

# Fuzzy Tuned PI based Shunt Hybrid Power Filter for Power Quality Improvement

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## Abstract

**Objective:** This paper explores the power condition abilities of Shunt Hybrid Power Filter (SHPF) with fuzzy tuned PI based control method in a distribution system. **Method:** A fuzzy tuner is proposed in this paper for tuning the parameters of proportional plus integral (PI) controller so that to improve the performance of the SHPF. The compensation process is based on source current sensing only. Synchronous Reference Frame (SRF) theory is used for generating reference currents, whereas linear current controller has been used to track these reference currents. Space Vector Pulse Width Modulation (SVPWM) has been employed to obtain the switching signals required for Voltage Source Converter (VSC). **Findings/Improvements:** Simulation analysis has been carried out to assess the performance of proposed control scheme. The simulation analysis proved that shunt hybrid power filters to be a potent solution for compensating the harmonics and reactive power of the distribution system. From the Simulation results, total harmonic distortion (THD), steady state response and dynamic behavior of the fuzzy tuned PI controller based SHPF is found to be better than conventional PI controller.

**Keywords:** Fuzzy tuned to PI, Reactive Power, SHPF, SRF, SVPWM, Total Harmonic Distortion (THD)

## 1. Introduction

Power Quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage. The widespread increase in renewable energy generation, increased usage of power electronic equipment and nonlinear loads for the industrial and commercial applications, has increased the harmonic distortion levels in the end use facilities and on the overall power system. On the other hand, the demand for clean power supply is increasing for sensitive loads such as medical electronic equipment and automated processes<sup>1,3</sup>. This demand has led to the advancement of various harmonic mitigation techniques<sup>3-8</sup>.

The most basic method of harmonic mitigation is to use Passive LC filters. The tuned LC filters are connected in parallel to harmonic generating load/source. The tuned LC filters exhibit low impedance at tuned

frequency<sup>3</sup>. Because of their simplicity, low cost and high efficiency passive filters have been used in the power system to absorb the harmonics. But passive filters are bulky in nature<sup>4</sup>. Installing passive filter for each and every dominant harmonic component is difficult and rigorous. Multiple passive filters connected to utility might cause series and parallel resonance in the power system. To overcome the aforementioned issues, active power filters have been proposed in the literature. To mitigate the harmonic components, active power inject equal and opposite components there by cancelling original harmonics. For current harmonic mitigation an active power filter (APF) connected in parallel with load is used<sup>5</sup>. The shunt APF is operated in closed loop, such that to force the source current to be free of harmonics and at unity power factor (UPF). But they are limited by high maintenance, high cost, low power to volume ratio and difficulty in operating under high voltage conditions.

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Hybrid Active Power Filter (HAPF) is the better solution for the harmonic issue. Hybrid active power filter incorporate compensation characteristics of both passive and active filters. The HAPFs are designed to improve the performance of active filters by combining with passive filters. The Control strategy of SHPF is the key element for its successful performance in improving the power quality and is implemented in various stages <sup>6</sup>. First stage is generation of reference compensation current signal and the second stage is to track the current signal to generate switching signals to drive the converter. Numerous control techniques have been reported in the literature for active and hybrid active filters <sup>5-9</sup>. Instantaneous reactive power theory based reference current generation is one of the most used methods because of which it avoids park transformation [8]. However this method uses a high pass filter which creates delay in the reference current and to nullify this delay, phase lead or phase lag compensator need to be used. While the other method based on synchronous reference frame theory using park transformation doesn't require low pass or high pass filters <sup>2</sup>. These conventional reference current generation techniques use linear controller which need accurate model of the system. To overcome these problems, intelligent control methods have been developed, like fuzzy logic controllers and artificial neural networks <sup>10-13</sup>. Among the various current control methods, two methods are often used. One is non linear current control and another one is linear current control. Non linear controllers such as hysteresis controllers are used to regulate the converter current through saturation limit for the current signal. Hysteresis controller doesn't need additional pulse width modulator to drive the inverter. Hysteresis controllers are easy to implement but operate at varying switching frequency. Linear current controllers are designed using linear mathematical model of the plant. They are followed by a pulse width modulator, can be sine based or space vector based. Linear current controllers are robust and have modularity.

