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Optimal Shunt Active Power Filter for Power Quality Improvement Using the Lemur Algorithm

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Abstract- Power quality issues such as harmonic distortion, reactive power demand, and voltage imbalances are increasingly prevalent in modern power systems due to the proliferation of nonlinear loads and renewable energy sources. Shunt Active Power Filters (SAPFs) are effective devices for mitigating these issues and improving power quality. This paper proposes an optimal design of a SAPF for power quality improvement. A novel control approach using a Tilt-Integral-Derivative Fractional Order Proportional-Integral-Derivative (TID-FOPID) controller optimized with the Lemur Optimizer (LMO) algorithm. The LMO, inspired by the social behaviour of lemurs, offers a robust and efficient optimization approach. The proposed algorithm is used to determine the optimal parameters of the SAPF controller, including the proportional-integral (PI) gains and the DC-link voltage, to minimize total harmonic distortion (THD) and improve power factor. Simulations performed in MATLAB/Simulink demonstrate the effectiveness of the proposed LMO-based SAPF in mitigating harmonic distortion, compensating reactive power, and improving overall power quality compared to traditional approaches.

Keywords- *Shunt Active Power Filter (SAPF), Power Quality, Harmonic mitigation, Reactive Power compensation, TID-FOPID Controller, Lemur Optimizer (LMO), Total Harmonic Distortion (THD).*

1. Introduction

The increasing demand for electric power, coupled with the widespread use of nonlinear loads such as power electronic converters, adjustable speed drives (ASDs), and arc furnaces, has led to significant power quality degradation. Harmonics, reactive power, and voltage imbalances are common power quality problems that can cause equipment malfunction, reduced efficiency, and increased power losses [1].

Traditional methods for mitigating power quality problems include passive filters, which are cost-effective but have limitations such as fixed compensation, resonance issues, and bulkiness [2]. Active Power Filters (APFs) offer a more flexible and effective solution by actively injecting compensating currents to cancel out the harmonic and reactive components generated by nonlinear loads [3]. Among various APF configurations, Shunt Active Power Filters (SAPFs) are widely used due to their ability to compensate for current harmonics and reactive power at the Point of Common Coupling (PCC).

The performance of a SAPF heavily relies on the effectiveness of its control algorithm. The control algorithm typically

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involves extracting the harmonic and reactive components from the load current and generating appropriate switching signals for the inverter. PI controllers are commonly used in SAPF control loops due to their simplicity and ease of implementation. However, the performance of PI controllers is highly sensitive to the selection of their gains, and improper tuning can lead to instability and poor performance.

Therefore, optimal tuning of the SAPF controller parameters is crucial for achieving desired performance. Various optimization techniques have been employed for this purpose, including trial and error [4], Ziegler-Nichol's method [5], genetic algorithm (GA) [6], particle swarm optimization (PSO) [7], and cuckoo search algorithm (CSA) [8].

This paper proposes to enhance the dynamic response and robustness, this study integrates a TID-FOPID Controller Optimized with the Lemur Optimizer (LMO) algorithm for optimally tuning the parameters of a SAPF controller for power quality improvement. The LMO, inspired by the social behaviour of lemurs in food sharing and movement, has demonstrated superior performance compared to other optimization algorithms in various applications [9]. The effectiveness of the proposed LMO-based SAPF is demonstrated through simulations performed in MATLAB/Simulink.

2. Shunt Active Power Filter Configuration and Control

A typical SAPF configuration consists of a voltage source inverter (VSI) connected in parallel with the load at the PCC, a DC-link capacitor, and a coupling inductor, as shown in Figure.1

