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Fuzzy Tuned PI Controller for Shunt Active Power Filter

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Abstract — *This paper focuses on Fuzzy Logic controller (FLC) design that supervises Proportional Integral Controller (PI) for Shunt Active Power Filter. The main objective is to make conventional PI more adaptive by dynamically adjusting the controller gain values. The designed controller is presented to compensate for the current generation task in a non-linear shunt active filter. The performance of the proposed Fuzzy supervised PI in SAPF is evaluated through Matlab/Simulink simulation under different steady-state and transient conditions and compared with conventional PI Controller and Fuzzy-PI. The Total Harmonics Distortion (THD) of the source current after compensation is well below 5%, the harmonic limit imposed by the IEEE-519 standard.*

Keywords – *Elimination of harmonics, Shunt Active Power Filter (SAPF), PI controller, Fuzzy-PI Controller, Hysteresis Band Current controller.*

I. INTRODUCTION

Recent advancements in power electronic devices lead to roliferation of non-linear components in the grid [4]. These non-linear loads increase pollution in the power system and cause most power quality issues. Power quality is one of the major trends. It has become a consequential and growing problem due to the propagation of non-linear loads such as power electronic converters in typical power circulation systems [2]. Quality of Strength on the power supply is ever elevating due to the increase of sensitive loads [1]. The passive filtering is a simple way to eliminate the harmonic currents. However, passive filtering is not suitable for all the harmonic frequencies. But in past years, the active filter is utilized to improve power quality on the load side from the grid current by injecting compensating currents. The SAPF can be developed with a current source inverter or voltage source inverter. Generally, the voltage source inverter (VSI) is preferred for the SAPF circuit due to lower dc-side capacitor losses [3]. The conventional proportional plus integral control is probably the most commonly used technique to control the dc bus bar of SAPF. The controller is the most important part of the SAPF; much research is being conducted in this area.

The fuzzy supervised PI controller is utilized to estimate peak reference current besides maintaining the DC side capacitor voltage of the inverter nearly constant. Hysteresis band current controller is utilized to generate the switching signals for switches in the inverter. The SAPF is investigated under different steady-state and transient conditions utilizing PI, Fuzzy-PI. It is found that fuzzy supervised PI is efficacious for compensation. The proposed fuzzy supervised PI reduces ripples in the dc side capacitor. The paper is organized as follows. An overview of the PI controller in the active shunt filter is presented in section 2. The proposed Fuzzy PI controller for SAPF is discussed in section 3. Section 4 gives the experimental results of the proposed Fuzzy supervised PI controller and its comparison with the previous approaches. Finally, section 5 presents a brief conclusion of the work done.

II. PI CONTROLLER IN SHUNT ACTIVE FILTER

Non-linear loads, especially industrial loads, create harmonic currents and voltages in the power systems [4]. Nowadays, various active power filters (APF) have been developed to suppress the harmonics and compensate for reactive power so that the utility grid will supply sinusoidal voltage and current [4]. Balancing of harmonics in non-linear loads is done using SAPF. SAPF is to compensate current harmonics by injecting an equal magnitude of opposite sign harmonic compensating current. In this case, SAPF operates as a current source injecting the harmonic components generated by the load but phase-shifted by 180^0 [2]. This principle applies to any loads.

Moreover, with a reasonable control scheme, the active power filter can additionally compensate for the load power factor. In this manner, the power distribution system visually perceives the non-linear load and the active power filter as an ideal resistor. The current compensation characteristics of the shunt active power filter shown in fig.1.the main components of the active shunt filter are described in the following section.

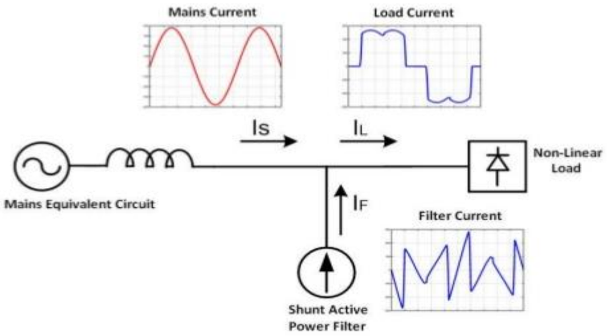

Fig.1.Compensation characteristics of a SAPF

A. Voltage Source Inverter

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

- Hysteresis current control method
- Sinusoidal Pulse Width Modulation (SPWM) Control
- Space Vector PWM Control (SVPWM)

B. Hysteresis Current Control Method

The current control strategy provides a major role in the fast response of inverters in active power filters. This hysteresis current control strategy 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 functional derivative of the output current [5]. The fig.2 below represents the voltage waveform of the hysteresis current control method.

