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Fuzzy Based Hysteresis Current Controlled Shunt Active Power Filter for Power Conditioning

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Abstract: *Shunt Active power filters (SAPF) technology has emerged nowadays as a very suitable option for power quality improvement in electrical power systems control. This paper presents the simulation study of a fuzzy logic hysteresis band current controlled, three-phase SAPF to enhance power quality by harmonic elimination, power-factor correction, reactive power compensation and balancing of nonlinear loads. The advantage of fuzzy control is that it is based on a linguistic description and does not require a mathematical model of the system. Further, in this paper, the hysteresis based current control method is implemented for pulse width-modulation (PWM) switching signals. Results obtained by simulations with Matlab/Simulink show that dynamic behavior of the fuzzy controller is more effective than the conventional proportional-integral (PI) controller method on compensating reactive power and harmonic currents of the load. It is found to be more robust to changes in load and other system parameters compared to the conventional PI controller under steady state and transient conditions.*

Keywords: *Fuzzy logic controller, Hysteresis band current control, Power quality improvement, and Shunt active power filter*

I. Introduction

Shunt active power filters (SAPF) represent a feasible solution to the problems caused by the non- linear loads. These loads draw non-sinusoidal currents from the 3-phase sinusoidal, balanced voltages which are classified as identified and unidentified loads. The SAPF can compensate for the harmonics, correct the power factor and work as a reactive power compensator, thus providing enhancement of power quality in the system [1, 2]. The control scheme of a SAPF must calculate the current reference waveform for each phase of the inverter, maintain the dc voltage constant, and generate inverter gating signals. The current reference circuit generates the reference currents required to compensate the load current harmonics and reactive power, and also try to maintain constant the dc voltage across the capacitor [3].

In literature [1- 14], most reference compensation current strategies of the SAPF are determined either with or without reference-frame transformations. For instance, the theory proposed in [1, 2] requires transformation of both source voltages and load currents from the a-b-c reference frame to α-β reference frame to determine the SAPF reference compensation currents in the three-phase three-wire system. For detecting the reference compensating current, the instantaneous active and reactive power theory (p-q theory) are widely used, which can provide an instantaneous and accurate reference compensating current [2, 3]. Grady *et al.* [4] have presented a survey of active power line conditioning methodologies with a list of the advantages and limitations of each one. Cavallini and Montanari [5] have proposed the unity power factor strategy known as classic strategy in which conditions the line currents to fit the voltage waveform, provides line current RMS values always lower than those obtained by keeping the instantaneous real power equal to its mean value. Chang and Shree [6] have proposed a simple and efficient compensation strategy that is suitable for three-phase shunt active power filters without reference-frame transformation requirement. Bhende *et al.* [7] have proposed Takagi–Sugeno (TS)-type fuzzy logic controller to a three-phase shunt active power filter and compared to conventional proportional-integral (PI) controller. Bhim Singh and Verma [8] have an indirect current control scheme of parallel hybrid power filter system consists of a shunt passive filter with an active filter in series with it connected at the point of common coupling (PCC) in parallel with nonlinear load. Bhuvaneswari and Nair [9] have proposed an algorithm based on the real component of fundamental load current (I cosΦ). Suresh *et al.* [10] have presented the implementation of a hybrid adaptive fuzzy hysteresis current controller for shunt active power filter using i_d–i_q strategy. Tang *et al.* [11] have proposed a LCL-filter-based shunt active power filter which gives good switching harmonic suppression and minimizes the possibility of over-modulation.

Chandra *et al.* [12] have presented an improved control algorithm of the SAPF which used two closed loop PI controllers and carrier wave PWM signal generation. Akagi [13] has listed trends in active power line conditioners. Singh *et al.* [14] have presented a review on classification of active filters for power quality improvement based on converter type, topology and the number of phases.

In the generalized instantaneous reactive power theory [2], transformation of a-b-c axes to *d*–*q* synchronous reference frame is done for harmonic and reactive power compensation. However, the synchronous reference frame (SRF) strategy [3] only computes the sinusoidal fundamental components of the load currents; the reactive power compensation and a null neutral current thus cannot be achieved if the load imbalance at the fundamental frequency occurs. A phase-locked loop (PLL) per each phase must be used. In theory, the aforementioned approaches work very well on harmonic and/or reactive power compensation for nonlinear loads under ideal source voltages. However, if the source voltages are imbalanced and/or distorted, the generated SAPF reference compensation currents are discrepant and the desired balanced/sinusoidal source currents cannot be maintained [6].

