An Optimal Tuning of PI Controller for Shunt Active Power Filter based on PI-PSO Approach

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***Abstract*— This paper presents an optimal tuning of a Proportional-Integral (PI) controller for a shunt active power filter (SAPF) using the Particle Swarm Optimization (PSO) approach for nonlinear load applications. The widespread use of power electronics in home, commercial, and industrial sectors introduces significant harmonic distortion, which degrades power quality and causes inefficiencies in electrical systems. Conventional PI controllers are commonly used for harmonic mitigation in SAPFs but suffer from suboptimal performance under varying load conditions due to difficulty in parameter tuning. This research is motivated by the need to enhance the performance of SAPFs and improve power quality by reducing harmonic distortion. By leveraging the PSO algorithm, the PI controller parameters are optimally tuned to improve SAPF performance. The proposed PI-PSO approach is evaluated through MATLAB/Simulink simulations, demonstrating a significant reduction in Total Harmonic Distortion (THD) from 22.06% without a filter to 3.66%, compared to 4.87% using conventional methods. These results highlight the effectiveness of the PI-PSO technique in achieving superior power quality, making it a promising solution for mitigating harmonics in systems with nonlinear loads.**

Keywords*— *Active Filter; Control Technique, Harmonic Mitigation, Shunt Active Power filter (SAPF), VSI, Particle Swarm Optimization (PSO), PI-PSO, PI Controller

I. INTRODUCTION

Power electronic gadgets are as a common knowledge, always present around us and represent one of the most significant technological advances in the history of the world. In our day-to-day lives, the power electronic gadget can be utilized in a variety of contexts. It has also become a component of the modern era, and it has helped to improve the quality of our lives. Because of this circumstance, the use of power semiconductor switching devices in electronics like televisions, computers, and other microprocessors that create harmonics in the electrical power system will expand [1,2]. High harmonics in electrical equipment can cause a variety of problems; therefore, they need to be decreased to enhance the power quality[3]. The option of utilizing either an active or passive power filter, both of which are viable solutions for lowering harmonic levels [1-4]. The passive filter is comprised of a blend of components a capacitor and an inductor that can be configured to resonate at a single frequency or across a band of frequencies [5,6]. Due to limited size and tuning that cannot be changed, a passive harmonic filter is not a great choice to filter the harmonics. Aside from that, an active harmonic filter can function with a large number of changing speeds, actively cut down on noise, and do so by continuously monitoring electricity and injecting currents to attenuate harmonics. Because of this, active filters are the best choice for a system that has a lot of non-linear loads [5-8].

Initially, shunt active power filters (SAPFs) were primarily utilized for reactive power compensation and current balancing (Hirofumi Akagi, 1996) [9]. Their main purpose was to regulate the harmonics present in the current drawn by nonlinear loads. By identifying the harmonics in the load current, a shunt active filter injects current into the system to counterbalance the reactive load. The potential of SAPF to enhance power quality has led to a global focus on their research [10-12]. Active power filters are commonly found in electronic devices, and the utilization of shunt active power filters (SAPF) has emerged as a viable and efficient approach for mitigating harmonics and power disturbances [12].

In a study by [13], the robustness of a Unified Power Quality Conditioner (UPQC) was enhanced through a neural network-based controller for admittance estimation. The neural network was employed to predict the system admittance accurately under different disturbances and load variations. The proposed method demonstrated robust performance in mitigating power quality issues such as voltage sags, swells, and harmonics. Although the neural network provided high adaptability, its computational complexity could limit real-time implementation in some systems. The paper highlighted that despite the effectiveness of neural network approaches, simpler methods like PI controllers could be enhanced with optimization techniques

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such as Particle Swarm Optimization (PSO) for systems where computational resources are constrained.

Approach by [14] involved coordinating the different voltage control devices with optimization techniques that aimed to minimize power losses while ensuring voltage stability. This method proved effective in handling the uncertainties introduced by renewable energy sources. However, the integration of advanced optimization algorithms, such as PSO, could further improve the dynamic response and adaptability of controllers like PI in shunt active power filters (SAPF).