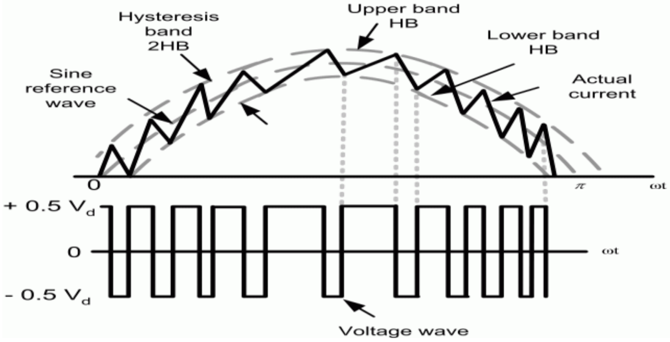

Fig.2 Hysteresis Current Control

This approach consists of a PI controller, a limiter, and a three-phase sine wave generator for the current generation and generation of switching signals. The maximum peak value of reference currents is estimated by regulating the DC link voltage. The genuine capacitor voltage is compared with a set reference value [7]. The error signal is manipulated through a PI controller, contributing to zero steady error in tracking the reference current signal. The output of the PI controller is considered as the maximum peak value of the supply current (Imax), which is composed of two components: (a) fundamental active power component of load current and (b) loss component of APF to maintain the average capacitor voltage to a persistent value. The maximum peak value of the current (Imax) is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating. These estimated reference currents (Isa*, Isb*, Isc*) and sensed genuine currents (Isa, Isb, Isc) are compared at a hysteresis band, which gives the gating signal for modulation technique[2]. This gating signal decides the operation of the converter switches. In this current control circuit configuration, the source/supply currents Is_{abc} are made to follow the sinusoidal reference current Iabc within a fine-tuned hysteretic band. The hysteresis window width determines the source current pattern, harmonic spectrum, and switching frequency of the devices. The DC-link capacitor voltage is kept ideal throughout the operating range of the converter. Each phase of the converter is controlled independently.

The transfer function of the PI Controller is represented as

$$H(s)=K_P+K_I/S \qquad (1)$$

Kp is the proportional constant that determines the dynamic response of the DC-side voltage control, and Ki is the integral constant that determines it's settling Time. The proportional-integral controller eliminates the steady-state error in the DC- side voltage.

III. PROPOSED FUZZY-PI CONTROLLER FOR SAPF

A. Fuzzy

Fuzzy logic is a problem-solving control technique in control system engineering. Zadeh developed the concept of fuzzy logic in 1965. The first fuzzy controller developed by Mamdani and Pappis in 1977 was a steam engine controller and later fuzzy traffic lights[8]. The FLC design shown in Figure 3 can be normally divided into three areas: allocation of the fuzzification area into a linguistic value, a fuzzy Inference system(creation of rules), and defuzzifying into a real value.

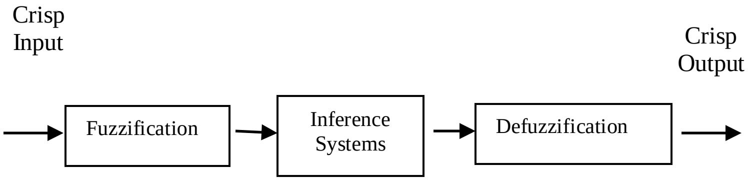

Fig.3. Fuzzy Logic Controller

B. Fuzzification

The FLC's first component is the fuzzifier that transforms crisp inputs into a set of membership values in the interval [0,1] in the corresponding fuzzy sets. The membership function shapes are typically triangular, trapezoidal, and Gaussian. In these membership functions, Gaussian M[illegible] good robustness than other membership functions. Gau[illegible] membership function inputs are error (e) and its char[illegible] error (Δe) with fuzzy labels NB (negative big), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive medium) and PB (positive big). The membership functions' corresponding outputs are propagation gain (KP) and integration gain (KI) for respective input labels.

Crisp
Output

C. Rule Elevator

FLC uses linguistic variables instead of numerical values. The basic FLC operation uses the following fuzzy set rules to control the system.

