current is obtained for the system without compensation.

It is shown clearly that the Total Harmonic Distortion (THD) is relatively high (29.01%) (Fig. 9 and 10). The simulation results of the pq control theory is shown in the Fig. 11 a-c.

The waveform of the input source current, compensation current and Percentage of THD of the output load current are obtained for each case with compensation. The Fig. 12a, b shows the waveforms for balanced condition.

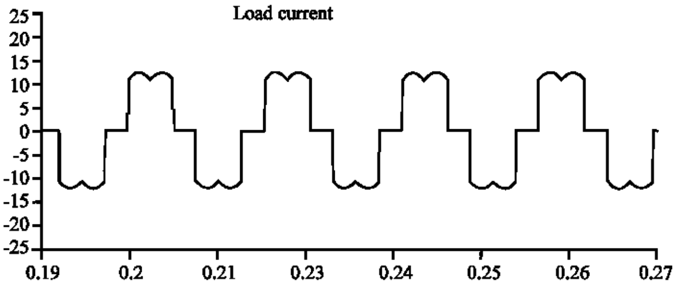

Fig. 9: Load current before compensation

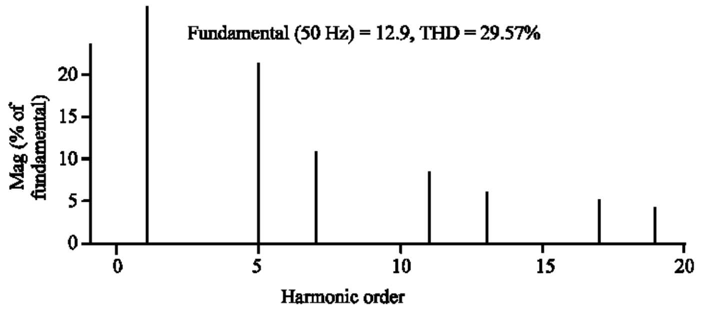

Fig. 10: Load current THD before compensation

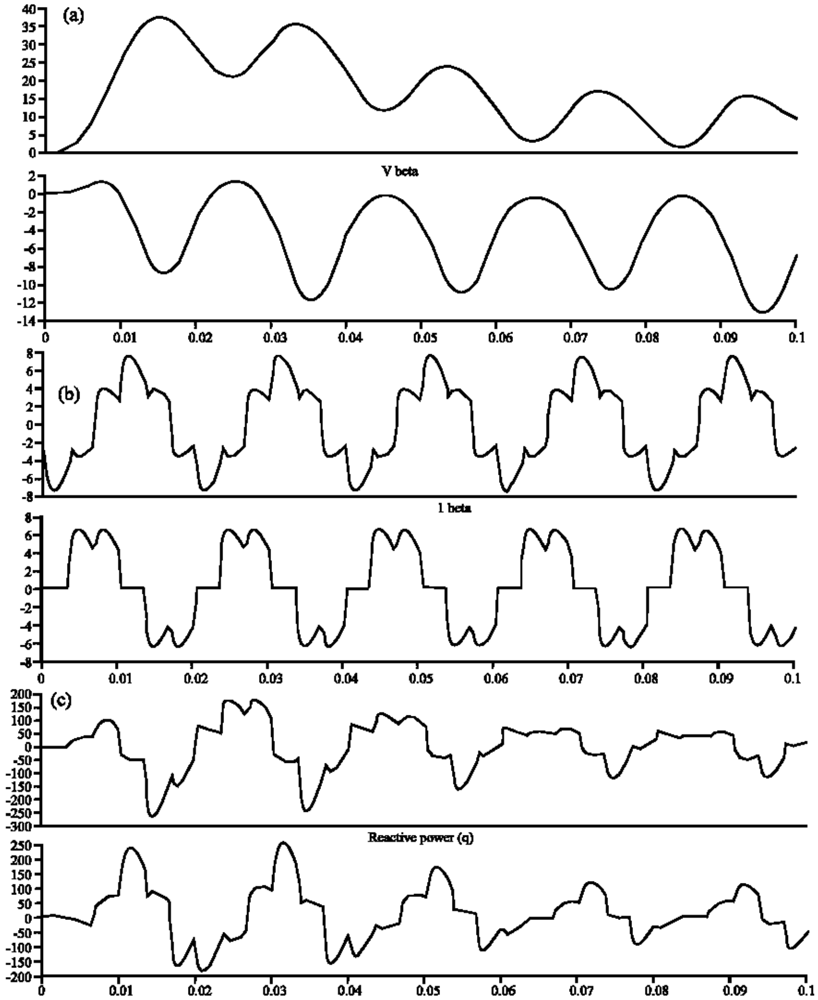

Fig. 11: a) Vα, Vβ to PQ controller; b) reference α-β current; c) power waveform

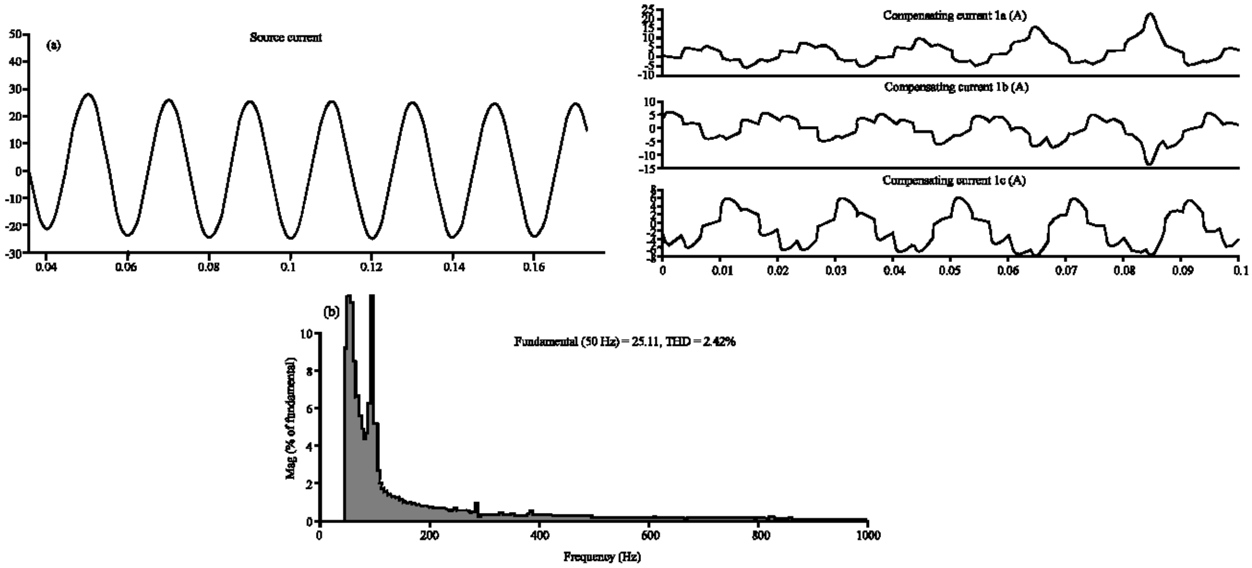

Fig. 12: a) The current waveforms and b) Percentage of THD of the source current

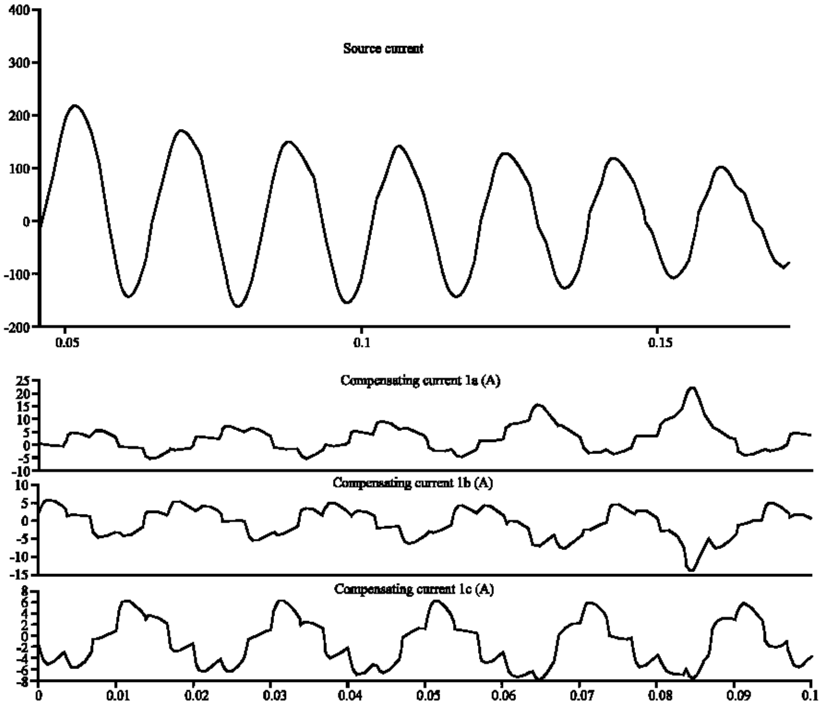

Fig. 13: The current waveforms

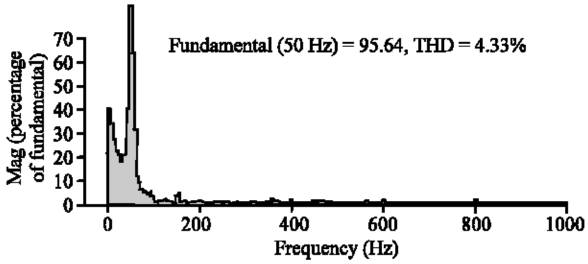

Fig. 14: Percentage of THD of the source current

Figure 13 shows the waveforms for unbalanced condition. Thus, the waveforms shows that the source current becomes closely sinusoidal and in phase with source voltage; the source power factor is then near unity.

The percentage of THD of the source (Fig. 14) current in both cases after compensation is well below the permissible limit of 5% according to IEEE-519 standard.

CONCLUSION

A Fuzzy Logic Control based Shunt Active Power Filter to compensate harmonics produced in the case of a non-linear load and reactive power is presented in this study. The reference current's identification is made by p-q theory to be used in voltage source perturbations. p-q theory gives a simple approach in analysis and control of the active and reactive components of the harmonic load and introduces the active power filter for appropriate corrective measure for the total harmonic distortion for improvement of the power quality. The THD measure in the presence of a controlled Shunt Active Filter is within the IEEE-519 harmonics standard. The Fuzzy Logic Controller based SAPF demonstrates a better dynamic behavior than conventional methods. It does not require any mathematical model of the system and can also work with imprecise inputs. The analyzed results conclude that the proposed FLC based SAPF improves the harmonic filtering performance and gives better transient and steady state response to the system under both balanced and unbalanced conditions. Recently a genetic algorithm has been proposed for the design of membership functions and rule sets which will be reported later.

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