The performance of an SAPF largely depends on the effectiveness of its control strategy. Proportional-Integral (PI) controllers are widely used in SAPFs due to their simplicity and robust performance in regulating current and voltage [13-14]. However, tuning the parameters of a PI controller (i.e., the proportional gain and the integral time constant) to achieve optimal performance can be challenging. Conventional tuning methods often fail to provide satisfactory results under varying load conditions and system disturbances, leading to suboptimal power quality improvement [15-16].

To address these challenges, this paper proposes an innovative approach for the optimal tuning of PI controllers in SAPFs using Particle Swarm Optimization (PSO). PSO is a population-based optimization technique inspired by the social behaviour of birds flocking or fish schooling. It has been successfully applied in various engineering fields due to its simplicity, flexibility, and ability to converge to global optima efficiently. By leveraging the strengths of PSO, the proposed PI-PSO approach aims to enhance the performance of PI controllers in SAPFs, ensuring better power quality and system stability [17-19].

The primary contributions of this research are twofold. First, a mathematical model of the SAPF is develop and a PI controller is designed for its operation. Then, the PSO algorithm is applied to optimally tune the PI controller parameters, demonstrating the effectiveness of the PI-PSO approach through extensive simulations. The results show significant improvements in harmonic mitigation and reactive power compensation compared to traditional tuning methods.

II. SYSTEM CONFIGURATION AND OPERATING PRINCIPLE

A. *Mathematical Model of Shunt Active Power Filter (SAPF)*

The SAPF is designed to mitigate harmonics and compensate reactive power in the power system. The SAPF typically consists of a Voltage Source Inverter (VSI) connected in parallel with the load via a coupling inductor. The mathematical model can be derived from Kirchhoff's laws and the fundamental principles of power electronics.

The VSI is a critical component of the SAPF. It is responsible for generating compensating currents that counteract the harmonic and reactive components of the load current. The performance of the VSI directly impacts the effectiveness of the SAPF.

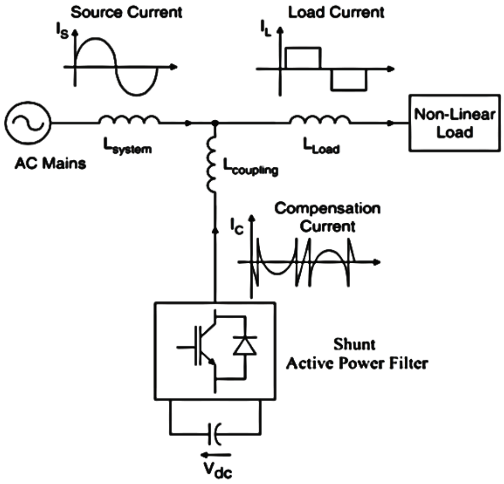

Fig.1: Basic Scheme of Shunt Active Power Filter

Fig. 1 shows the basic layout of a shunt active power filter (SAPF). This circuit consist of an inductor (L_f) and the combination DC capacitor and power switching active filter. A SAPF provides a current with the same magnitude and polarity as load-induced harmonic current is injected at the common-coupling point, where it cancels out and the source current becomes sinusoidal. It is a potent technique for compensating not just current harmonics caused by load distortion, but also reactive power. They are more compact, adaptable, discriminating, and less susceptible to failure[3,5].

The VSI generates the required compensating current by switching its power electronic devices (e.g., IGBTs or MOSFETs) according to the control signals derived from the PI controller. The inverter operates by synthesizing an AC voltage from the DC link voltage, which drives the filter current i_f through the coupling inductor L_f.

The mathematical formulation for inverter model can be described as:

$$V_{dc} \frac{di_s}{d_t} = V_s - V_L - R_f I_f - L_f \frac{di_f}{d_t} \quad (1)$$

where V_{dc} is the DC link voltage, i_s is the source current, V_s is the source voltage, V_L is the load voltage, R_f and L_f are the resistance and inductance of the filter respectively, and i_f is the filter current.

B. *PI Controller Design*

The PI controller is used to regulate the filter current i_f by adjusting the inverter output voltage. The control law of the PI controller is given by:

$$U(t) = K_p e(t) + K_i \int e\,(t)dt \quad (2)$$

where $u(t)$ is the control signal, $e(t)$ is the error signal defined as the difference between the reference current i_{ref} and the actual filter current i_f, K_p is the proportional gain, and K_i is the integral gain.

