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Comparative Analysis on Control Methods of Shunt Active Power Filter for Harmonics Mitigation

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Abstract: ***This paper presents an overview of different control methods which are applied on Shunt Active Power Filter to achieve harmonics reduction and power factor improvement. In recent decades, the world has seen an expansion in the use of non-linear loads. These loads draw a non-sinusoidal current from the source and distribute them throughout the system. As a result the power quality degrades. Therefore, Active Power Filter and its control have been proposed which provides excellent harmonic compensation and power quality improvement.***

Keywords: Active Power Filter, Harmonics, PI Controller, Fuzzy Logic Controller

1. Introduction

In everyday life, there are loads that create harmonic currents. The higher switching frequency and the non-linearity of the power electronics devices are mostly responsible for these harmonic currents which can interact adversely with a wide range of power system equipments, control systems, protection circuits, and other harmonic sensitive loads. They can overheat building wirings, causes tripping of source supplies and can result in total equipment failures.

In linear load when a pure sinusoidal voltage is applied, the current drawn by the load is proportional to the voltage. Examples of linear load include resistive heaters, lamps and synchronous motors. In non-linear loads, the current vary disproportionately with the applied voltage and hence such current is non-sinusoidal in nature. These current waveforms contain harmonics having multiple frequencies imposed on fundamental frequency. Examples of such loads include battery chargers, electronic ballasts, Switch Mode Power Supplies (SMPS).

In order to tackle the problems of harmonics, many solutions have been proposed in the literature. Earlier, tuned LC circuits and high pass passive shunt filters were used [1]. The passive filters could filter only the frequencies they were previously tuned for and also suffered from resonance affecting the stability of the system. Because of these disadvantages of passive filters, extensive study on active filters was conducted with different control methods. One of the time-domain control methods is the instantaneous active-reactive power theory (p-q theory) [2]. Another method is instantaneous active-reactive current component method (i_d-i_q method) based on synchronous rotating frame [3]. The p-q theory is valid for both the steady state and transient response controlling the SAPF in time domain. Another advantage of this theory is the simplicity of calculations, since only algebraic operations are required [4]. The present paper mainly focuses on two controllers namely Proportional Integral (PI) and fuzzy in which the p-q method of active power filter control is used. On observing, fuzzy controller shows some superior performance over pi controller.

2. Active Power Filter

An active power filter (APF) is a converter which is placed between the power supply and the load so as to absorb all the disturbances generated by the load as shown in figure (1).

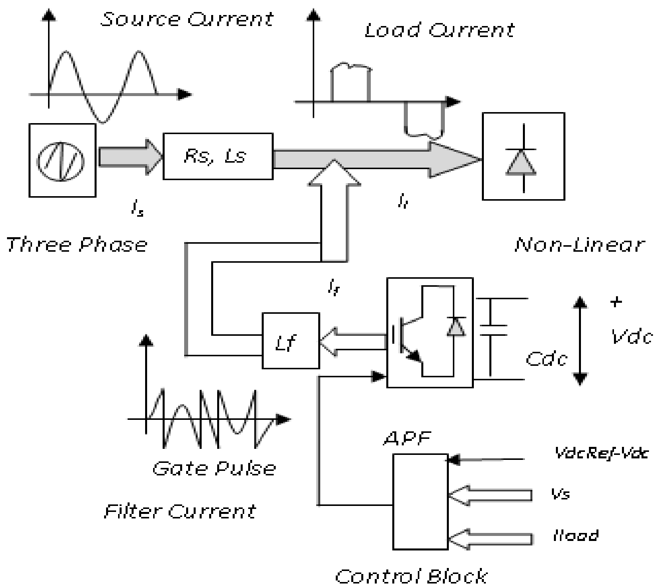


Figure 1: Basic Circuit of SAPF

If we denote i_{ca}, i_{cb} and i_{cc} the load absorbed currents and i_{sa}, i_{sb} and i_{sc} the desired power supply currents, then the active filter must provide currents i_{fa}, i_{fb} and i_{fc} such that $i_{fa}=i_{ca}-i_{sa}$, $i_{fb}=i_{cb}-i_{sb}$ and $i_{fc}=i_{cc}-i_{sc}$ so that the currents taken from the power supply are sinusoidal and the fundamental of these currents are in phase with the supply voltages. APF's can be used in series, shunt or a combination of both known as hybrid filters. The shunt active power filter is intended to generate exactly the same harmonics contained in the polluting current but with opposite phase.