Among different PWM methods, hysteresis is one of the most popular PWM strategies [6- 10] and widely applied in SAPF for current quality compensation, owing to its advantages such as ease of implementation, fast dynamic response and current limiting capability.

Recently, fuzzy logic controllers have generated a great deal of interest in various applications and have been introduced in the power-electronics field. The advantages of fuzzy logic controllers over the conventional PI controller are that they do not need an accurate mathematical model; they can work with imprecise inputs, can handle nonlinearity, and may be more robust than the conventional PI controller. The Mamdani type of fuzzy controller used for the control of APF gives better results compared with the PI controller [7, 10, and 14].

To achieve full compensation of both reactive power and harmonic/neutral currents of the load, this paper presents a simple method to determine the SAPF reference compensation currents using dc voltage, PI and Fuzzy controller and source voltages. This method does not require any reference frame transformations. Hysteresis band current control PWM strategy is used to drive current controlled voltage source inverter (CC- VSI). The two schemes, conventional PI controller and Fuzzy controller are compared in this paper. A MATLAB based simulation is performed on proposed system and the results are presented to discuss in regard to the voltage regulation, harmonic elimination, power-factor correction and load balancing capabilities of the SAPF system.

II. CONTROL SCHEME OF SAPF

The control scheme of a shunt active power filter must calculate the current reference waveform for each phase of the inverter, maintain the dc voltage constant, and generate the inverter gating signals. The block diagram of the control scheme of a shunt active power filter is shown in Fig. 1. The current reference circuit generates the reference currents required to compensate the load current harmonics and reactive power, and also try to maintain constant the dc voltage across the electrolytic capacitors. Also, the compensation effectiveness of an active power filter depends on its ability to follow with a minimum error and time delay, the reference signal calculated to compensate the distorted load current. Finally, the dc voltage control unit must keep the total dc bus voltage constant and equal to a given reference value. The dc voltage control is achieved by adjusting the small amount of real power absorbed by the inverter. This small amount of real power is adjusted by changing the amplitude of the fundamental component of the reference current. Different control topologies of SAPF are well documented in recent years [1- 14].

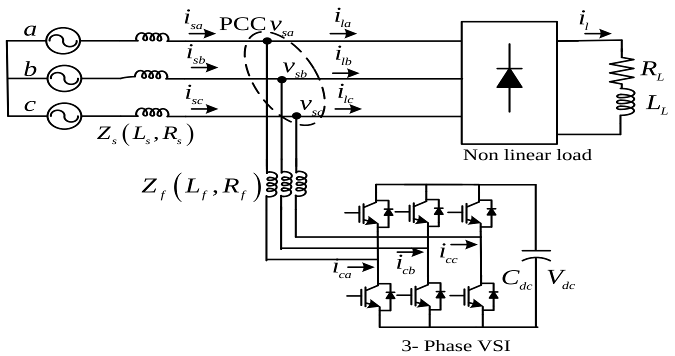

Figure 1: Basic Compensation Principle of Shunt Active Power Filter (SAPF)

2.1 Generation of Source Currents

SAPF is controlled to draw/supply a compensating current from/to the utility, so that it cancels current harmonics on the ac side and makes the source current in phase with the source voltage. From Fig. 1, the instantaneous currents can be written as:

$$i_S(t) = i_L(t) - i_C(t) \tag{1}$$

Source voltage is given by:

$$v_S(t) = V_m \sin\omega t \tag{2}$$

If the nonlinear load is applied, then the load current will have a fundamental component and harmonic components, which can be expressed as:

$$\begin{aligned} i_L(t) &= \sum_{n=1}^{\infty} I_n \sin(n\omega t + \varphi_n) \\ &= I_1 \sin(n\omega t + \varphi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \varphi_n) \end{aligned} \tag{3}$$