To make the Shunt hybrid Power filter more dynamic and robust, a fuzzy tuned PI controller is used for reference current generation thereby making use of synchronous reference frame theory. A linear current controller has been used for current control. To effectively utilize the DC side capacitor voltage Space Vector Pulse Width Modulation (SVPWM) has been used to drive the converter. The performance of the proposed control method

is assessed through simulation analysis under steady state and dynamic conditions.

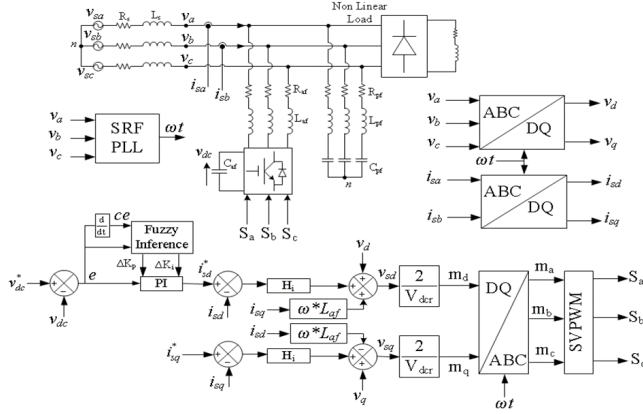
## 2. Shunt Hybrid Power Filter and its Proposed Control Scheme

Figure 1 shows the schematic diagram and control structure of proposed SHPF. The main purpose of the SHPF is to do current harmonic mitigation and reactive power compensation of the load. Figure 1 also illustrates the proposed control scheme for the SHPF. D and Q axis currents are regulated separately. To obtain the information of phase and amplitude of source voltage vector, Phased Locked Loop (PLL) has been used. SRF-PLL, most commonly used in the grid connected converters <sup>[14-15]</sup>, has been used for synchronizing the converter. In the SRF-PLL, by synchronizing PLL reference frame vector to grid voltage vector, the instantaneous phase angle  $\theta$  or  $\omega t$  is determined.

The control strategy employs outer voltage loop (to control DC link voltage) with inner current loop (to control source currents). The current loop is very fast compared to the voltage loop so that inner current loop can trace the references generated by outer voltage loop. The inner current loops regulate the active and reactive currents in Synchronous Reference Frame (SRF) which is aligned to source voltage vector. The active and reactive currents are controlled independently. Most of the cases the loads are lagging reactive loads. While the converter is injecting reactive power to the power system the fundamental voltage at the inverter terminals ( $V_{s1}$ ) should be more than PCC voltage ( $V_{pcc}$ ), which demands high voltage on dc side ( $V_{dc}$ ). But the DC link voltage is limited by insulation levels and DC side capacitor specifications. To achieve satisfactory operation even under lesser DC link voltages, Space Vector Pulse Width Modulation (SVPWM) has been used.

For appropriate control of SHPF in closed loop, the DC link capacitor voltage ( $V_{dc}$ ) is sensed and compared with reference value ( $V_{dc}^*$ ). The error  $e(V_{dc}^* - V_{dc})$  obtained and change in error ( $ce(n) = e(n) - e(n-1)$ ) at  $n^{th}$  sampling instant are given to Fuzzy inference mechanism. The fuzzy process generates desired adjustments to the  $K_p$  and  $K_i$  values. The fuzzy adjusted or tuned PI controller generates d-axis source current ( $i_{sd}^*$ ) to inner current loop. The inner current loop generates modulation signals in dq domain. The modulation signals are further transformed

back to stationary coordinates and fed to SVPWM block which drives converter switches. Cross coupling terms are added at the output of current controller to decouple d and q axis currents. As the d-axis is aligned to grid voltage vector ( $V_q = 0$ ), for UPF operation  $I_q^* = 0$ .