3. Harmonics Currents Extraction Method

The harmonic currents extraction method basically uses two techniques. The first technique uses Fast Fourier Transform (FFT) to extract harmonics in frequency domain. This method requires heavy calculations and requires a lot of memory. The other technique is to extract current harmonics in time domain. Some of its methods are based on instantaneous active and reactive power. Others are based on the calculation of direct and indirect current components. Since, time domain methods allow a faster response and less calculations, we have incorporated this method in our work.

4. Reference Current Generation

The following methods are used to generate reference currents for the SAPF.

1. Instantaneous active and reactive power theory also known as p-q theory.
2. Synchronous reference Method also known as d-q theory.
3. Root Mean Square (RMS) based algorithm.
4. Active and Reactive current methods.

4.1 Instantaneous Active and Reactive Power Method

This method, which is also known as p-q method uses the transformation of distorted currents from three phase frame abc into bi-phase stationary frame αβ. This theory is based on a set of instantaneous powers defined in the time-domain [6]. The three phase supply voltages (V_{sa},V_{sb},V_{sc}) and currents (I_{sa},I_{sb},I_{sc}) are transformed using the Clarke (or α-β) transformation into a different co-ordinate system yielding instantaneous active and reactive power components. The Clarke's transformation for voltage variables is given by

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad \ldots(1)$$

Similarly, this transformation can be applied on distorted load currents as;

$$\begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_{la} \\ I_{lb} \\ I_{lc} \end{bmatrix} \quad \ldots(2)$$

The instantaneous active power $p(t)$ is defined by

$$p(t)=V_{sa}.I_{sa}+V_{sb}.I_{sb}+V_{sc}.I_{sc} \quad \ldots(3)$$

This expression can be given in the stationary frame by

$$\begin{cases} p(t) = V_\alpha I_\alpha + V_\beta I_\beta \\ p_0(t) = V_0 I_0 \end{cases} \quad \ldots(4)$$

where, $p(t)$ is the instantaneous active power and $p_0(t)$ is the instantaneous homo-polar sequence power. Similarly, the instantaneous reactive power is given by

$$q(t) = \frac{-1}{\sqrt{3}}\left[\left(V_{sa}-V_{sb}\right)I_{sc}+\left(V_{sb}-V_{sc}\right)I_{sa}+\left(V_{sc}-V_{sa}\right)I_{sb}\right] \quad \ldots(5)$$

which is equivalent to $q(t) = V_\alpha I_\beta - V_\beta I_\alpha$ …(6)

The instantaneous reactive power $q(t)$ takes into consideration all the current and voltage harmonics. From equations (4) and (6), the expression for $p(t)$ and $q(t)$ can be written in matrix form as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad \ldots(7)$$

In general, each one of the active and reactive instantaneous power contains a direct component and an alternating component. The direct component represents the fundamentals of current and voltage. The alternating term represents the harmonics of currents and voltages.

In order to separate the harmonics from the fundamentals of the load currents, it is enough to separate the direct term of the instantaneous power from the alternating one. A Low Pass Filter (LPF) with feed-forward effect can be used to accomplish this task as shown in figure.

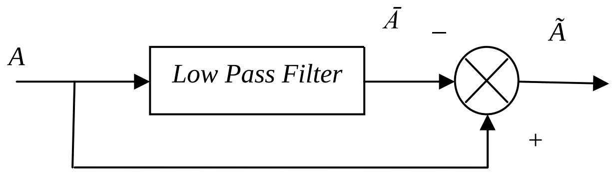


Figure 2: LPF with feed-forward effect

After the separation of the direct and alternating terms of instantaneous power, the harmonic components of the load currents can be given using the inverse of equation (7) as

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

Where ~ sign points to the alternating term. The APF reference current is then given by

$$\begin{bmatrix} I_{fa} \\ I_{fb} \\ I_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \tilde{I}_\alpha \\ \tilde{I}_\beta \end{bmatrix} \quad \ldots(9)$$

The figure (3) below shows the block diagram of p-q method for harmonic currents extraction.

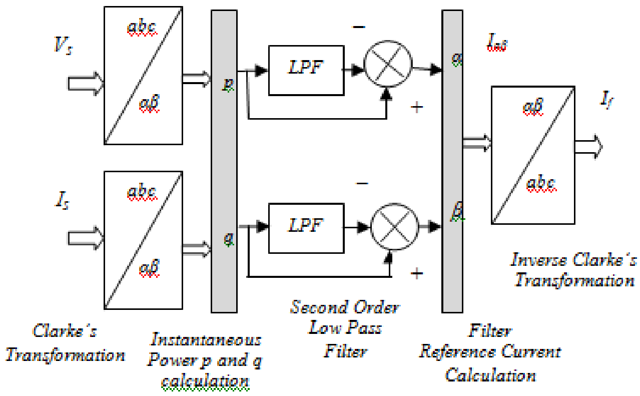


Figure 3: Instantaneous p-q method

5. Voltage Source Inverter

Voltage Source Inverter (VSI) is a device which is used to produce a three phase voltage source such that the amplitude, frequency and phase of the voltage are always controllable [5]. The VSI is controlled so that the output currents of the inverter are forced to follow their pre-defined reference currents. The main principle is based on the comparison between the actual current and the reference current generated by different extraction methods. Some of the methods of VSI control are;