AND–Intersection $\mu A \cap B = \min[\mu A(X), \mu B(X)]$ (2)

OR–Union $\mu A \cup B = \max[\mu A(X), \mu B(X)]$ (3)

Defuzzification:

According to real-world requirements, FLC rules generate the required output in a linguistic variable (Fuzzy Number). Linguistic variables have to be transformed into crisp output (Real number).

$\mu A(x) = \text{defuzz}(x, mf, type)$ (4)

According to the argument, defuzz (x, mf, type) returns a defuzzified value out of a membership function (MF) positioned at associated variable value x, using several defuzzification strategies. The variable type can be one of the following:

- Centroid method
- Max-membership principle
- Weighted average method
- Mean-max membership
- Center of sums
- Center of the largest area
- First of maxima, last of maxima

D. Entroid method

Centroid defuzzification returns the center of the area under the curve. Mathematically centroid of area (COA) can be expressed as:

$$COA = \frac{\sum_{i=1}^{\infty}(\mu A(Xi) \times Xi)}{\sum_{i=1}^{\infty}\mu A(Xi)} \quad (5)$$

E. Database

The Database keeps the definition of the Gaussian membership function, which is required by fuzzifier and defuzzifier.

F. Rule-Based

The Rule base stores the linguistic control rules required by the rule evaluator (decision-making logic). The rules used in this proposed controller [9][10][11].

G. Fuzzy-PI

The conventional PI controllers' parameters are necessary to tune the non-linear plant with unpredictable parameter variations automatically. The fuzzy system is a formal methodology for implementing a human's heuristic knowledge obtained from any system experience. A self-tuning fuzzy PI controller can be designed to reduce the effect caused by the parameter variations and achieve high performance of systems. The block diagram of the proposed self-tuning fuzzy PI controller for the SAPF is shown in fig 4.

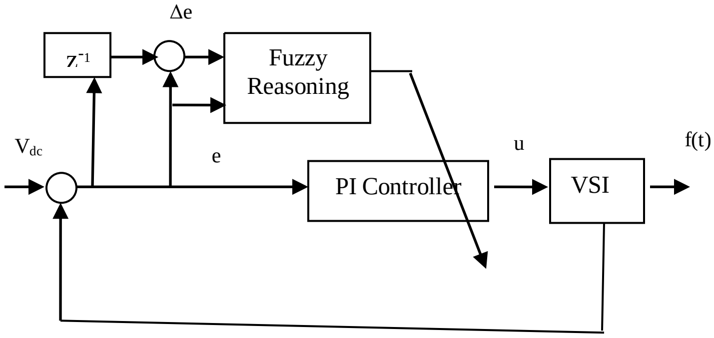

Fig.4.Fuzzy-PI Controller

To develop the fuzzy-PI control algorithm for APF, two inputs: 1) error 2) the change in error were considered over one sample period. The two inputs were represented by sets of seven membership functions and expressed in linguistic values as negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB). The shape of these membership functions was varied, and the effect on the system was studied. The two outputs set KP and KI of seven membership functions are also expressed in linguistic values as negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB) and the range for the "KP" output was set as[0.1 1] and that for "KI" was set as[0 300]. The input and output MFs so applied are shown in

Fig. 5-8. The 49 fuzzy IF-THEN rule base was designed to maintain the capacitor voltage constant by providing the required reference current amplitude. The AND method used during the IF-THEN rules interpretation was “minimum,” and this method represented as implication method. The final function of defuzzification is obtained by the centroid method. The output of the fuzzy-logic controller was given to the PI controller as it’s gain values. Any load changes, then the Kp and Ki will change by following it. The PI controller's output is a control signal to drive the inverter, which directly drives the capacitive voltage (Vdc).

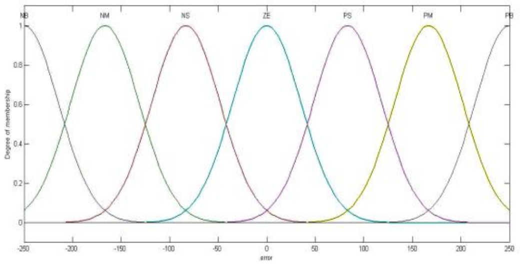

Fig 5.Gaussian membership function for input variable “error."