**Figure 1.** Proposed Control Scheme for the Shunt Hybrid Power Filter

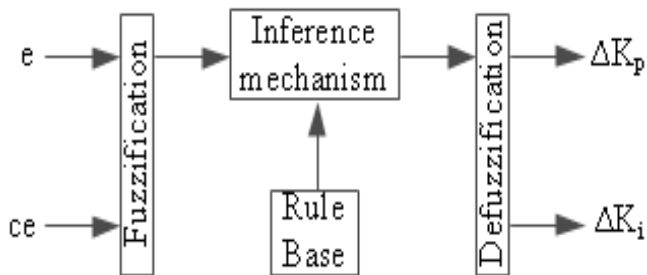
## 2.1 Fuzzy Tuner

The fuzzy tuner is used to auto tune the coefficients of proportional and integral controllers based on the error ( $e$ ) and change in error ( $ce$ ).

$$K_p = K_p^* + \Delta K_p \quad (1)$$

$$K_i = K_i^* + \Delta K_i \quad (2)$$

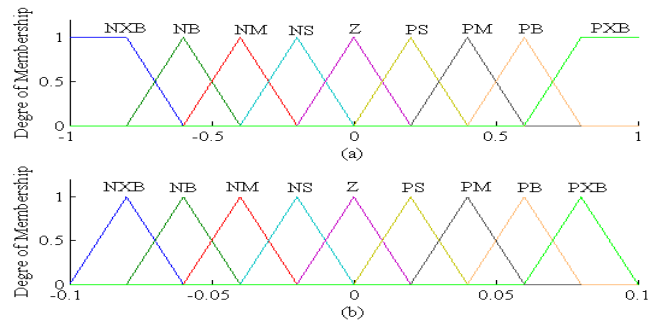
Where  $K_p^*$  and  $K_i^*$  are predesigned parameters for voltage loop proportional and integral controllers respectively. In the present work  $K_p^*$  and  $K_i^*$  are determined through loop shaping method. Fuzzy logic controller doesn't require the mathematical model of the system for its implementation. However, in a fuzzy logic controller, the control action is governed by the evaluation of a set of basic linguistic rules<sup>16</sup>. The linguistic rules are configured based on heuristic information of the plant to



**Figure 2.** Block Diagram of Fuzzy Tuner

be controlled. With proper design of fuzzy logic tuner, improved system stability and dynamic performance can be achieved.

The block diagram of fuzzy logic tuner is depicted in Figure 2. The fuzzification block converts the real world crisp inputs to fuzzy sets. In order to convert the crisp inputs from the real world to linguistic variables, nine linguistic values are chosen. The ranges of linguistic variables  $e(n)$ ,  $ce(n)$ ,  $\Delta K_p$  and  $\Delta K_i$  are acquired based on SHPF parameters and heuristic experience. The membership functions, which describe the certainty of real quantity to linguistic values, will be used in fuzzification and defuzzification. Figure 3 shows the normalized membership functions for the input and output variables.



**Figure 3.** Membership Functions for the fuzzy variables. (a) Membership Function of  $e(n)$  and  $ce(n)$ . (b) Membership function of  $\Delta K_p$  and  $\Delta K_i$

The heart of fuzzy logic control is the fuzzy linguistic rule, which is acquired mainly from the intuitive feeling and experience of the plant. Table 1 shows the fuzzy control rule table. The elements of this rule table are obtained based on the knowledge of the filter behavior in the dynamic and steady state. The fuzzy linguistic rules are saved in the rule base. The inference mechanism uses the fuzzy linguistic rules in the rule base to produce fuzzy conclusions (concluded fuzzy sets). The defuzzification block converts these concluded fuzzy sets into the crisp outputs. The Center of Gravity (COG) method has been used for defuzzification.