a. Hysteresis current control method
b. Sinusoidal Pulse Width Modulation (SPWM) Control
c. Space Vector PWM Control (SVPWM)

5.1 Hysteresis Current Control Method

The current control strategy plays an important role in fast response current controlled inverters such as the active power filters. This method provides instantaneous current corrective response, good accuracy and unconditioned stability to the system. Hysteresis current control is a method of controlling a voltage source inverter so that an output current is generated which follows a reference current waveform [7]. The hysteresis control strategy aims to keep the controlled current inside a defined rejoin around the desired reference current. The status of the switches is determined according to the error as shown in figure (4).

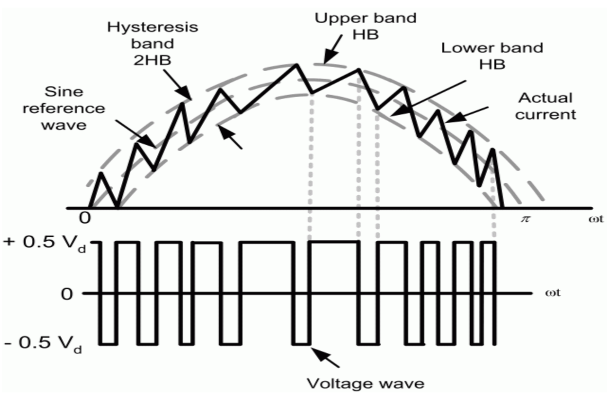


Figure 4: Hysteresis Current Control

The hysteresis current control is used to generate the gate pulses required for the shunt APF to operate effectively. In the fix hysteresis band control of the VSI, the switching frequency is a function of the derivative of the output current. It is important to notice that the coupling filter affects the switching frequency and the dynamic behavior of the active filter. The simple implementation procedure is the main advantage of this control method. However, the variable switching frequency is the major draw-back of this method. This variable frequency affects mainly the function of power electronic elements which can't support high switching frequency in high power applications.

In order to solve, the problem of variable switching frequency, a new hysteresis control strategies like 'modulated hysteresis control' and 'variable hysteresis band' were proposed. In the modulated hysteresis control , it is difficult to define the hysteresis bandwidth.

6. Control of the Shunt Active Power Filter

The dynamic response of shunt APF is controlled by either PI or Fuzzy Logic Controller (FLC). Recent trends make use of Artificial Intelligence (AI) technologies such as Artificial Neural Networks (ANN) and Genetic Algorithms [8]. The area of AI has penetrated deeply into electrical and electronics engineering and their applications in power electronics and motion control appears very promising.

6.1 PI Control

The figure (4) below shows the block diagram of PI Controller.

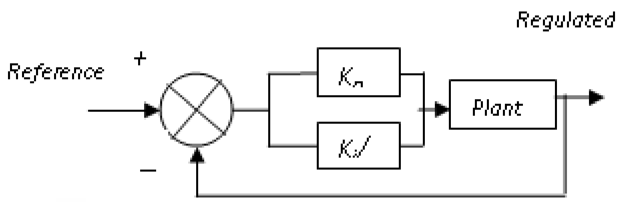


Figure 5: Basic PI Controller

In this method, the DC side capacitor voltage is sensed and compared with a reference voltage. This error $e=V_{dc\ (ref)}-V_{dc}$ is used as an input for PI Controller. The error signal is passed through Butterworth design based Low Pass Filter (LPF). The LPF filter has cut-off frequency at 50Hz that can suppress the higher order components and allow only fundamental components. The transfer function of the PI Controller is represented as

$H(s) = K_p + K_i/S$ … (9)

where, K_p is the proportional constant that determines the dynamic response of the DC-side voltage control and K_i is the integral constant that determines it's settling time.