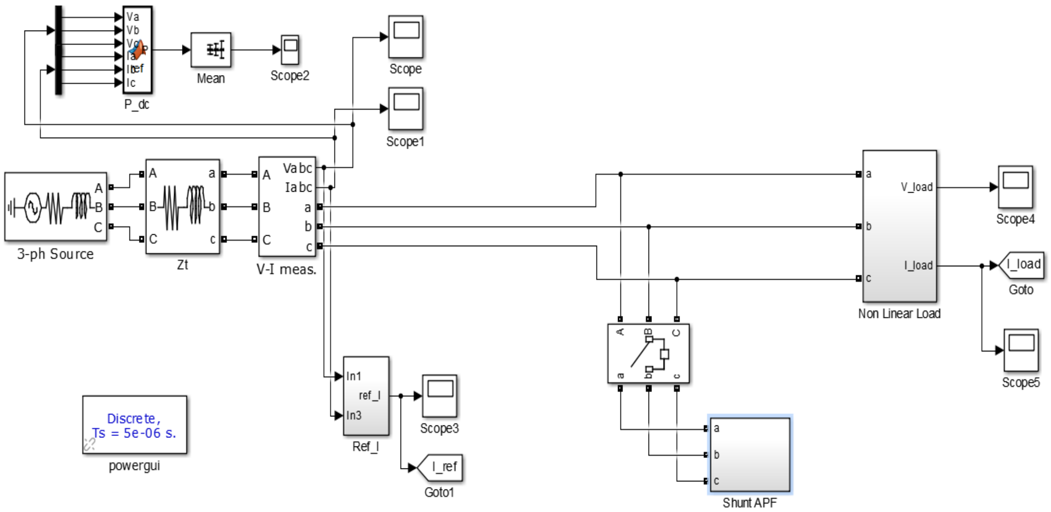

Fig. 1. System Model

The control strategy of the SAPF involves extracting the harmonic and reactive components from the load current and generating appropriate switching signals for the VSI. A common control scheme involves:

- **Current Harmonic Extraction:** This involves separating the fundamental component from the load current. Techniques like Instantaneous Reactive Power Theory (p-q theory) [10], Synchronous Reference Frame (SRF) theory [11], and Discrete Fourier Transform (DFT) [12] are commonly used.
- **Reference Current Generation:** The extracted harmonic and reactive

components are used to generate the reference current signal for the SAPF.

- **Current Control:** This control loop aims to force the SAPF current to track the reference current signal. Hysteresis current control, PI current control, and predictive current control are commonly employed.
- **DC-link Voltage Control:** This control loop maintains the DC-link voltage at a desired level to ensure proper operation of the VSI. A PI controller is typically used for this purpose.

3. Proposed TID-FOPID Controller

To achieve superior power quality improvement, a TID-FOPID controller is used for precise current control in SAPF. The advantage of the controller includes enhanced robustness to system disturbances, Improved transient and steady-state performance and better adaptability to varying load conditions.

The parameters of the TID-FOPID controller are optimally tuned using the Lemur Optimization Algorithm. The algorithm ensures optimal controller performance by minimizing Total Harmonic Distortion (THD), enhancing power factor correction, reducing voltage fluctuations and ensuring faster system response to disturbances.

The transfer function for the TID controller is as follow:

$$C_1(s) = K_p s^{-\left(\frac{1}{n}\right)} + \frac{K_i}{s} + K_d s \quad (1)$$

The transfer function for the FOPIDN controller is as follows:

$$C_2(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d S^{\mu} \frac{N_c s}{N_c + s} \quad (2)$$

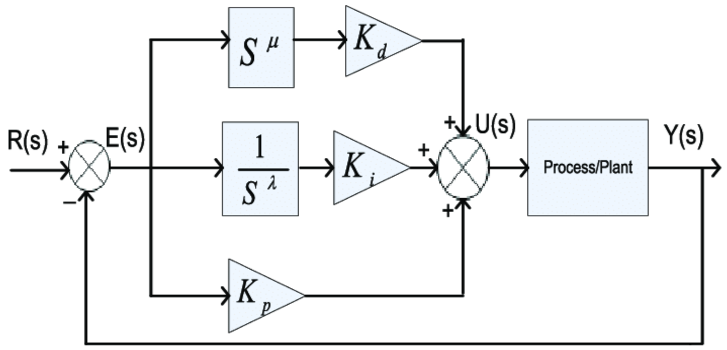

Fig. 2 TID-FOPID controller structure

In the cascaded TID-FOPIDN structure, the TID controller manages the outer loop, efficiently handling slower disturbances across control zones by stabilizing output via the area control error (ACE). This strategy makes use of the TID controller's adaptability to changing behaviours in each zone.

The FOPIDN controller, on the other hand, manages the inner loop and is meant to provide rapid frequency response.