The instantaneous load power can be given as:

$$\begin{aligned} p_L(t) &= v_s(t) * i_L(t) \\ &= V_m I_1 sin^2 \omega t * cos\varphi_1 + V_m I_1 sin\omega t * cos\omega t * sin\varphi_1 \\ &\quad + V_m sin\omega t * \sum_{n=2}^{\infty} I_n sin(n\omega t + \varphi_n) \\ &= p_f(t) + p_r(t) + p_h(t) \end{aligned} \tag{4}$$

From (4), the real power drawn by the load is:

$$p_f(t) = V_m I_1 sin^2 \omega t * cos\varphi_1 = v_s(t) * i_s(t) \tag{5}$$

From (5), the current supplied by the source, after compensation is:

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 * cos\varphi_1 * sin\omega t = I_{sm} sin\omega t$$

Where $I_{sm} = I_1 * cos\varphi_1$

There are also some switching losses in the PWM converter and, hence, the utility must supply a small overhead for the capacitor leakage and converter switching losses in addition to the real power of the load. The total peak current supplied by the source *(I_{sp})* is therefore:

$$I_{sp} = I_{sm} + I_{sl} \tag{6}$$

Where I_{sl} is the peak value of loss current.

If the active filter provides total reactive and harmonic power, then $i_s(t)$ will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide the following compensation current:

$$i_c(t) = i_L(t) - i_s(t) \tag{7}$$

2.2 Generation of Reference Source Currents

There are many possibilities to determine the reference current required to compensating the non-linear load. Normally, shunt active power filters are used to compensate the displacement power factor and low-frequency current harmonics generated by non-linear loads. One alternative to determine the current reference required by the VSI is the use of the instantaneous reactive power theory, proposed by Akagi [1], the other one is to obtain current components in *d–q* or synchronous reference frame [2], and the third one to force the system line current to follow a perfectly sinusoidal template in phase with the respective phase-to-neutral voltage [3]. In this paper, a simple method is used to generate the source reference currents using DC voltage error and source voltage peak detection. The reason, why it is selected and functioning of the control method is explained below.

III. Proposed Method With Pi Controller

The aim of the method is to generate the current reference signal required to compensate reactive power and current harmonics. Basically, all the different schemes try to obtain the current reference signals that include the reactive components required to compensate the displacement power factor and the current harmonics generated by the non-linear load. Fig. 2 shows the PI controller based scheme used to generate the current reference signals required by a shunt active power filter. In this circuit, the distorted load current is filtered, extracting the fundamental component, I_l.

3.1Design of DC Link Voltage PI Controller

The three phase reference currents (peak value) for the control of active filter are generated in accordance with the PI controller error between the average dc bus voltage V_{dc} (n) and its reference value V_{dcref} (n) of the active filter. The dc bus voltage error V_e (n) at n^{th} sampling instant is:

$$V_e(n) = V_{dcref}(n) - V_{dc}(n) \tag{8}$$

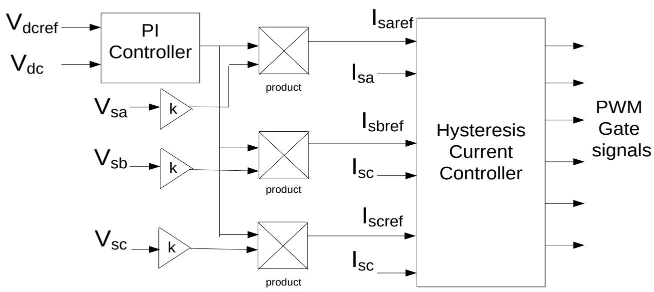

Figure 2: PI -hysteresis current controller based PWM generation using proposed method for SAPF.

This error signal V_e (n) is processed in PI controller and output K (n) at n^{th} sampling instant is expressed as:

$$K(n) = K(n-1) + K_p\{V_e(n) - V_e(n-1)\} + K_i\{V_e(n)\} \quad (9)$$

Where K_p and K_i are the gains of the PI controller.