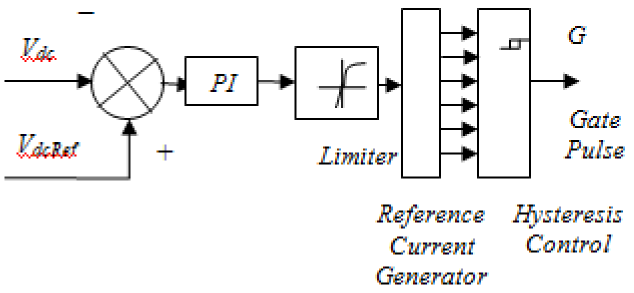


Figure 6: PI Controller for SAPF

The proportional integral controller eliminates the steady state error in the DC- side voltage. The output of the PI controller is considered as the peak value of supply current (I_{max}), which is composed of the fundamental active power component of load current and loss component of APF [9]. Peak value of the current (I_{max}) so obtained, is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. These estimated reference currents (Isa*, Isb*, Isc*) and sensed with actual currents (Isa, Isb, Isc) and are compared at a hysteresis band, which gives the gating signals for the APF.

The calculated values of K_p and K_i are 0.0052 and 1.15 respectively from equations below.

$$K_p = \frac{2\xi K_i}{\omega_n} \text{ and } K_i = \frac{\omega_n^2 V_{dcref} C_{dc}}{V_s^2} \quad \ldots (10)$$

where symbols have usual meanings and ξ=0.707.

6.2 Fuzzy Control

The design of a conventional control system is normally based on mathematical model of the plant. If an accurate mathematical model is available with known parameters, then it can be analyzed. However, fuzzy logic controller does not require the mathematical model of the system and can give robust performance of the linear and non-linear plant with parameter variation.

The FLC mainly consists of three blocks

- Fuzzification
- Inference
- Defuzzification

In the process of fuzzification, the fuzzy logic controller requires that each input/output variable which define the control surface be expressed in fuzzy set notations using linguistic levels. The linguistic values of each input and output variables divide its universe of discourse into adjacent intervals to form the membership functions. The member value denotes the extent to which a variable belong to a particular level.

The behavior of the control surface which relates the input and output variables of the system is governed by a set of rules known as inference. Defuzzification is the process of conversion of fuzzy quantity into crisp quantity. A fuzzy controller converts a linguistic control strategy into an automatic control process and fuzzy rules are constructed by knowledge database [10]. The error and the rate of change of error forms the two inputs to the fuzzy controller. The output of the FLC is the current (I_{max}) as in the case of PI controller. The block diagram for the FLC controller is given below (figure 7).

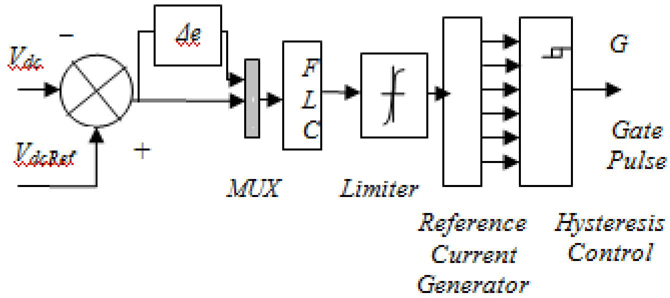


Figure 7: Fuzzy Logic Controller for SAPF

The fuzzy controller is characterized as follows [11]:

- Seven fuzzy sets for each inputs and outputs :NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big)
- All triangular membership functions.
- Fuzzification using continuous universe of discourse.
- Implication using Mamdani's 'min' operator.
- Defuzzification using the 'height' method.