## 3. Simulation Results

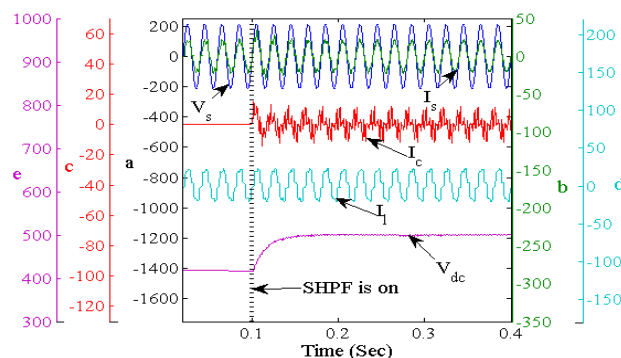
To verify the feasibility of the proposed control strategy, the SHPF has been simulated using MATLAB-SIMULINK environment. The main electrical parameters of the power circuit and control data are mentioned in the table. The Passive Power Filter (PPF) is tuned to offer

**Table 1.** Fuzzy Control Rule Table

| Error (e) | Change in Error (ce) |     |     |     |     |     |     |     |     |
|-----------|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|
|           | NXB                  | NB  | NM  | NS  | Z   | PS  | PM  | PB  | PXB |
| NXB       | NXB                  | NXB | NXB | NXB | NXB | NB  | NM  | NS  | Z   |
| NB        | NXB                  | NXB | NXB | NXB | NB  | NM  | NS  | Z   | PS  |
| NM        | NXB                  | NXB | NXB | NB  | NM  | NS  | Z   | PS  | PM  |
| NS        | NXB                  | NXB | NB  | NM  | NS  | Z   | PS  | PM  | PB  |
| Z         | NXB                  | NB  | NM  | NS  | Z   | PS  | PM  | PB  | PXB |
| PS        | NB                   | NM  | NS  | Z   | PS  | PM  | PB  | PXB | PXB |
| PM        | NM                   | NS  | Z   | PS  | PM  | PB  | PXB | PXB | PXB |
| PB        | NS                   | Z   | PS  | PM  | PB  | PXB | PXB | PXB | PXB |
| PXB       | Z                    | PS  | PM  | PB  | PXB | PXB | PXB | PXB | PXB |

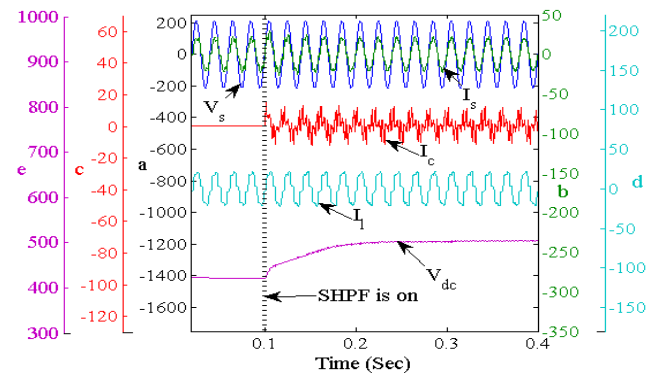
low impedance at 5<sup>th</sup> harmonic component. An inductive load is used as a low power factor load and a three phase diode rectifier with an RL load was used as harmonic generating load. The values of  $K_p$  and  $K_i$  for reference current generation are respectively. Simulation results with the conventional PI controller and with the Fuzzy tuned PI controller are presented in Figures 4 and 5 respectively.

Figure 4 depicts the response of SHPF with Fuzzy tuned PI controller. The hybrid filter is turned on at 0.1sec. It is seen that the DC side capacitor voltage reached its set value within 0.06sec (3 cycles). It has been also observed that soon after switching on the hybrid filter the source is in phase with source voltage. Since the Passive filter is tuned for 5<sup>th</sup> harmonic component, it is observed that the 5<sup>th</sup> harmonic in the source current is nullified. Figure 5 shows the response of SHPF with conventional PI controller with the SHPF switching on at 0.1sec. It is observed that the DC link voltage took 0.14sec (7 cycles) to attain its set value.



