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Fuzzy and PSO tuned PI controller based SAPF for Harmonic Mitigation

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ABSTRACT- The development of a reliable power filter is essential for meeting the need for high-quality power. Current and voltage harmonics are a major contributor to poor power quality and must be eliminated. Shunt active power filters (SAPFs) can be installed to reduce the negative effects of harmonics. Fuzzy logic and proportional integral (PI) controllers excel at regulating DC link voltage in shunt active power filters (SAPFs). This research assessed how well Particle Swarm Optimization controls the DC link voltage in a Shunt Active Power Filter (SAPF), thereby mitigating harmonics. The appropriate PI control parameters are first determined using the Particle Swarm Optimization technique. The PSO-tuned PI parameters are combined with a fuzzy logic controller for the SAPF simulation. It has been demonstrated in simulations that a Shunt Active Power Filter (SAPF) with reference currents are generated in accordance with the instantaneous real and reactive power (p-q) theory, employing fuzzy and PSO -PI controller for diode rectifier type non-linear load. It is extremely effective for harmonic correction in distribution networks. The simulation work is carried out using MATLAB-SIMULINK.

Keywords: Hysteresis Current Controller, p-q theory, PSO, diode rectifier, and Shunt Active Power Filter.

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1. INTRODUCTION

Waveforms in the energy supply system have changed in recent years [1] due to the growing prevalence of power electronics and additional non-linear electric loads, because of the harmonics they produce. The generation of harmonics by non-linear loads is the root cause of inefficiency. Power loss, and interference with surrounding communication networks. The total harmonic distortion (THD) of the source current exceeds the 5% limit defined by IEEE - 519 [2]. In 1983, the instantaneous power theory (p-q theory) was developed by Akagi, Kanazawa, and Nabae as a means of restricting harmonics (Akagi et al (1983)),[3].Large component sizes, constant compensation, and the tendency to resonate with supply impedance are some of the drawbacks of using passive filters to reduce harmonic distortion [4],[5]. To reduce the harmful effects of harmonics brought on by nonlinear loads, the optimal shunt active power filter system was designed. In accordance with the instantaneous power theory, it emphasises the importance of the device used for harmonics selecting from observed values. It is responsible for generating the compensation currents. A number of researches have looked into the use of an active filter in conjunction with a diode rectifier in a non-linear load [6] design. Combining the best features of passive and active filters, hybrids are a relatively recent development [7]. Several studies employing Fuzzy logic HCC controller [8], optimization methods to determine the optimal values for Kp and K_i have been reported in the scientific literature [9],[10]. By optimising the filter to achieve the lowest feasible THD value, more non-linearity may be tolerated by the supply system. From the literature the impact of changing Kp and K_i on the THD and try to determine the best setting for this PI controller. In 1995, Dr. Kennedy and Ebehart [11] created a method called particle swarm optimization (PSO) to find a value with the lowest total harmonic distortion (THD). In several other research [12],[13], the PSO methodology was proved to be an excellent tool for optimising active filters. A harmonic filter can either be a Shunt Active Filter or a Series Active Filter. The filter's layout and how it is wired are the main distinguishing features. [14]. When used in conjunction with other methods, a Shunt Active Power Filter (SAPF) may enhance voltage quality and decrease current harmonics in a power grid [15]. In this research, development of a SAPF coupled to a diode rectifier driving a nonlinear load to mitigate current harmonics, in this work combination of fuzzy and PSO tuned pi controller can be used as controller for SAPF. In order to lower harmonics in the system, SAPF monitors load current and generates compensatory current.[16].