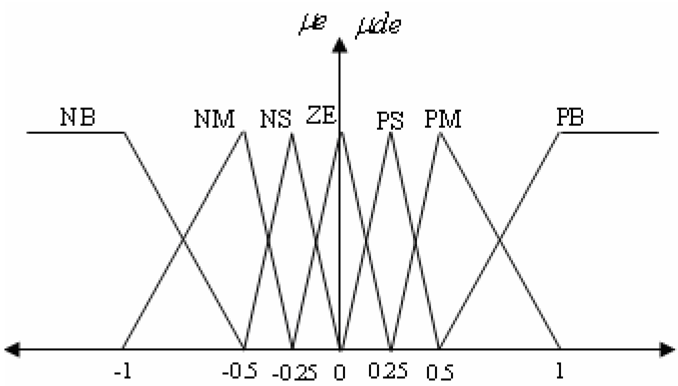


Figure 8: Error *(e)* and Change in Error *(Δe)*

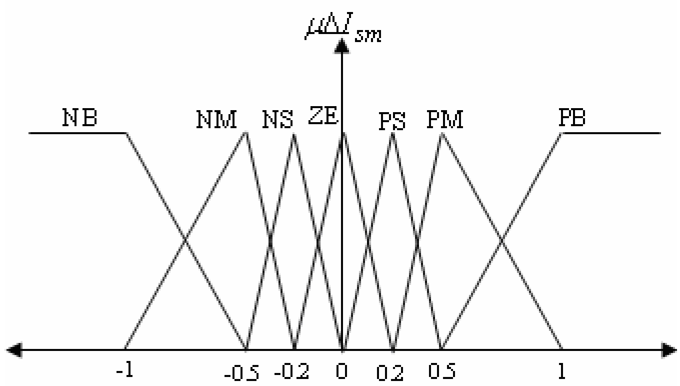


Figure 9: Change in Output Current

Table 1: Control Rule Table

Change in Error (Δe)	Error (e)						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The elements of table 1 are determined based on the theory that in the transient state, large error needs coarser control and in steady state smaller errors need fine control.

7. Simulation Results and Discussions

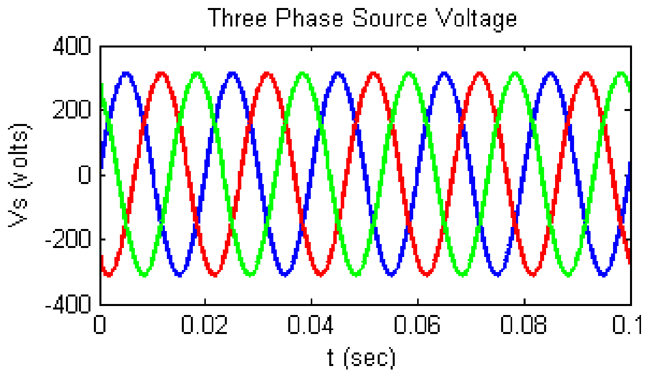
The simulation of both the PI and fuzzy controllers for shunt APF was carried out using MATLAB/Simulink with the following system parameters.

	System Parameters	*Value*
1.	Three Phase Source Voltage, V_s	400 V
2.	Frequency, f	50 Hz
3.	Source Load, R_s, L_s	0.3 Ω, 1μH
4.	Load Resistance, R_l	10 Ω
5.	Filter Load, L_f	0.66mH
6.	DC Capacitance, C_{dc}	2200μF
7.	DC Reference Voltage, V_{dc}	850 V
8.	Proportional Constant, K_p	0.0052
9.	Integral Constant, K_i	1.15

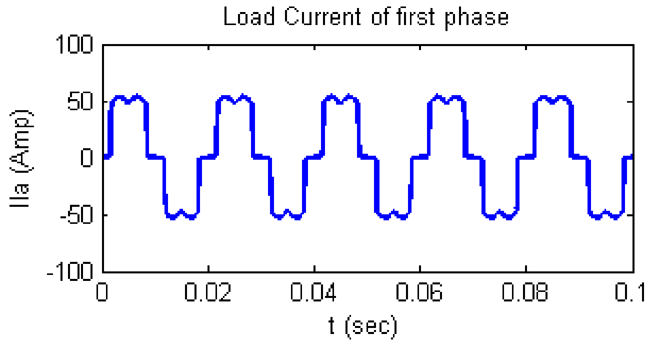
The simulation results are as follows:

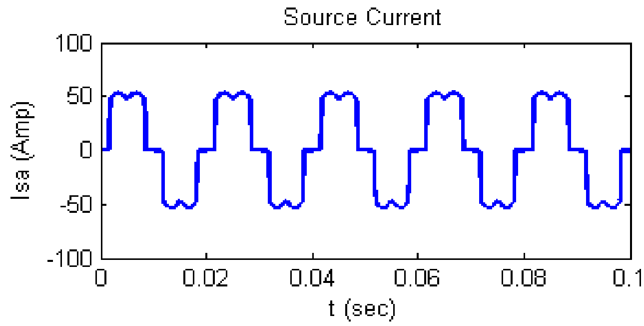
Case I: When the APF is not connected.