The output of the PI controller has been considered as the amplitude of the desired source current, and the reference currents are estimated by multiplying this peak value with the unit sine vectors in phase with the source voltages. In order to provide the reactive power required by the load, the current signal obtained from the PI Controller I_{l1} is synchronized with the respective phase to- neutral source voltage so that the inverter ac output current is forced to lead the respective inverter output voltage, thereby generating the required reactive power and absorbing the real power necessary to supply the switching losses and also to maintain the dc voltage constant. The real power absorbed by the inverter is controlled by adjusting the amplitude of the fundamental current reference waveform, I_{l1}, obtained from the reference current generator.

Ideal compensation requires the mains current to be sinusoidal and in phase with the source voltage, irrespective of the load current nature. The source reference currents, after compensation, can be given as:

$$\begin{aligned} i^*_{sa} &= I_{sp}\sin\omega t \\ i^*_{sb} &= I_{sp}\sin\left(\omega t - 120^0\right) \\ i^*_{sc} &= I_{sp}\sin\left(\omega t + 120^0\right) \end{aligned} \quad (10)$$

Where I_{sp} is the amplitude of the desired source current, while the phase angle can be obtained from the source voltages. Hence, the waveform and phases of the source currents are known, and only the magnitudes of the source currents need to be determined.

The main characteristic of this method is the direct derivation of the compensating component by sensing dc voltage, source voltages and currents, without use of any reference frame transformation. Nevertheless, this PI controller presents a low frequency oscillation problem in the active power filter dc bus voltage. To improve this technique, fuzzy hysteresis band current controller has been implemented in this paper.

IV. PROPOSED FUZZY CONTROL ALGORITHM

Fig. 3 shows the schematic diagram of the fuzzy control scheme. In order to implement the control algorithm of a shunt active power filter in a closed loop, the dc capacitor voltage V_{dc} is sensed and then compared with the reference value V_{dcref}. In case of a fuzzy logic control scheme, the error $e = V_{dcref} - V_{dc}$ and integration of error signal $\int e$ are used as inputs for fuzzy processing. The output of the fuzzy controller after a limit is considered as the magnitude of peak reference current I_{max}. The switching signals for the PWM converter are obtained by comparing the actual source currents (i_{sa}, i_{sb}, i_{sc}) with the reference current templates (i^*_{sa}, i^*_{sb}, i^*_{sc}) in the hysteresis current controller. The output pulses are then given to the switching devices of the PWM converter.

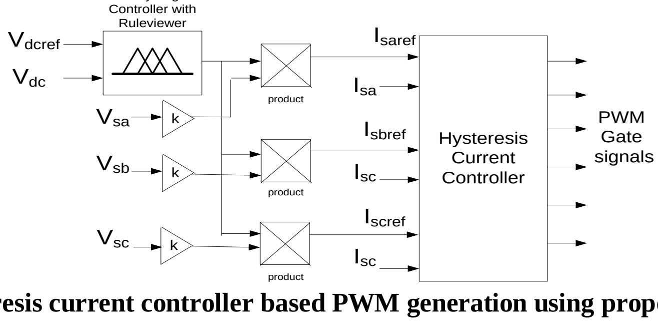

Figure 3: Fuzzy -hysteresis current controller based PWM generation using proposed method for SAPF.

4.1. Basic Fuzzy Algorithm

In a fuzzy logic controller, the control action is determined from the evaluation of '*a'* set of simple linguistic rules. The development of the rules requires '*a'* thorough understanding of the process to be controlled, but it does not require a mathematical model of the system. The design of a fuzzy logic controller requires the choice of membership functions. The membership functions should be chosen such that they cover the whole universe of discourse. It should be taken care that the membership functions overlap each other. This is done in order to avoid any kind of discontinuity with respect to the minor changes in the inputs. To achieve finer control, the membership functions near the zero region should be made narrow. Wider membership functions away from the zero region provides faster response to the system. Hence, the membership functions should be adjusted accordingly. After the appropriate membership functions are chosen, a rule base should be created. It consists of a number of Fuzzy If-Then rules that completely define the behaviour of the system. These rules very much resemble the human thought process, thereby providing artificial intelligence to the system [3].

The internal structure of the fuzzy controller is shown in Fig. 4. The error *e* and change of error *ce* are used numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy levels or sets are chosen as: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) and presented in input and output normalized membership functions (Figs. 5 (a) and (b)).