2. SAPF OPERATION

An example of the primary SAPF compensation concept is presented in *figure 1*. Without SAPF, harmonics in the source and load currents are proportional to one another (i.e., their signatures are same). After being connected into the PCC, the SAPF injects a compensating current that is precisely regulated to cancel out any harmonics in the supply current. From *eq. (1)*, the grid voltage [17] can calculated:

$$v_s(t) = v_m \sin \omega t \tag{1}$$

The instantaneous value of grid current from eqn (2)

$$i_s(t) = i_L(t) - i_c(t) \tag{2}$$

The load current which is having fundamental and harmonic component from Eqn(3)

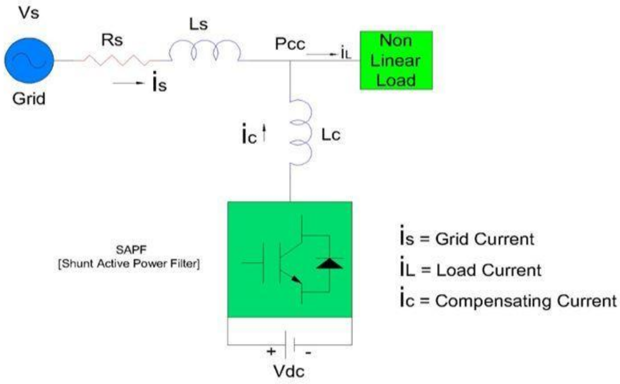

Figure 1: Schematic diagram of SAPF

$$\begin{aligned} i_L(t) &= \sum_{k=1}^{\infty} i_k \sin(n\omega t + \emptyset_k) \\ &= i_1 \sin(\omega t + \emptyset_1) \\ &+ \textstyle\sum_{k=2}^{\infty} i_n \sin(k\omega t + \emptyset_k) \end{aligned} \tag{3}$$

The power at load side which is multiplication of source voltage and load current from *eq. (4).*

$$\begin{aligned} p_L(t) &= v_s(t) * i_L(t) \\ &= v_m i_1 \sin^2 \omega t * \cos \phi_1 \\ &+ v_m i_1 \sin \omega t * \cos \omega t * \sin \phi_1 \\ &+ v_m \sin \omega t * \textstyle\sum_{k=2}^{\infty} i_n \sin(k\omega t + \phi_k) \end{aligned} \tag{4}$$

$$p_L(t) = p_f(t) + p_r(t) + p_h(t) \tag{5}$$

Where, $p_f(t)$ - fundamental power, $p_r(t)$ - reactive energy and $p_h(t)$ -harmonic power.

$$\begin{aligned} p_f(t) &= v_m i_1 \sin^2 \omega t * \cos \phi_1 \\ &= v_s(t) * i_s(t) \end{aligned} \tag{6}$$

Also, the grid current provided from *eq. (5)* after correction is given in *eq. (6)*

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = i_1 \cos \phi_1 \, sin \, \omega t \quad = i_{sm} \sin \omega t \tag{7}$$

Where

$$i_{sm} = i_1 \cos \phi_1$$

The Active power loss must be taken into consideration because the inverter has high-frequency switches. Finally, SAPF will inject compensation current at PCC given in *eq. (7).*

$$i_c(t) = i_L(t) - i_s(t) \tag{8}$$

3. P-Q THEORY

This is an example of a well-defined SAPF control method for generating reference compensation currents [18]. *Figure 2* below depicts the estimated reference current based on instantaneous active and reactive power.

H. Akagi and colleagues first proposed this theory, which use the Clarke transformation to translate a-, b-, and c-coordinate three-phase current and voltages into -coordinates. [19].

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{10}$$

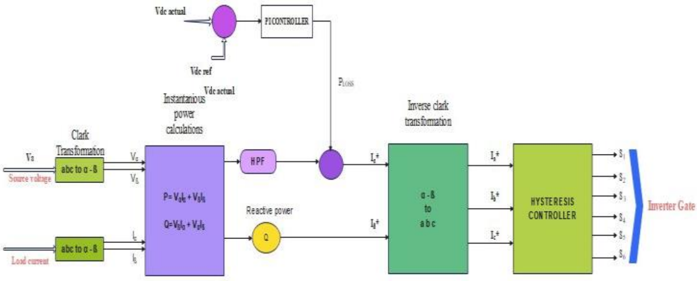

Figure 2: Diagram of the P-Q control theory

The instantaneous power is given in *eq. (9)*

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{11}$$

The total power consists of ac component and dc component as given in *eq. (10)*

$$\text{p} = \bar{p} + \tilde{p} \tag{12}$$

In which the dc value p and the ac value $\tilde{p}$ are respectively used. Reference current may be determined using the following *equation*.