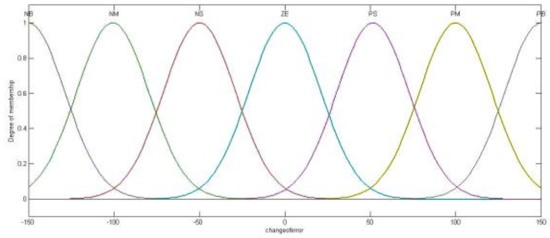

Fig.6.Gaussian membership function for input variable “change of error."

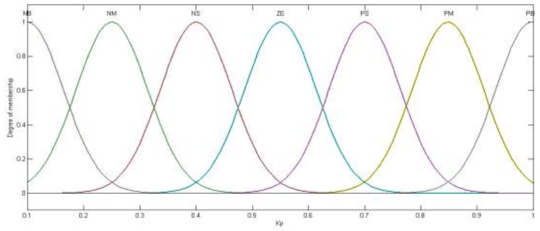

Fig.7.Gaussian membership function for output variable“K_P.”

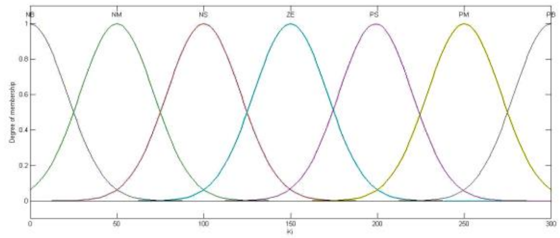

Fig.8.Gaussian membership function for output variable“K_I.”

Table 1. Fuzzy control rule K_P

Er/ CEr	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

Table 2. Fuzzy control rule for K_I

Er/ CEr	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	ZE	NM	NS	ZE
NM	PB	PB	PB	ZE	NS	ZE	PS
NS	PB	PB	PM	ZE	ZE	PS	PM
ZE	PB	PM	PS	ZE	PS	PM	PB
PS	PM	PS	ZE	ZE	PM	PB	PB
PM	PS	ZE	NS	ZE	PB	PB	PB
PB	PS	NS	NM	ZE	PB	PB	PB

IV. SIMULATION RESULTS

The performance of the PI and Fuzzy-PI are analyzed using MATLAB/Simulink Software. The system parameters and values of PI and Fuzzy-PI Controller are represented in below Table 3.

Table 3. System Parameters

System Parameters	Value
Source Voltage(Vs), frequency	311.12V, 50Hz
Source Resistance(R_S)	0.1Ω
Source Inductance(L_S)	1mH
Load Resistance(R_L)	15 Ω
Load Inductance(L_L)	60mH
Filter resistance(R_F)	0.01 Ω
Filter Inductance(L_F)	1 mH
DC link Capacitance(C_{DC})	3000µF
DC link Voltage(V_{DC})	800V

Case I: PI Controller

PI based SAPF system simulation results are verified and presented. Theservo response and regulatory response of source voltage, source current, filter current and load current are shown in fig.9 and fig.10. Also the servo response and regulatory response of Vdc using the PI controller is examined and which are shown in fig.11 and fig.12 respectively. The harmonic analysis is shown in fig.13.