The PI controller adopted due to its simple structure and ease of implementation., the performance of the PI controller depends heavily on the proper tuning of K_p and K_i. Traditional tuning methods may not provide the desired performance under varying load conditions and disturbances[22]. The integral action in the PI controller helps to eliminate steady-state error, ensuring accurate tracking of the reference signal. In SAPF applications, this allows for better regulation of harmonic currents and precise compensation of reactive power.

Although simple, due to their proven reliability and decades of use, PI controllers are a standard choice in the industry. This makes them well-supported by existing hardware and control platforms, allowing for easier integration into existing power systems.. The PI controller's parameters can be fine-tuned for a wide variety of system dynamics, including SAPFs. By optimizing the PI gains using methods like PSO, it is possible to achieve significant performance improvements, as shown in the study.

C. PSO Algorithm

Particle Swarm Optimization (PSO) is a population-based optimization technique inspired by the social behavior of birds flocking or fish schooling. It is used to find the optimal values of the PI controller parameters (K_p and K_i) [18,19].

PSO is an evolutionary computation technique developed by Kennedy and Eberhart in 1995, inspired by the social behaviour patterns of birds flocking or fish schooling. It is widely used for optimizing a wide range of functions, especially in control systems and engineering applications.

Initially, particles are randomly positioned and given random velocities. They evaluate their positions using a fitness function that measures how good the solution is. Each particle remembers its best position, called the personal best, and the best position found by the entire swarm, called the global best.

They evaluate the fitness of each particle using the objective function. The fitness value indicates how well a particle's position solves the optimization problem. The objective function can be defined to minimize or maximize a specific criterion, such as error, cost, or performance metrics.

Particles update their velocities based on a combination of their current velocity, the distance to their personal best position, and the distance to the global best position. This update guides the particles towards better solutions over time. The process of evaluating, updating, and moving particles continues iteratively until the swarm converges to an optimal or near-optimal solution.

Update the velocity of each particle using the following equation:

$$V_i(t+1) = \omega V_i(t) + c_1 r_1 \left(p_{best,i} - x_i(t)\right) + c_2 r_2 \left(g_{best} - x_i(t)\right) \quad (3)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (4)$$

where $V_i(t)$ is the velocity of particle i at time t, $x_i\,(t)$ is the position of particle i at time t, $P_{best,i}$ is the personal best position of particle i, g_{best} is the global best position, ω is the inertia weight, c_1 and c_2 are acceleration coefficients, and r_1 and r2 are random numbers between 0 and 1.

PSO's effectiveness comes from balancing exploration (searching new areas) and exploitation (refining known good areas) of the search space, making it a powerful tool for optimizing complex problems.

D. PI-PSO Algorithm Proposed Approach

The proposed PI-PSO approach combines the PI controller and the PSO algorithm to achieve optimal tuning of the PI controller parameters for the SAPF.

The objective function is designed to minimize the total harmonic distortion (THD) of the source current and improve the power factor. It is defined as:

$$Objective = \min(THD(i_s) + \lambda|1 - Power\ Factor|) \quad (5)$$

where λ is a weighting factor to balance the THD and power factor components.

In step of extracting optimal control parameters, once the PSO algorithm has converged, the optimal control parameters (PI gains) is extracted corresponding to the optimal particle's position. These control parameters will yield the desired SAPF performance in mitigating harmonics and enhancing power quality.

Then, the control parameters obtained are validated by simulating the SAPF system with the optimised PI controller. The appropriate test cases and power quality metrics are utilised to evaluate the system's performance.

The PI controller gains K_p and K_i must be within predefined bounds to ensure system stability and performance. The THD must be within acceptable limits as defined by international standards (e.g., IEEE 519).

Finally, there is a lot of process and study/research needed in order to complete the whole part of SAPF Simulink model. After completing developing the model, the proposed control technique will be analyzed.

III. SIMULATION RESULT & DISCUSSION

The simulation model of SAPF with non-linear load is developed using MATLAB/Simulink as illustrated in Fig. 2. The system is composed of a three-phase AC voltage source, a non-linear load (consisting of a resistor connected to a three-phase universal diode), and a shunt active power filter.

The simulation parameters for the proposed method SAPF with PSO is given in Table I and Table II.