$$\begin{bmatrix} i_{c\alpha} * \\ i_{c\beta} * \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{13}$$

$$p = \tilde{p} + P_{\text{loss}} \tag{14}$$

Where P_{loss} is the active power loss component in the filter

$$\begin{bmatrix} i_{ca} * \\ i_{cb} * \\ i_{cc} * \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/\sqrt{2} & -\sqrt{3}/2 \\ -1/\sqrt{2} & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{c\alpha} * \\ i_{c\beta} * \end{bmatrix} \tag{15}$$

Use the above formulas [20] to compare these currents to the actual filter current inside the hysteresis controller. This will give you signals for the compensating current.

4. PARTICLE SWARM OPTIMIZATION

PSO is based on the premise that the issue may be modelled as the search for the shortest route across a network, and it uses an evolutionary meta-heuristic strategy to do so. In *figure 3* we can see a computational flow diagram of the PSO approach. PSO is an optimization technique that was inspired by a flock of birds that operate in a complex, multifunctional environment. Numerous objective functions have been optimised using the method developed by Dr. Kennedy and Ebehart.[21].

In PSO, the search space's solution can be a bird or a particle. Position, velocity, and a fitness rating are all assigned to each particle. The fitness function optimizes fitness values while the particles flying direction is controlled by the velocity. The following statement is used to refine the location of each particle.

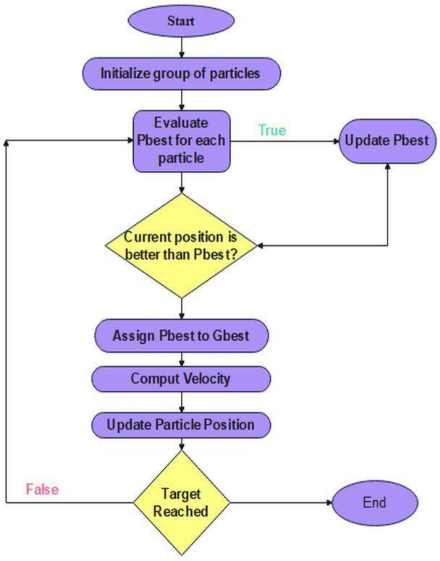

Figure 3: Flow chart of PSO

- Particle's best distance from its current positions P_{Best}.
- G_{Best} isdistance from where a particle is right now to wherever that is.
- $P_{Best}$is a particle's best estimate of its true value, based on its own past experiences.
- The optimum value isG_{Best}.

Each particle's velocity and location are updated using these two optimal values in the following equations.

$$V_i^{n+1} = [W * V_i^k + C_1 * R_1 * (P_{besti} - X_i^k) + C_2 * R_2 * (G_{besti} - X_i^k)] \quad (16)$$

$$X_i^{n+1} = X_i^n + V_i^{n+1} \quad (17)$$

Where

$C1$ *and* $C2$: Acceleration constants
R_1,R_2: Randomly generated the values between 0 and 1
n: Number of Iterations.
w: Inertia weight.

W is given in *eq.* as having a linear variation (16)

$$W = W_{max} - \left(\frac{W_{max} - W_{min}}{iter_{max}}\right) \times \text{ iter} \quad (18)$$

$(V_i^{k+1}$: partcal′s velocity at (k + 1)iteration)
$(X_i^{k+1}$: partcal′s position at (k + 1)iteration)

In order to achieve this goal, this study will use PSO [22] to optimize SAPF. When the load changes, PSO is used to recalculate Kp and K_i. In this case, reference compensating currents were generated using the SAPF p-q theory [23].A schematic of the PSO technique of controlling the DC link voltage is shown in *figure 4*. and the error voltage (V_{dc}), which is the difference between the reference dc voltage level and the supplied dc voltage, are both used to suggest gain settings for the PI controller. When this occurs, the filter reference current is set by the PI controller input. In the Hysteresis band, a comparison is made between the reference signal and the actual current, which results in pulse generation for the Thyristor or IGBTs found within the Power Converter.