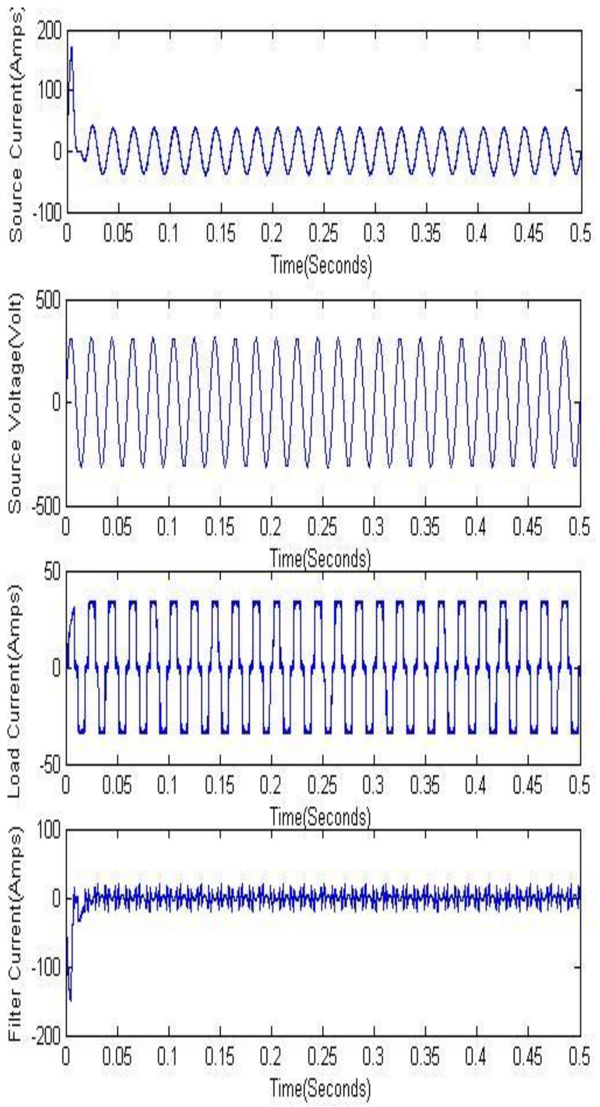

Fig 9. Servo Response of the system after compensation using a PI control algorithm

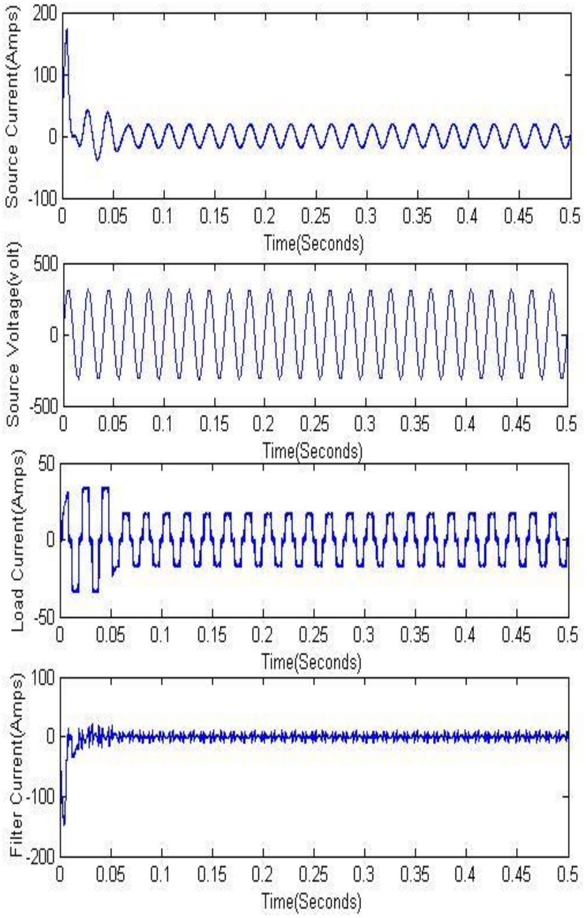

Fig 10. The regulatory response of the system after compensation using a PI control algorithm