The source voltage is given as below

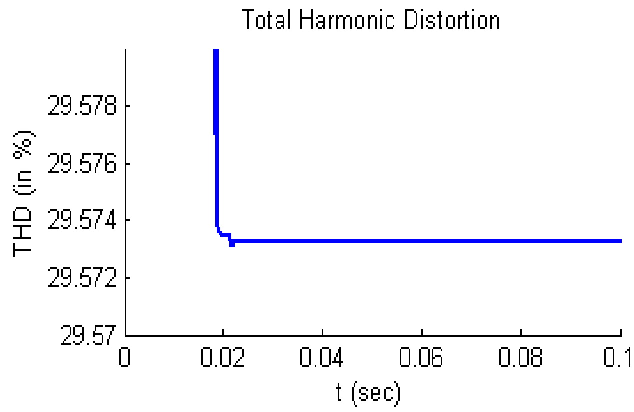


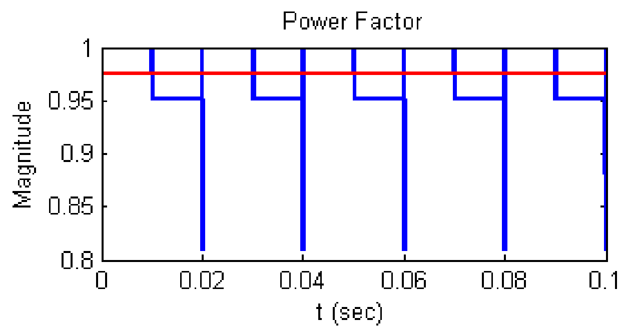
The load current and the source current are the same when APF is not connected.





The Total Harmonic Distortion (THD) is the ratio of the root-sum square value of the harmonic content of the current to the root-mean-square value of the fundamental current. This is THD of the current waveform. Similarly, THD of the voltage harmonics can be described as above.

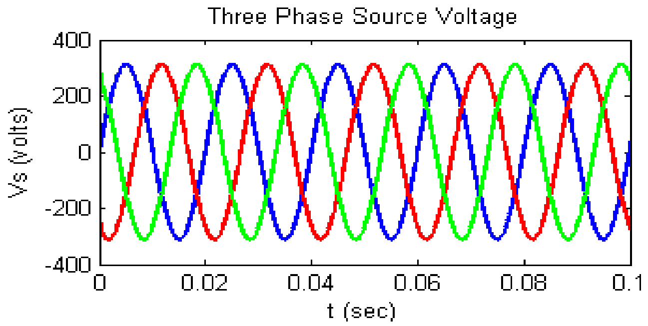


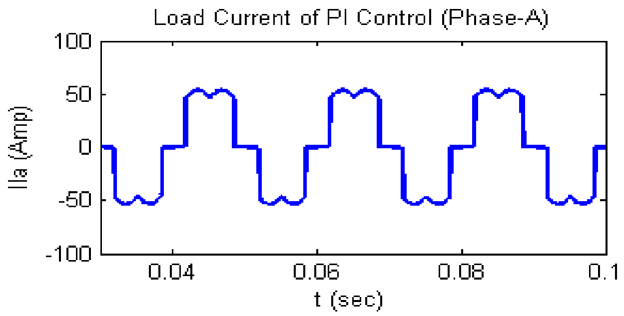


The THD of the circuit when APF is not connected is 29.573 % and the power factor (PF) is 0.9755.

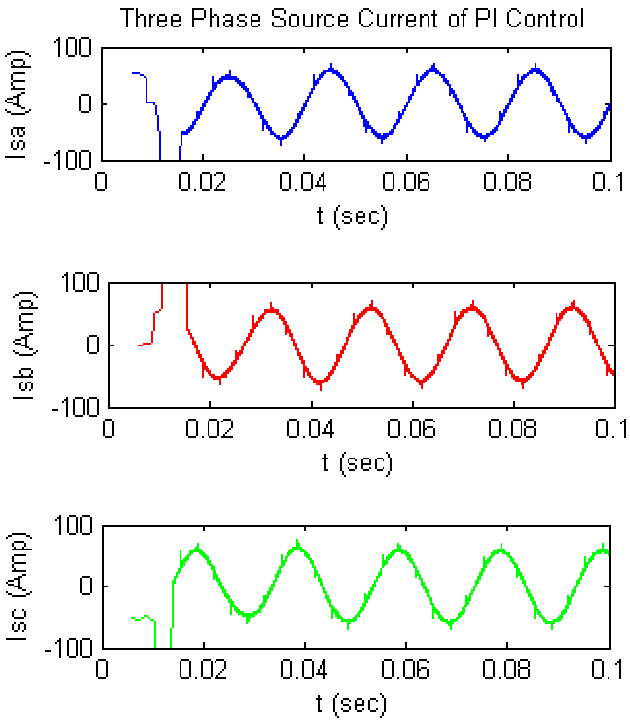
Case II: With PI Controller

The results obtained for PI control is as follows:

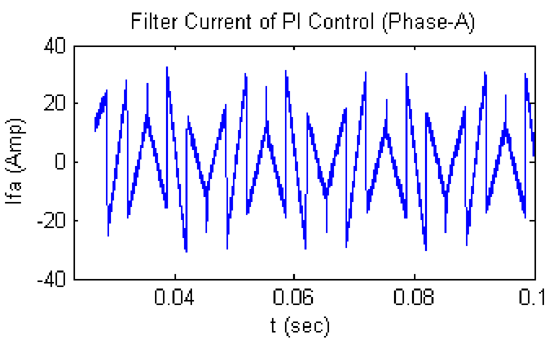




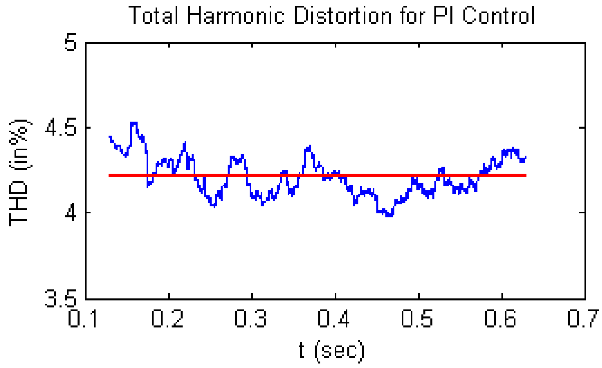
The current drawn by the load becomes sinusoidal when shunt APF is started.

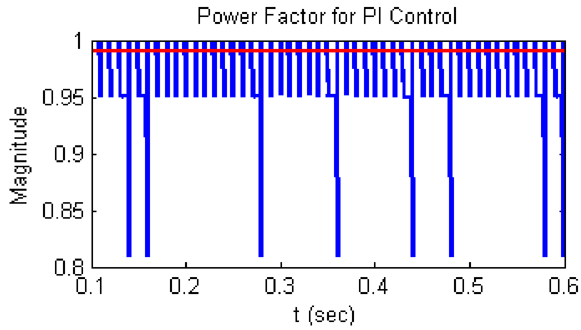


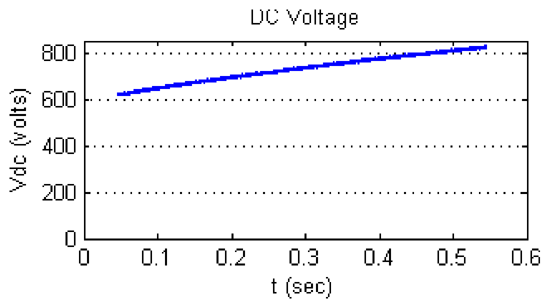
The Filter Current for the APF is as shown below.



The graphs for THD and PF are as follows:

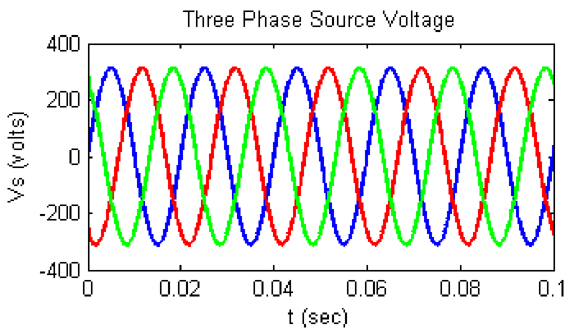


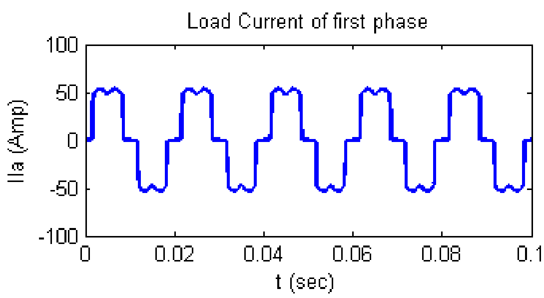


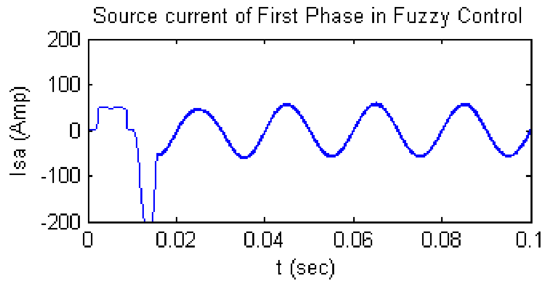


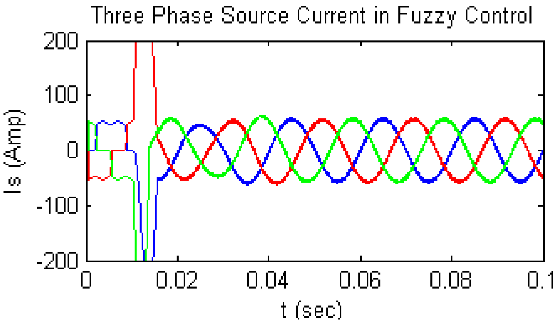
For the PI controller, The THD was reduced to 4.24 % and the PF was increased to 0.9906. The DC voltage was constant around 800 V as shown above.