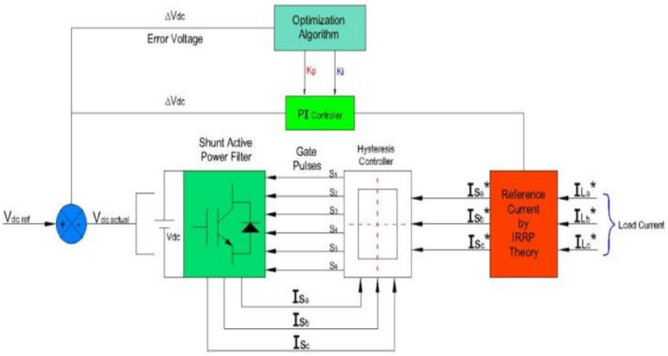

Figure 4: DC voltage control of SAPF using PSO-PI controller

5. PROPOSED IMPLEMENTATION

The optimal gain settings for the PI controller that was utilized to control DC voltage in this investigation were found using the Particle Swarm Optimization technique. The DC voltage may be managed by reducing the value of a goal or cost function. Setting an appropriate number of iterations to retrieve the values is discussed in further depth below. *Figure 5* depicts the proposed PSO-PI controller.

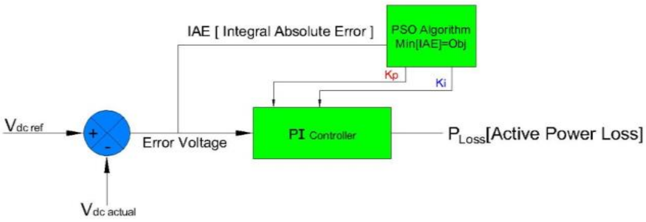

Figure 5: Proposed implementation of PSO-PI Controller

Connectivity between the PSO-PI controller and the Fuzzy logic controller is represented in *figure 6*. A total of seven fuzzy sets were used to define the inputs and outputs of the scenario.$(N_1, N_2, N_3, Z, P_1, P_2,$ *and* $P_3)$ $(N_1, N_2, N_3, Z, P_1, P_2, P_3)$. For defuzzification, we employ the centroid method via the triangle membership function. *Table 1* displays the foundational principles upon which the fuzzy controller is built.

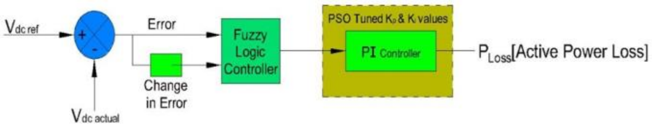

Figure 6: Proposed implementation of Fuzzy Logic Controller with PSO-PI Controller

Table 1: Fuzzy Rules

Table 1. Fuzzy Rules

Change in Error

Error

Out put

→ CE E ↓	N_1	N_2	N_3	Z	P_1	P_2	P_3
N_1	N_1	N_1	N_1	N_1	N_2	N_3	Z
N_2	N_1	N_1	N_1	N_2	N_3	Z	P_1
N_3	N_1	N_1	N_2	N_3	Z	P_1	P_2
Z	N_1	N_2	N_3	Z	P_1	P_2	P_3
P_1	N_2	N_3	Z	P_1	P_2	P_3	P_3
P_2	N_3	Z	P_1	P_2	P_3	P_3	P_3
P_3	Z	P_1	P_2	P_3	P_3	P_3	P_3