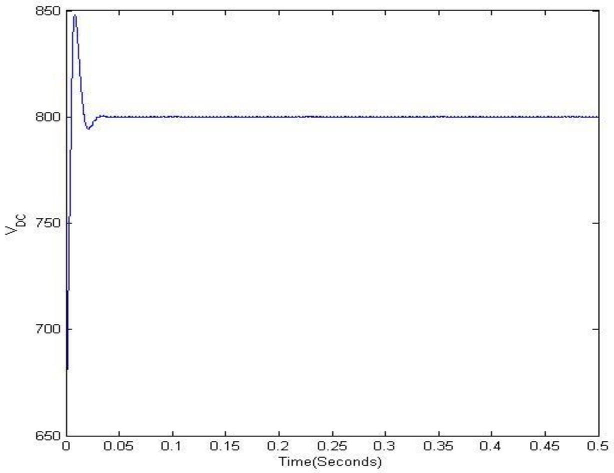

Fig.11. Vdc waveform of SAPF using PI controller servo response

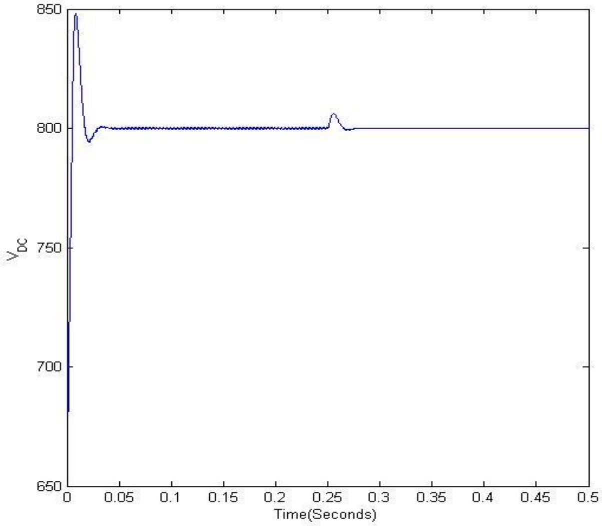

Fig.12. Vdc waveform of SAPF using PI controller-regulatory Response

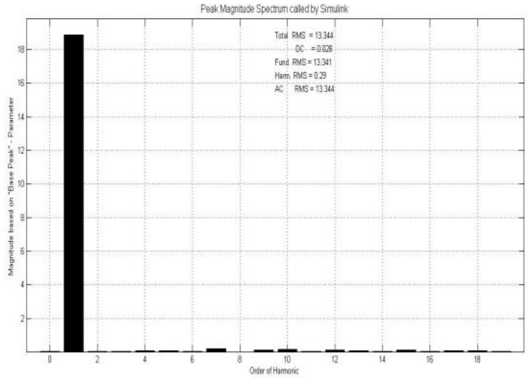

Fig 13. Harmonic analysis of source current after compensation using a PI control algorithm

Case II: Fuzzy-PI Controller

Fuzzy-PI-based SAPF system simulation results are verified and presented. The servo response and regulatory response of source voltage, source current, filter current, and load current is shown in fig.14 and 15. Also, the servo response and regulatory response of Vdc using the PI controller are examined and which are shown in fig.16 and fig.17, respectively. The harmonic analysis is shown in fig.18.

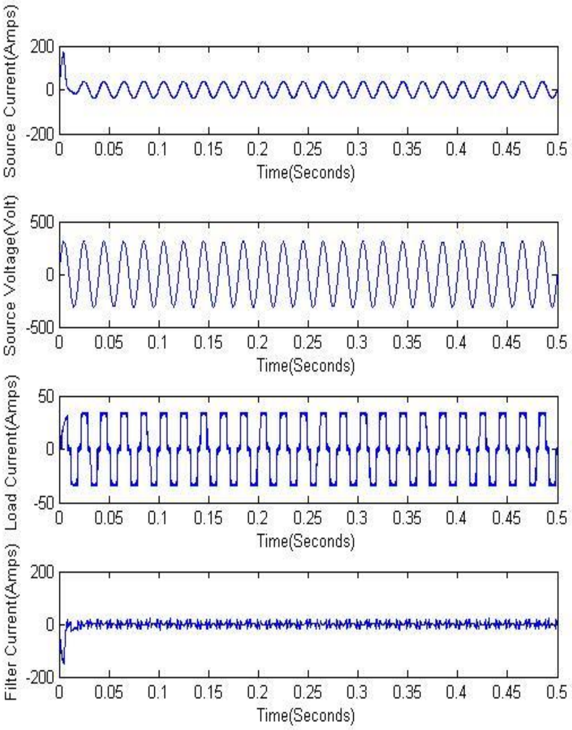

Fig 14.Servo response of the system after compensation using Fuzzy-PI control algorithm

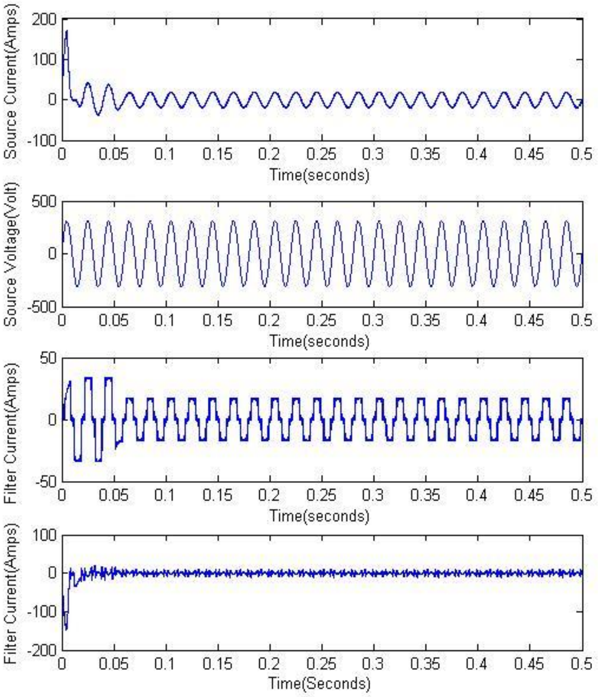

Fig 15. The regulatory response of the system after compensation using Fuzzy-PI control algorithm