4. Lemur Optimizer (LMO) Algorithm

The Lemur Optimizer (LMO) is a metaheuristic optimization algorithm inspired by the social behaviour of lemurs. Lemurs exhibit cooperative foraging behaviour and share food resources within their groups. The LMO algorithm mimics these behaviours to search for the optimal solution in a multi-dimensional search space. The main steps of the LMO

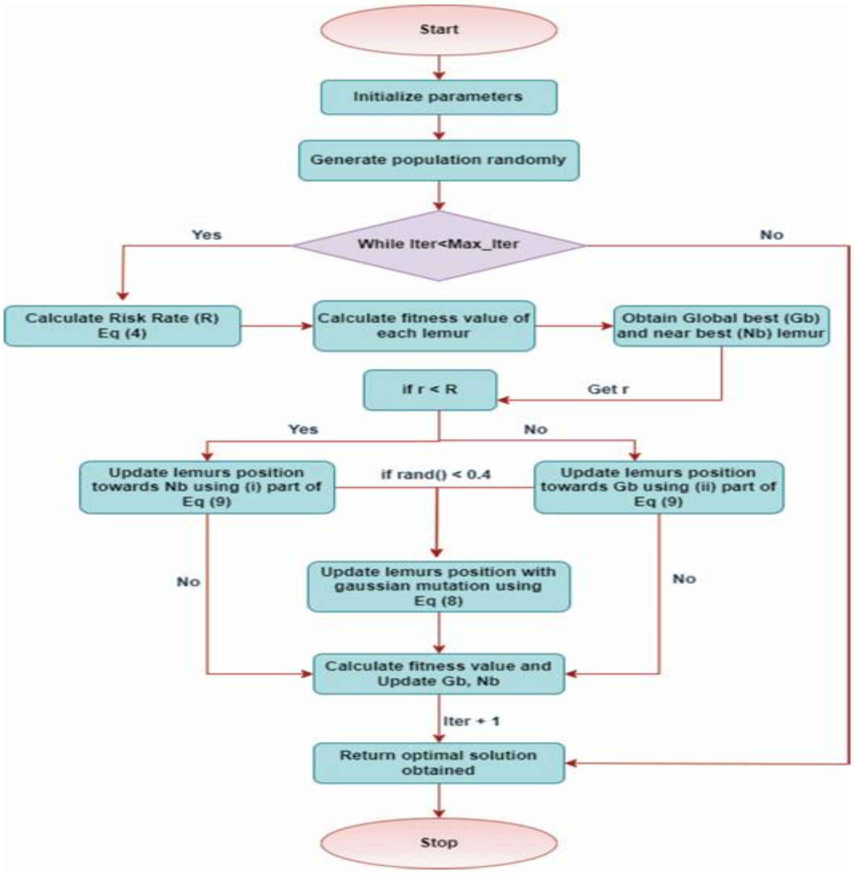

Figure 2. Lemur Optimization

1. **Initialization:** The algorithm starts by initializing a population of lemurs, where each lemur represents a potential solution to the optimization problem. The position of each lemur in the search space represents the values of the decision variables.
2. **Fitness Evaluation:** The fitness of each lemur is evaluated based on an objective function that quantifies the quality of the solution represented by the lemur.
3. **Food Sharing Phase:** In this phase, lemurs share food resources with their neighbours. This is implemented by updating the position of each lemur based on the position of its best neighbour. This phase promotes exploitation of promising regions in the search space.
4. **Movement Phase:** In this phase, lemurs move to new locations in search of better food resources. This is implemented by randomly perturbing the position of each lemur. This phase promotes exploration of the search space and prevents the algorithm from getting trapped in local optima.
5. **Selection:** The algorithm selects the best lemurs based on their fitness values to form the next generation. This ensures that the population gradually converges towards the optimal solution.
6. **Termination:** The algorithm terminates when a predefined stopping criterion is met, such as a maximum number of iterations or a satisfactory fitness value.

5. Optimal Design of SAPF using LMO

The objective of this paper is to optimally tune the parameters of the SAPF controller using the LMO algorithm to minimize harmonic distortion and improve power factor. The objective function is defined as:

$$\text{Fitness} = w1 * THD + w2 * (1 - PF) \quad (3)$$

where:

- *THD* is the Total Harmonic Distortion of the source current.
- *PF* is the power factor at the PCC.
- *w1* and *w2* are weighting factors that determine the relative importance of THD and power factor.