6. OPTIMIZATION PARAMETERS

This research seeks to provide the ideal values for the integral gain K_i and proportional gain $K_p$to stabilise the voltage across the dc link. Here, we use PSO to get the best possible values for $K_p$and K_i. In this essay, the issue is stated as follows:

$$P_{loss} = K_p(\Delta V_{dc}) + K_i \int_0^t (\Delta V_{dc})dt \qquad (19)$$

P_{loss} is the out put of PI controller

Where

P_{loss} = Power Loss

$\Delta V_{dc} = V_{dc}$ reference $- V_{dc}$actual

K_p = Praportional constant

K_i = Integral constant

Integral Absolute Error (IAE)is the Objective Function to minimize

$$IAE(K_p, K_i) = \int_0^t abs(\Delta V_{dc})dt \qquad (20)$$

The Integral Absolute Error (IAE) approach equally considers positive and negative errors. The limitations of the improvements are further discussed here.

$$p_1 < K_p < p_2 \; \& \; i_1 < K_i < i_2$$

p_1 and i_1 =Smaller values for $K_p$and K_i

p_2 and i_2 = Higher values for $K_p$and K_i

7. RESULT AND ANALYSIS

A three-phase Diode rectifier load linked directly to a distribution system constitutes the nonlinear load. A common connection point, also known as a PCC, was used in to connect the SAPF. In this article, we look at how SAPF may be used in a distribution network to fix one of the main issues with power quality called harmonics.

In this study distribution system consists of source, nonlinear load and SAPF which is connected at PCC, without SAPF grid current is distorted due to nonlinear load. This report describes discussion of five different case examples. The first case involves computing the THD without SAPF and then doing the FFT analysis. In the second example, a PI-controller is utilized to determine the THD, but in the third, a FUZZY Controller is used instead. Fuzzy PSO-PI and SAPF are both investigated in detail in the fourth and fifth cases.

7.1 Case (1): Without Shunt Active Power Filter

Figure 7 depicts the suggested SIMULINK model, which includes a three-phase nonlinear load but no shunt active power filter. For grid current, we determine its Total Harmonic Distortion (THD). Our lack of a rebate in this instance indicates that there is no filter linked to the grid to supply the necessary reactive power. A high degree of grid current distortion will have an effect on all loads connected to the PCC. For reference, *figure 8* displays a THD value of 18.42% for the grid current.

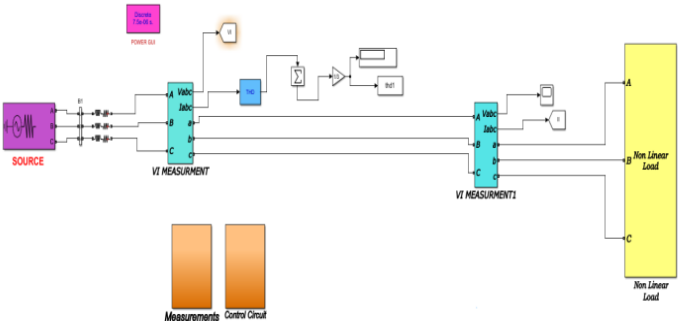

Figure 7: Simulink model of Grid connected Non-linear load without SAPF

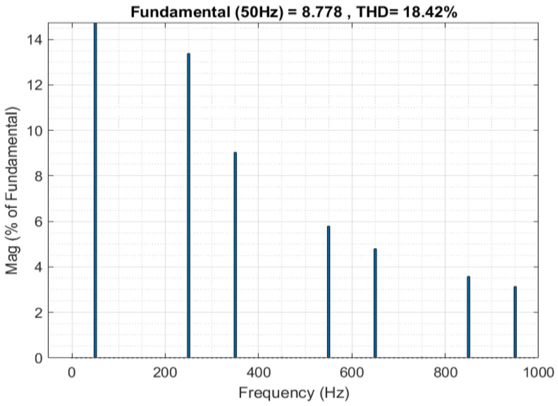

Figure 8: Grid current THD values without SAPF

Figure 9 depicts the output voltage, current, compensatory current, and load current waves. Since there is no filter in the circuit, the current from the source is not sinusoidal, and the current needed to compensate it is zero.