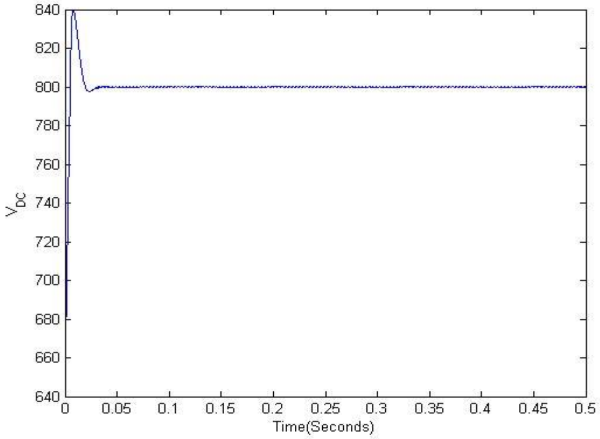

Fig 16Vdc waveform of SAPF using Fuzzy-PI controller servo response

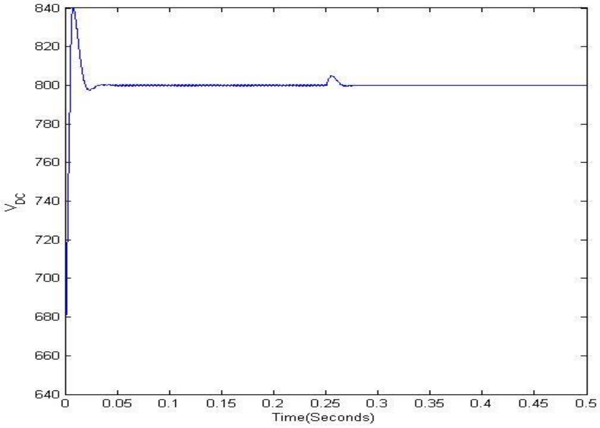

Fig.17. Vdc waveform of SAPF using Fuzzy-PI controller-regulatory response

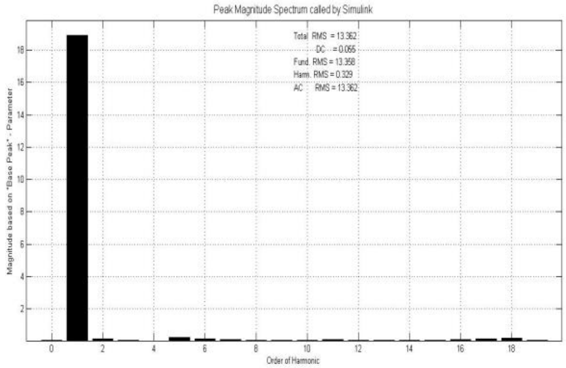

Fig 18. Harmonic analysis of source current after compensation using Fuzzy-PI control algorithm

Performance Comparison:

We found that the THD is reduced from 27.2% to 2.438% with the Fuzzy-PI controller, which is well within the permissible limit of 5% as recommended by IEEE-519 standard, and it improves the active filter performance in comparison with the PI controller

Table 4. Compression PI and Fuzzy-PI Controller

Controller	Performance index			
	THD (%)	Rise Time(sec)	Peak Over Shoot (%)	Settling Time(micro sec)
PI	2.438	0.0081	6.25	0.42
Fuzzy-PI	2.46	0.0072	5	0.35

V. CONCLUSION

The Fuzzy-PI-based SAPF system's proposed scheme mitigates the harmonic distortions in the line current (value below the level prescribed in IEEE standard-519-1992) in a three-phase supply system. Generated Switching signals from fuzzy-PI controller drives the voltage source inverter better than normal PI. From the simulation results, it is observed that the fuzzy-PI controller has lesser overshoot, settling Time THD, and dynamically adjusts the gain of a PI controller. Hence, it performs better than the conventional PI controller under the steady-state and dynamic state of the SAPF. As the power system is of high dynamics in the real-life implementation of FUZZY, Supervised PI will be better to mitigate harmonics.

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