The decision variables for the optimization problem are the proportional-integral (PI) gains of the current controller (Kp_i, Ki_i), the PI gains of the DC-link voltage controller (Kp_v, Ki_v), and the reference DC-link voltage (Vdc*). The optimization problem can be formulated as:

Minimize: Fitness = w1 * THD + w2 * (1 - PF) (4)

Subject to:
Kp_i_min <= Kp_i <= Kp_i_max
Ki_i_min <= Ki_i <= Ki_i_max
Kp_v_min <= Kp_v <= Kp_v_max
Ki_v_min <= Ki_v <= Ki_v_max
Vdc*_min <= Vdc* <= Vdc*_max

where Kp_i_min, Ki_i_min, Kp_v_min, Ki_v_min, Vdc*_min and Kp_i_max, Ki_i_max, Kp_v_max, Ki_v_max, Vdc*_max are the lower and upper bounds for the decision variables, respectively.

The LMO algorithm is used to find the optimal values of the decision variables that minimize the objective function. The steps involved in the LMO-based SAPF design are as follows:

1. **Initialization:** Initialize the population of lemurs with random values for the decision variables within their respective bounds.
2. **Simulation:** For each lemur, simulate the SAPF system in MATLAB/Simulink using the corresponding values of the decision variables.
3. **Fitness Evaluation:** Calculate the fitness value for each lemur based on the simulated THD and power factor values.
4. **LMO Optimization:** Apply the LMO algorithm to update the positions of the lemurs iteratively, based on the food sharing and movement phases, until the termination criterion is met.
5. **Optimal Parameter Selection:** Select the values of the decision variables corresponding to the lemur with the best fitness value as the optimal parameters for the SAPF controller.

SYSTEM PARAMETERS

Table 1 Source parameter

S.NO	PARAMETERS	VALUES
1.	3-Phase Source	400V, 50HZ
2.	3-Phase Series RLC Branch (Type = R) (ZT)	R=0.01 Ω, L=10^{-6} H
3.	3-phase V-I Measurement	Phase to Ground

4.	3-Phase Breaker	Switching Time: 0	
		Ron = 10^{-6} Ω, Rs = 10^{6} Ω	

Table 2 SHUNT ACTIVE POWER FILTER

S.NO	PARAMETERS	VALUES	
1.	PI Controller	Discrete PI Controller	
		Kp = 0.1	Ki = 1
	Constant	850	
2.	DC Voltage Source	850V	
3.	Coupling Inductor	L=1.2×10^{-3} H	
4.	Universal Bridge (3 arms)	Rs = 1000 Ω, Ron = 1×10^{-4} Ω	

Table 3 NON-LINEAR LOAD

S.NO	PARAMETERS	VALUES	
1.	3-Phase Series RLC Branch (Type = RL) (ZT)	R=0.001 Ω, L=10^{-6} H	
2.	3-Phase Breaker (Open)	Switching Time: 0	
		Ron = 10^{-5} Ω, Rs = 10^{6} Ω	
3.	3-Phase Breaker (Close)	Switching Time: 0	
		Ron = 10^{-5} Ω, Rs = 10^{6} Ω	
4.	3-phase V-I Measurement	Phase to Ground	
5.	Diodes	Ron = 10^{-1} Ω, Lon = 0H	VF =0.8
		Rs = 1000, Cs=0.1×10^{-6} F	
6.	Series RLC Branch (Type = R) (Load)	R=10Ω	
7.	Series RLC Branch (Type = R) (Unbalanced Load)	R=2Ω, R=4Ω, R=6Ω	

The parameters of the LMO algorithm used in the simulations are as follows:

- Population Size: 30
- Maximum Iterations: 100
- Weighting Factors: w1 = 0.7, w2 = 0.3

- ## 6. Simulation Results and Discussion:
- The performance of SAPF with the proposed TID-FOPID controller optimized using LMO-based SA PF is evaluated through simulations performed in MATLAB/Simulink. A three-phase, four-wire system with a nonlinear load consisting of a three-phase diode rectifier with a resistive load is considered. The SAPF is connected to the PCC to mitigate the harmonic distortion and compensate for reactive power.
- The parameters of the system used in the simulations are as follows:

The simulations are performed under different operating conditions to evaluate the robustness of the proposed LMO-based SAPF. The performance of the proposed SAPF is compared with that of a SAPF with conventional PI controller tuning based on trial and error.