The fuzzy controller is characterized as follows:
(i) Seven fizzy sets for each input and output.
(ii) Triangular membership functions for simplicity.
(iii) Fuzzification using continuous universe of discourse.
(iv) Implication using Mamdani's 'min' operator.
(v) Defiizzificatioii using the 'centroid' method.

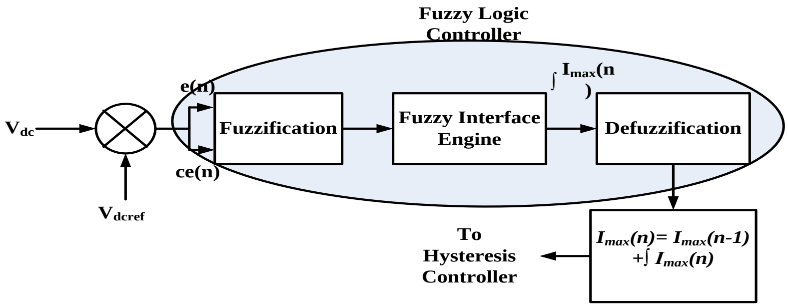

Figure 4: Internal Structure of Fuzzy controller.

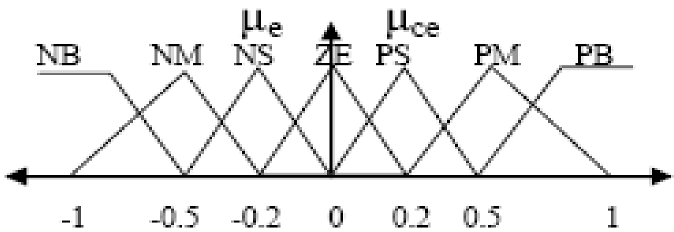

Figure 5(a): Input normalized membership function.

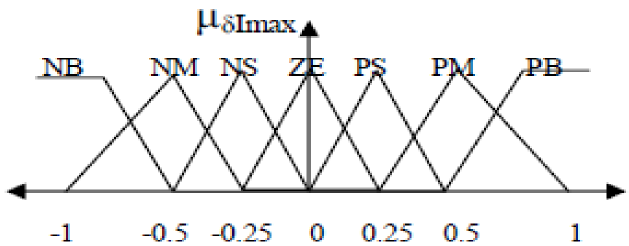

Figure 5(b): Output normalized membership function.

4.2.Rule Base

The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables; in the steady state, small errors need fine control, which requires fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table I, with 'e' and 'ce' as inputs.

Table.I Control Rule Base

ce e	NB	N M	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
N	NB	NB	NB	NM	NS	ZE	PS
NB	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
P	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

4.3 Hysteresis Current Controller for PWM Switching

The active filter is comprised of three-phase IGBT based current controlled VSI bridge. The upper device and the lower device in one phase leg of VSI are switched in complementary manner. The switching logic for "phase-a" is formulated as follows: if i_{sa} < (i^*_{sa}- h_b), upper switch is OFF and lower switch is ON in the phase "a" leg then S_a = 0. If i_{sa} > (i^*_{sa}+h_b) upper switch is ON and lower switch is OFF in the phase "a" leg then S_a= 1. Between the transitions the previous value of switches are maintained. Where, is switching function for switches of phase "a" and is the width of the hysteresis band around reference currents. Similarly, the switching logic of the other two phases ("b" and "c") is formulated.

V. Simulation Results And Discussion

Following are the system parameters considered for the study of SAPF for both PI and Fuzzy controller. V_s = 100 V (Peak), f = 50 Hz, R_s= 0.1 Ω, L_s= 0.15 mH, R_f = 0.1 Ω, L_f = 0.66 mH, R_l = 6.7, 15 Ω; L_l = 20mH, C_{DC} = 2000 µF, V_{dcref} = 220 V. In case of PI the gains chosen are k_p= 0.2 and k_i = 9.32. Initially, the load chosen is of R_l = 6.7 Ω, L_l = 20mH and later, the load has been changed to R_l = 15 Ω, L_l=20mH. The performance results of shunt active power filter with PI controller are presented in Figures 7- 9. Fig.6 shows THD content of Load current, Source current with PI controller and with Fuzzy controller. In Fig.7performance results of SAPF with PI controller are presented and results with fuzzy controller are presented in Fig. 8. Fig.9 shows results in support of power factor correction ability of SAPF. Comparisons of PI and fuzzy controllers are presented in Table II, III and IV based on % THD, settling time and overshoot. (Parameters notation is shown in Fig. 1.)