TABLE I. PROPOSED SAPF WITH NON-LINEAR LOAD SPECIFICATIONS

Parameter	Value
AC source voltage	$220\sqrt{2}$ V
Frequency	50Hz
DC-link capacitor	1500μF,750V
K_p	50
K_i	2

While in TABLE II, shows the parameter and default value setting in this study for PSO.

TABLE II. PSO DEFAULT SETTING

Parameter	Value
noP	30
Maxiter	10
wMax	0.9
wMin	0.4
C1	2
C2	2
vMax	(ub-lb)*0.2
Error Value	-
Kp	100
Ki	100

This research aims to conduct simulations and obtain results concerning the Total Harmonic Distortion (THD) of the shunt active power filter (SAPF) for nonlinear loads. The objective is to evaluate the effectiveness and performance of the SAPF.

To accurately assess the study performance, simulations have been performed to measure the THD when operating with nonlinear loads. Fig. 3, Fig.4 and Fig 5 below shows the simulation results of FFT analysis. Please refer Table III for result summarizing.

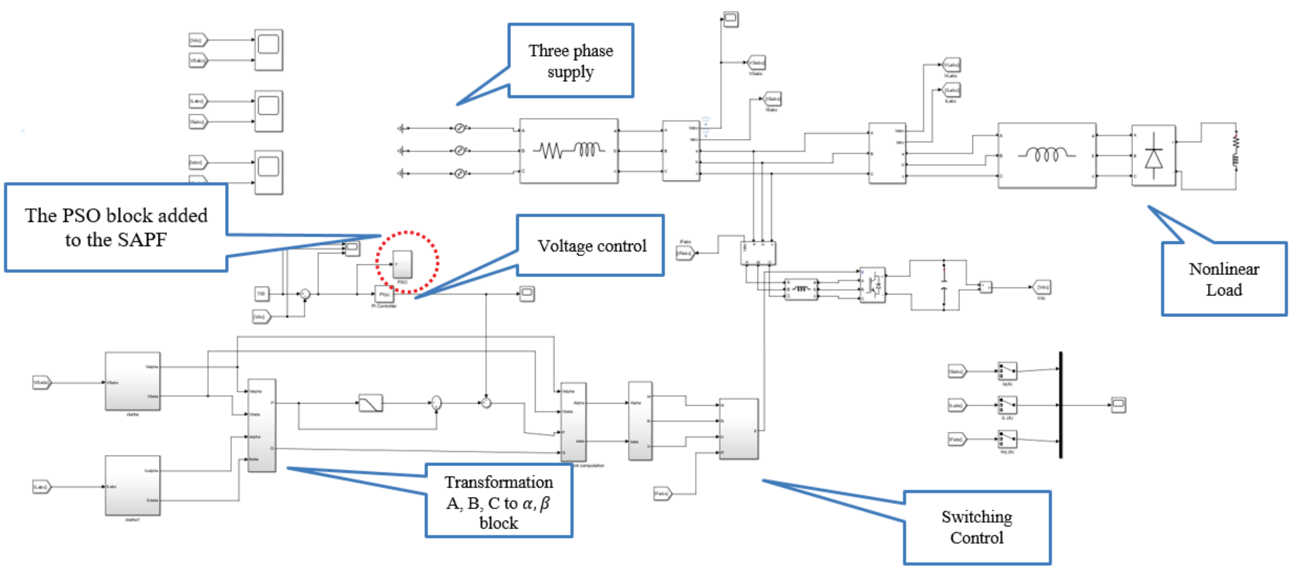

Fig. 2: The proposed method of SAPF with non-linear load by using MATLAB/Simulink