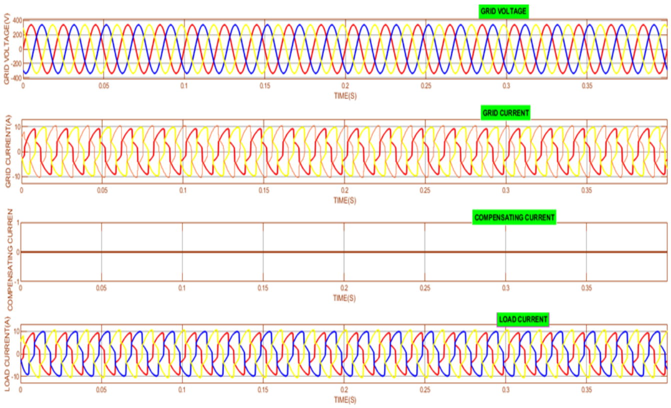

Figure 9: Without SAPF, the wave shapes of the source voltage, source current, compensating current, and load current

7.2 Case (2): Shunt Active Power Filter with Pi Controller

The recommended SAPF Simulink model is shown in *figure 10*. A power source, a nonlinear load, and a shunt active power filter make up the model.

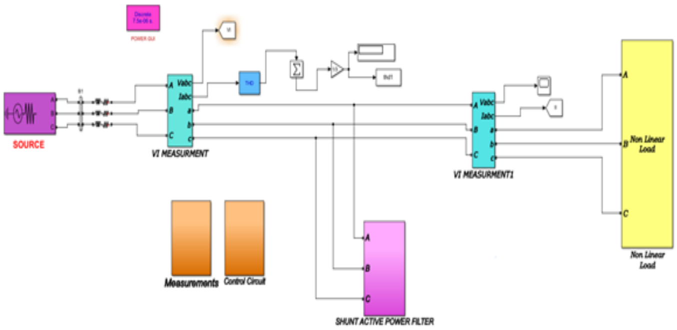

Figure 10: Simulink model with PI controller based SAPF

A traditional PI controller was used in conjunction with the P-Q Theory to supply a constant reference current in order to maintain a regulating voltage across the DC link. Proposed Simulink Model Parameters described in table given bellow in *table 2*. THD value is calculated for grid current and is reduced from 18.2% to 3.76% is as shown in *figure 11*.

Table 2: Simulink Model Framework

Specification	Values
Source Voltage	415V
Source Frequency	50 Hz
Source Impedance	0.1 ohm, 15H
Interfacing impedance	15mH
Load Real Power	4472 W
Load Reactive Power	1718 VAR
DC link Capacitance	100µF
DC link Reference voltage	1500 V

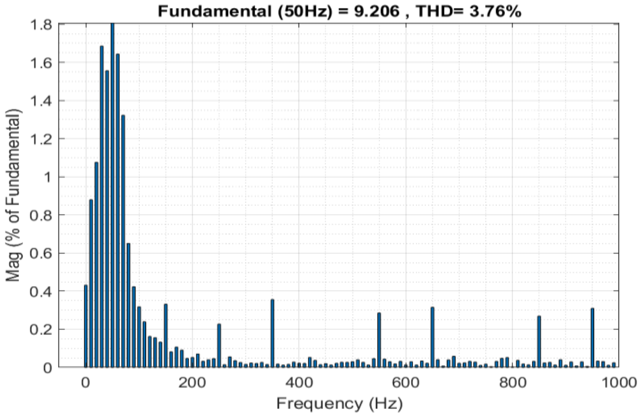

Figure 11: Grid current THD values with SAPF

7.3 Case (3): Shunt Active Power Filter with Fuzzy Controller

The Dc bus voltage in this system could be controlled by a fuzzy logic controller. An output membership function and an input similarity measure are the building blocks of a fuzzy logic controller with one input Error and other input change in error. There are 49 guidelines to follow for the best outcomes. *Figure 12* shows that after calculating the THD value for grid current, it was reduced from 3.76 percent to 1.52 percent