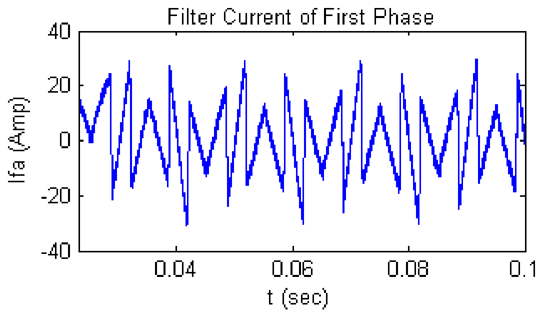
Case III: With Fuzzy Controller



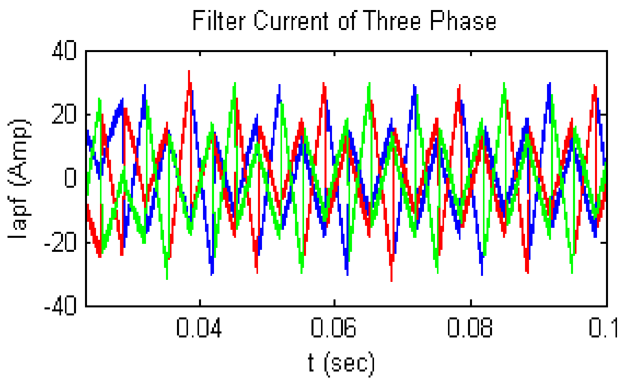


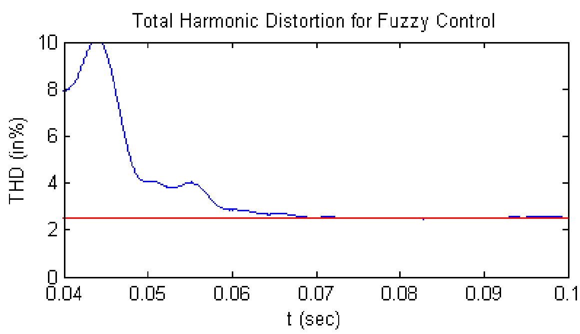


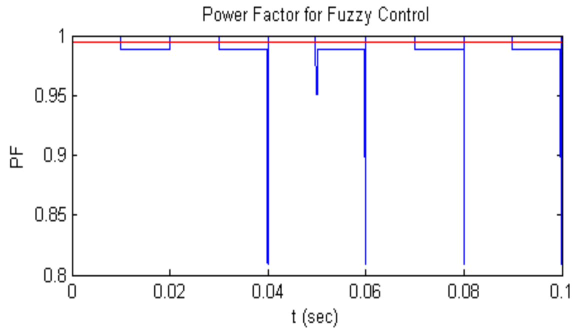


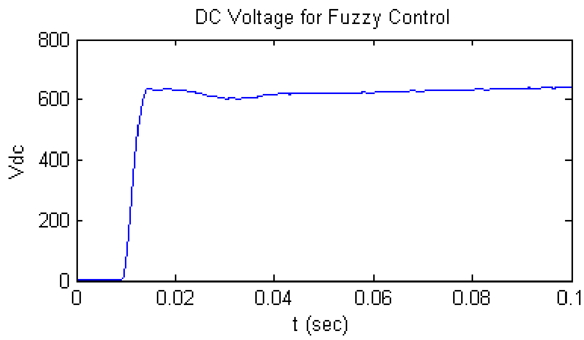


The three phase filter current for fuzzy control is given by









8. Conclusion and Future Scope

In this work, we have shown the effectiveness of PI and fuzzy controllers for harmonics mitigation using shunt APF. It is clearly understood that by using PI controller the harmonics level dropped to 4.24 % from 29.573 % when shunt APF is not connected, which is well below the restrictions imposed by IEEE Std. 519. In case of fuzzy logic controller, the THD was approx. 2.49%. Also, the power factor was improved from 0.9755 to 0.9906 in case of PI controller and to 0.9952 in case of fuzzy controller which proves the effectiveness of the PI and fuzzy controllers. Future work may include use of soft computing techniques such as Artificial Neural Network (ANN) to extract harmonic currents. Also neuro-fuzzy systems can be used for hysteresis current control.

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