**Figure 4.** Switch on Response of Fuzzy Tuned PI Based SHPF  
a (Dark Blue):- Source Voltage ( $V_s$ ) in volts, b (Green)  
:- Source Current ( $I_s$ ) in Amps, c (Red) :- Compensator

Current ( $I_s$ ) in Amps, d (Sky Blue) :- Load Current ( $I_s$ ) in Amps, e (Dark Blue):- DC Side Voltage ( $V_{dc}$ ) in volts



**Figure 5.** Switch on Response of Conventional PI Based SHPF

a (Dark Blue):- Source Voltage ( $V_s$ ) in volts, b (Green)  
:- Source Current ( $I_s$ ) in Amps, c (Red) :- Compensator  
Current ( $I_c$ ) in Amps, d (Sky Blue) :- Load Current ( $I_s$ ) in  
Amps, e (Dark Blue):- DC Side Voltage ( $V_{dc}$ ) in volts

**Table 2.** Parameters of System

| Parameter                  |                                  | Value        |
|----------------------------|----------------------------------|--------------|
| Source Voltage( $V_s$ )    |                                  | 150V         |
| Frequency( $F_s$ )         |                                  | 50Hz         |
| Source Inductance( $L_s$ ) |                                  | 1.5mH        |
| Source Resistance( $R_s$ ) |                                  | 0.1 $\Omega$ |
| Non-Linear Load            | Resistance ( $R_d$ )             | 20 $\Omega$  |
|                            | Inductance ( $L_d$ )             | 6mH          |
| Passive Filter             | Capacitance ( $C_{pf}$ )         | 12.5 $\mu$ F |
|                            | Inductance ( $L_{pf}$ )          | 32.5mH       |
|                            | Internal Resistance ( $R_{pf}$ ) | 0.1 $\Omega$ |

|                     |                                        |              |
|---------------------|----------------------------------------|--------------|
| Active Power Filter | Switching Frequency ( $F_{sw}$ )       | 20kHz        |
|                     | Input Inductor ( $L_{af}$ )            | 8.5mH        |
|                     | Input Inductor Resistance ( $R_{af}$ ) | 0.1 $\Omega$ |
|                     | DC Link Voltage ( $V_{dc}$ )           | 500V         |
|                     | DC Side Capacitor ( $C_{dc}$ )         | 1300 $\mu$ F |

Table 2 shows the parameters of the system used in simulation. On the basis of simulation results, important parameters for the conventional PI and fuzzy tuned PI controllers presented in Table 3 and Table 4. It is oblivious from the simulation results that dynamic performance of the DC side capacitor voltage and source current is improved with fuzzy tuned PI controller compared to the general PI controller. The steady state performance is also slightly improved with the fuzzy tuned PI controller compared to that of conventional PI controller.

**Table 3.** Harmonic Current of Load and Source currents at 14.9A(Fundamental) Load Current

| Harmonic Order | Load Current ( $I_L$ ) in A | Source Currents( $I_s$ ) in A |                                |
|----------------|-----------------------------|-------------------------------|--------------------------------|
|                |                             | With PI Controller            | With Fuzzy tuned PI Controller |
| 1              | 14.83                       | 14.53                         | 14.48                          |
| 5              | 2.85                        | 0.0565                        | 0.02828                        |
| 7              | 1.25                        | 0.106                         | 0.01414                        |
| 11             | 0.87                        | 0.2262                        | 0.191                          |
| 13             | 0.55                        | 0.205                         | 0.205                          |
| 17             | 0.346                       | 0.29                          | 0.275                          |
| 19             | 0.254                       | 0.035                         | 0.042                          |
| <b>THD</b>     | 25.26                       | 3.82                          | 3.56                           |

**Table 4.** Dynamic response parameters

| Parameter                        | PI Controller | Fuzzy PI Controller |
|----------------------------------|---------------|---------------------|
| Settling Time                    | 0.14          | 0.06                |
| Vdc Peak to Peak Ripple at 14.9A | 2.2V          | 1.9V                |

## 4. Conclusion

A fuzzy tuned PI controller based Shunt Hybrid Power Filter has been studied to improve the power quality by mitigating harmonics and reactive power demand of the nonlinear load. The performance of the fuzzy tuned PI controlled SHPF has been investigated and compared

with conventional PI controller. It is evident from the simulation results that the compensation process is based on source current sensing only. It has been observed that fuzzy tuned PI controller have better transient response compared to a conventional PI controller. It is also seen that steady state response also slightly improved with the proposed method. The Harmonic Distortion (THD) of the line currents after compensation is below 5%, the harmonic limit imposed by the IEEE – 519 regulations.

## 5. Acknowledgement

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