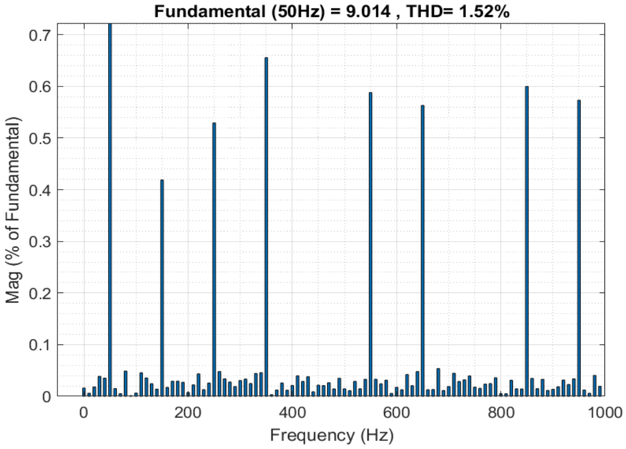

Figure 12: Grid current THD values with Fuzzy controller based SAPF

7.4 Case (4): Shunt Active Power Filter with PSO-Pi Controller

In this application, the voltage across the SAPF DC connection is regulated by a PSO-tuned proportional and integral (PI) controller (see *figure 13*). The PI controller's Kp and K_i gains will be adjusted to minimize the error voltage (IAE) using a Particle Swarm Optimization strategy that takes controller inputs into consideration.

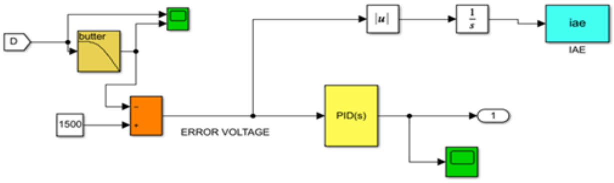

Figure 13: Simulink model of PSO Tuned PI controller

The source voltage, source current, compensation current, and the load current produced by a SAPF with a PSO-PI controller are graphically represented in *figure 14*. While a diode rectifier load is connected to the grid, SAPF injects compensating current at the PCC to keep the grid current sinusoidal. Alternative parameters for PSO are listed in *table 3*. *Figure 15* demonstrates that the estimated THD for the grid current decreases from 1.52% to 0.93%.

Table 3: PSO Parameters

Maximum iterations	1000
Total Population	50
Weight of Inertia	0.9
Constant of Acceleration(C1)	2
Constant of Acceleration(C2)	2
Total Variables	2
Higher Limit of K_i , K_p	200
Lower limit of K_i , K_p	0

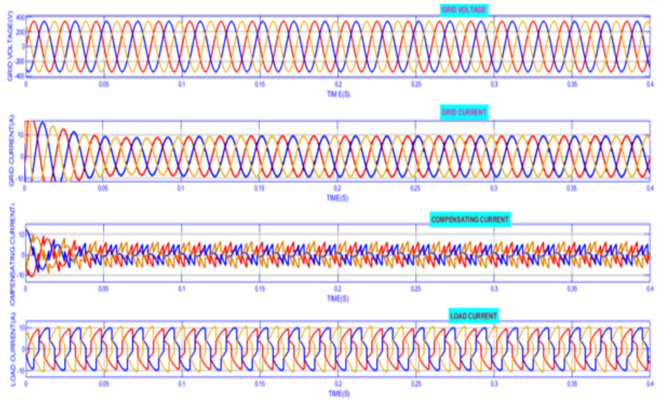

Figure 14: With PSO-PI SAPF, the wave shapes of the grid voltage, grid current, compensatory, Current and load current