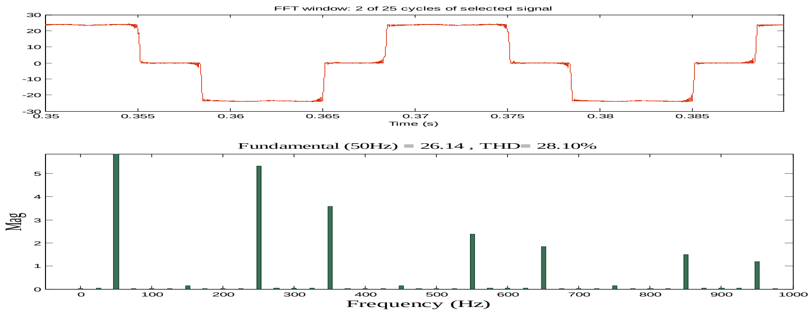

Figure 6 (a): THD % of load current

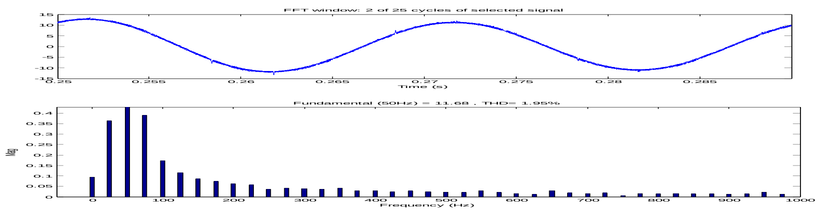

Figure.6 (b): THD % of Source current (PI)

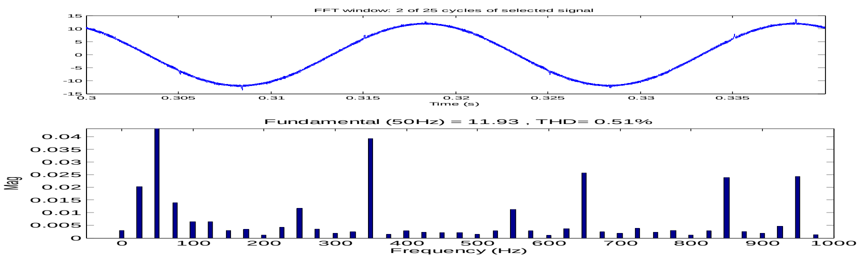

Figure.6(c) THD% of Source current (Fuzzy)