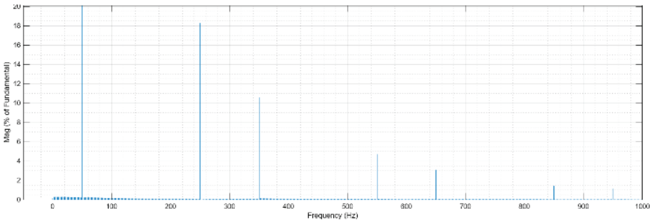

Fig.3: The FFT analysis of THD without SAPF

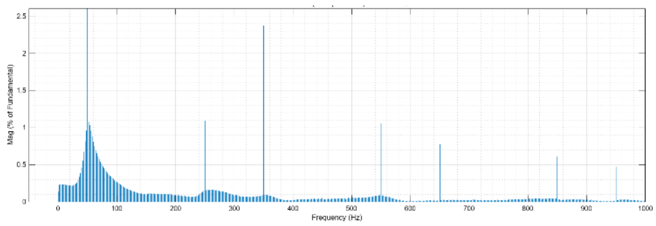

Fig. 4: The FFT analysis of THD with SAPF

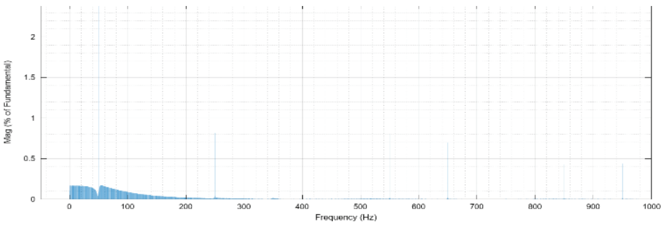

Fig. 5: The FFT analysis of THD with SAPF using PI-PSO

The results obtained from the Fig. 3-5 are summarized in the Table III below.

TABLE III. THE OVERALL RESULTS AND ANALYSIS

Parameter	Without using shunt active power filter (SAPF)	The conventional method (With SAPF)	The proposed method (Using PI-PSO)
Proportional gain (Kp)	50	50	18.025
Integral gain (Ki)	2	2	2.621
THD % of source current	22.06	4.87%	3.66%

The simulation results clearly demonstrate the effectiveness of the PI-PSO tuned controller over the traditional PI controller. The implementation of the conventional SAPF reduces THD from 22.06% to 4.87%. This reduction highlights the SAPF's role in improving power quality by addressing harmonic distortion.

The PI-PSO optimized SAPF achieves a THD of 3.66%, which is lower than the 4.87% achieved by the conventional method. This additional reduction indicates the advantage of using advanced optimization techniques like PI-PSO to fine-tune the SAPF parameters for optimal performance. The PI-PSO technique optimizes the tuning of the SAPF parameters more effectively, leading to superior harmonic mitigation. The reduction in THD signifies better power quality and enhanced performance of the electrical system.

While the PI-PSO approach shows improved harmonic mitigation in simulations, its robustness against sudden disturbances like voltage sags or load transients remains unevaluated. These disturbances, common in practical systems, may impact the PSO-tuned PI controller's stability. Additionally, the complexity introduced by the PSO algorithm could increase costs and maintenance, particularly in small-scale applications where simpler control strategies might be more suitable.

The PSO algorithm's performance can be sensitive to the selection of its control parameters (such as population size, inertia weight, and acceleration coefficients). Improper tuning of these parameters could lead to suboptimal results or slow convergence, particularly in highly dynamic systems. This requires a careful balance between exploration and exploitation in the search space, which may not always be straightforward in real-world applications.

The PI-PSO method shows great potential for improving power quality in systems with nonlinear loads, and further research on addressing these practical limitations could make it more viable for widespread implementation.

IV. Conclusion

This research presented an optimal tuning method for the PI controller in Shunt Active Power Filters (SAPFs) using the Particle Swarm Optimization (PSO) approach. The PI-PSO tuned controller significantly outperforms the traditional PI controller in terms of Total Harmonic Distortion (THD), achieving a reduction from 4.87% to 3.66%.

The results of this study have significant practical implications for improving power quality in electrical systems. By effectively reducing harmonics and improving the power factor, the PI-PSO tuned SAPF can enhance the overall efficiency and reliability of power distribution networks. This improvement in power quality can lead to reduced energy losses, extended lifespan of electrical equipment, and compliance with international standards for harmonic limits, such as IEEE 519.

While this research demonstrates the effectiveness of the PI-PSO approach, several areas for further research remain open. Researchers can explore other advanced optimization algorithms, such as Genetic Algorithms (GA), Differential Evolution (DE), or Hybrid approaches, to further enhance the tuning process and performance of the PI controller. Extending the optimization framework to consider multiple objectives simultaneously, such as minimizing energy consumption and maximizing system stability also potentially explore for futures works.

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