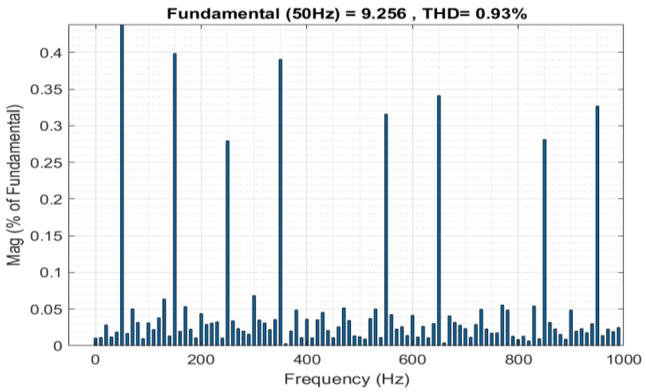

Figure 15: Grid current THD values with PSO-PI controller based SAPFWQ

7.5 Case (5): Shunt Active Power Filter with Fuzzy and PSO-Pi Controller

In this scenario, the SAPF DC link voltage is regulated using a Fuzzy and PSO-PI controller. When an error occurs, the PSO will communicate the error voltage to the fuzzy controller, which will use it to calculate the K_p and K_i gains for the PI controller. *Figure 17* displays a reduction from 0.93 percent to 0.87 percent in the THD value calculated for the grid current.

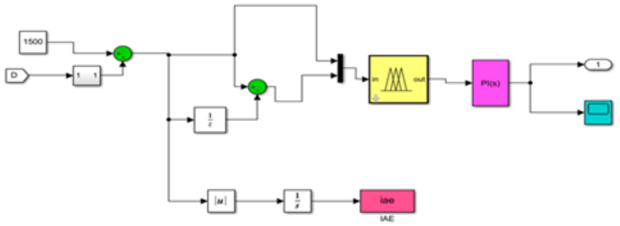

Figure 16: Simulink model of Fuzzy with PSO –PI Controller based SAPF

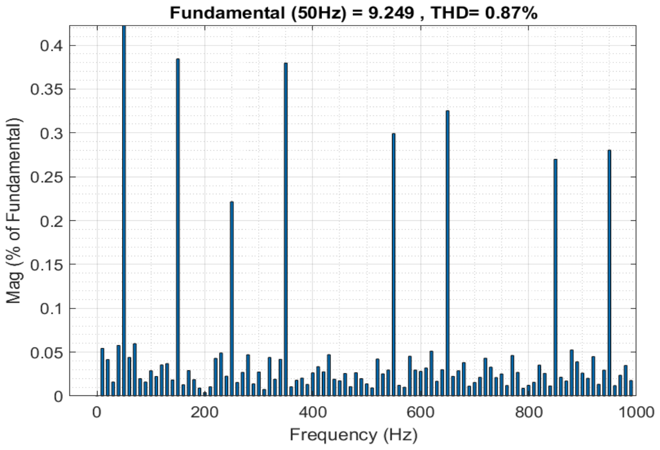

Figure 17: Grid current THD values of FUZZY logic controller with PSO –PI Controller based SAPF

The performance of SAPF among all five cases presented in *table 4* and *table 5* shows the proposed SAPF inverter injects just the reactive power necessary to meet the load's requirements, while the active power comes directly from the grid.

Table 4: Comparison Table

S. No.	FFT Analysis	Specification	(THD) IN %
1	Without **SAPF**	Grid Current	**18.42**
2	SAPF with **PI** Controller	Grid Current	**3.76**
3	SAPF with **Fuzzy** Logic controller	Grid Current	**1.52**
4	SAPF with **PSO-PI** Controller	Grid Current	**0.93**
5	SAPF with **Fuzzy and PSO-PI** Controller	Grid Current	**0.87**

Table 5: Active and Reactive power from Inverter, Load, Grid

Power	SAPF Inverter	Load	Grid
Real Power (kW)	0.215	4.472	4.687
Reactive Power (kVAR)	1.736	1.718	0.172

The performance of a shunt active power filter (SAPF) was studied in this work, to reduce harmonics in a distribution system model's grid current caused by nonlinear loads, The SAPF efficiency under various scenarios is analysed and compared. Five different scenarios are simulated with the help of MATLAB/SIMULINK for the model shown in *figure 7*. The results are outlined. The PSO-PI based SAPF, the standard FUZZY based SAPF, and the conventional PI based SAPF all perform poorly in terms of minimizing overall harmonic distortion, according to simulation data (THD). The Fuzzy with PSO-PI based SAPF is found to be more effective in simulation to achieve lower THD. It has been determined that this enhanced performance is acceptable (within 5% of the IEEE standard).

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