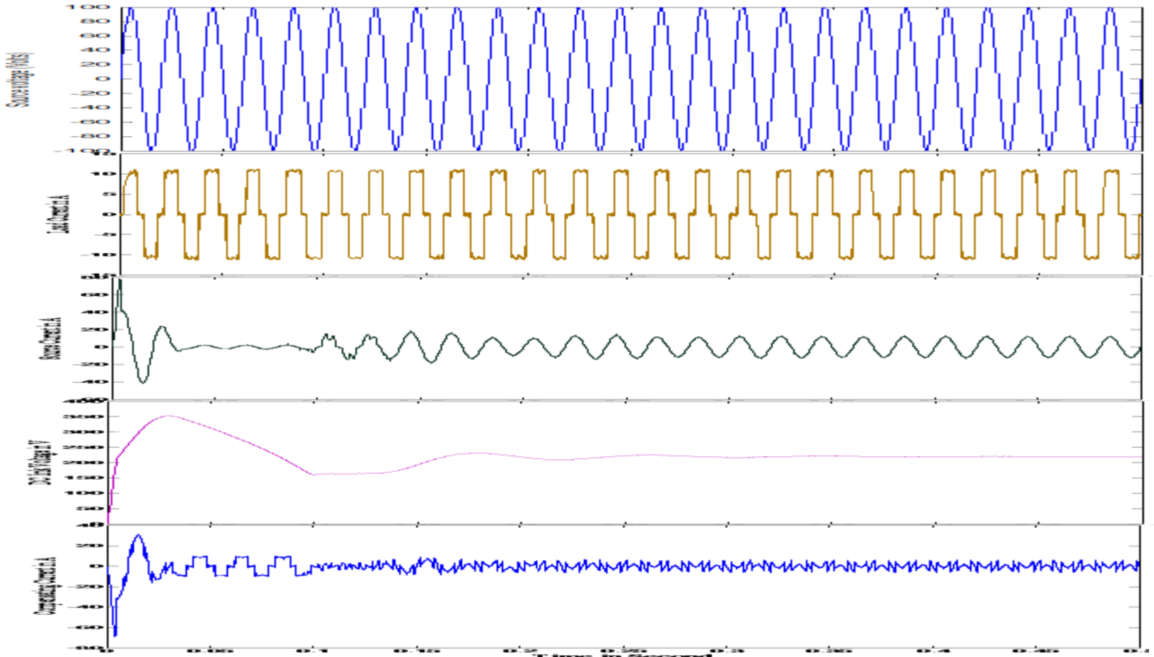

Figure.7: Performance results of shunt active power filter with PI controller for the load of Rl = 15 Ω, and Ll = 20 mH.

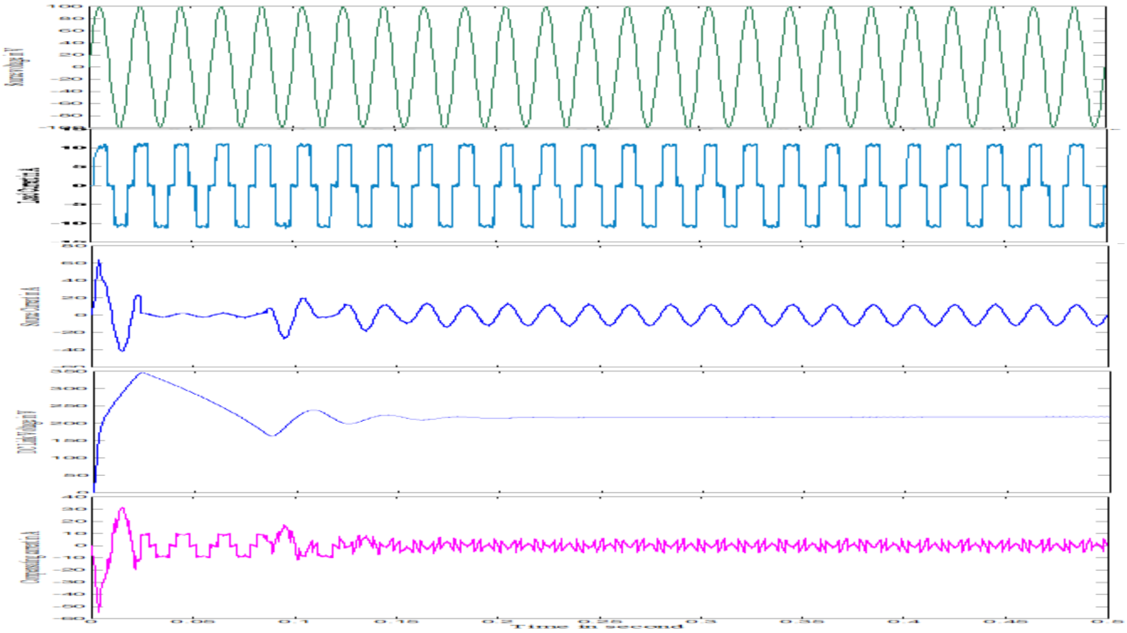

Figure.8: Performance results of shunt active power filter with fuzzy controller for the load Rl = 15 Ω, and Ll = 20 mH

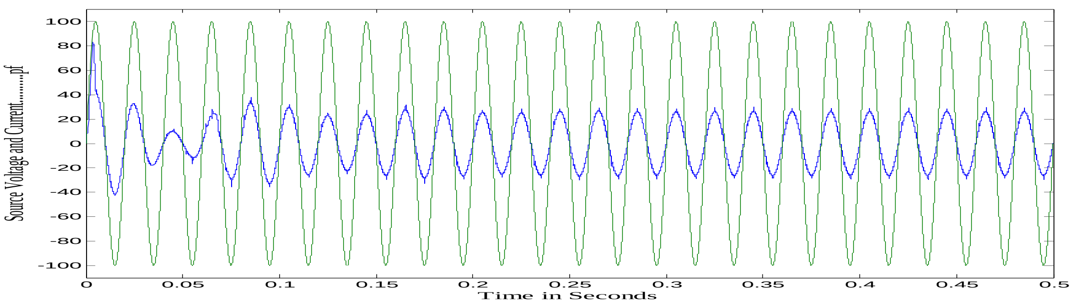

Figure 9(a): Source Voltage and current wave forms of Phase 'a' of PI controlled SAPF

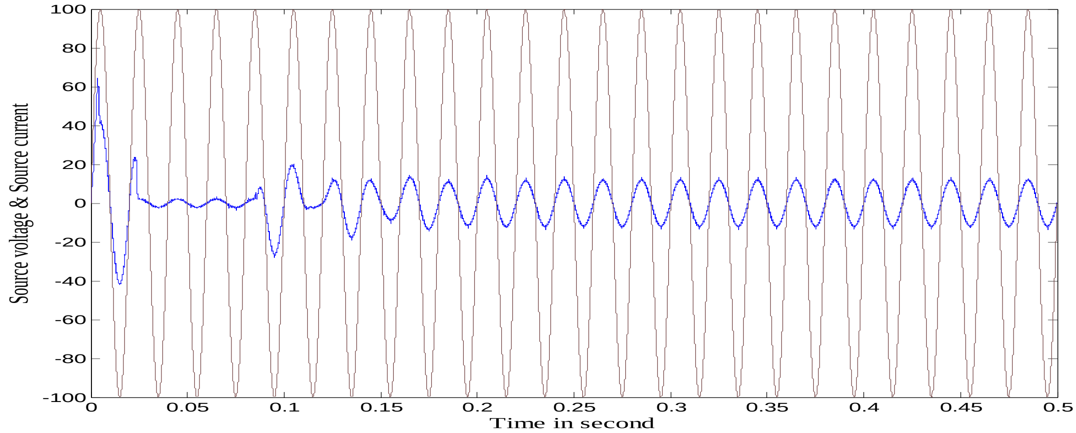

Figure 9(b): Source Voltage and current wave forms of Phase 'a' of Fuzzy controlled SAPF

TABLE.II: Thd % Comparison between Pi and Fuzzy Controllers

	% THD at two different loads	
	R_l = 6.7 Ω, L_l = 20mH	R_l = 15Ω, L_l = 20mH
Without controller	28.10	27.72
With PI controller	0.81	1.03
With Fuzzy controller	1.1	0.51

TABLE.III: Settling Time Comparison between Pi And Fuzzy Controllers

	Settling time for two different loadings (sec)	
	R_l = 6.7 Ω, L_l = 20mH	R_l = 15Ω, L_l = 20mH
With PI controller	0.26 s	0.33 s
With Fuzzy controller	0.18 s	0.24 s

TABLE.IV: Response of Pi and Fuzzy Controllers under Dynamic Load Conditions

	PI	Fuzzy
Switch on response (peak overshoot)	80 A	65 A
Settling time (after load change)	0.45 s	0.3 s
Load current overshoot (at load change)	45 A	35 A

VI. Conclusion

This paper has presented a simulation study of fuzzy based hysteresis current controlled shunt active power filter for harmonic and reactive power compensation of the non-linear load. A simple method is implemented to generate source reference currents without reference frame transformation using DC voltage regulator and source voltages. It gives less complexity in realizing the control circuit of the active power filter and still maintains good filter performance. The scheme has the advantage of simplicity and is able to provide self-supported dc bus of the active filter through power transfer from ac line at fundamental frequency. The performance of conventional PI controller and fuzzy controller has been studied and compared. Overall, the fuzzy controller gives the best SAPF performance in comparison with the PI controller in regards voltage regulation, % THD, settling time, current overshoot etc.

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