The simulation results show that the proposed LMO-based SAPF significantly reduces the THD of the source current and improves the power factor compared to the SAPF with conventional PI controller tuning. The LMO-based SAPF also exhibits faster transient response and better dynamic performance under varying load conditions.

Table 4 THD Values without controller, with PI, with optimal TID-FOPID controller.

PERFORMENCE OF FILTERS	
Without Filter THD	28.54%
With PI Filter THD	2.91%
With TID-FOPID Filter THD	2.81%

Table. 2 Values of THD Variations

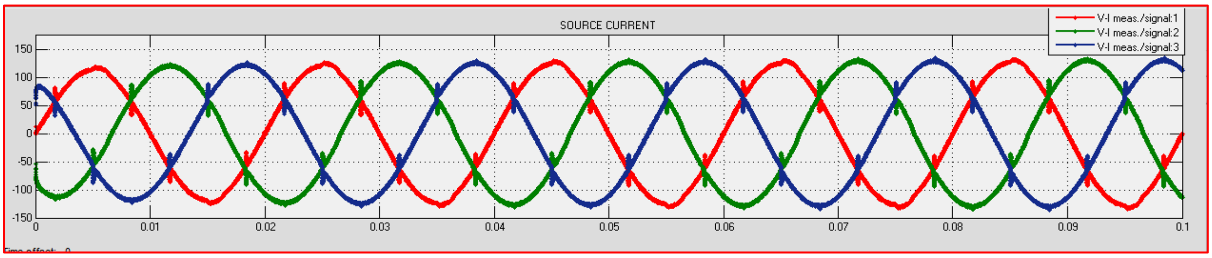

Fig. 3 Source Current

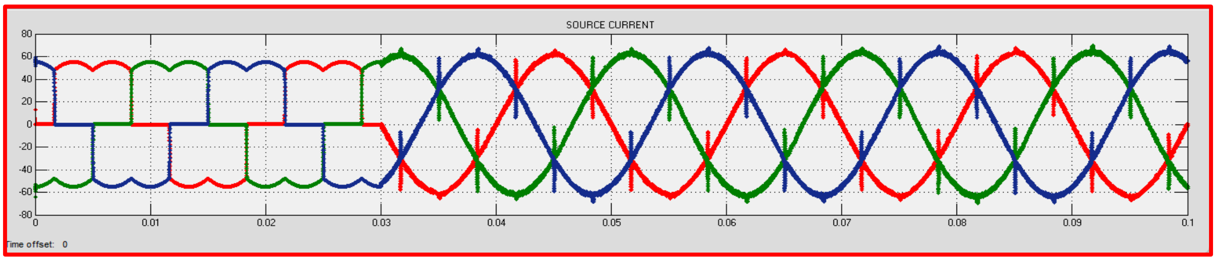

Fig.4 Source Current without Filter and with filter

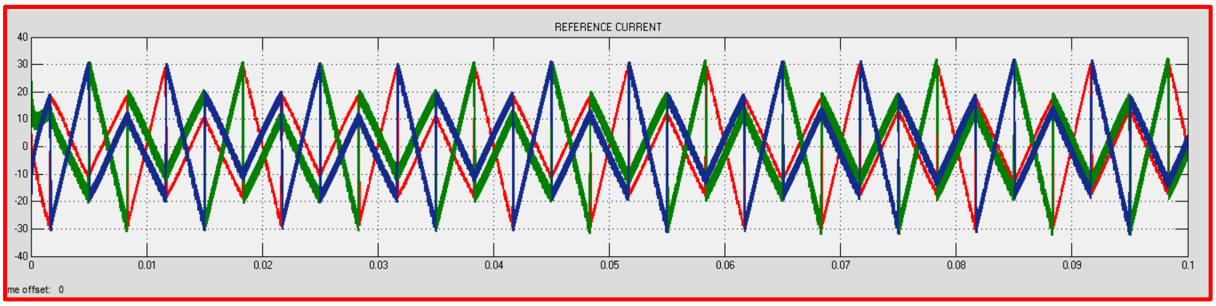

Fig. 5 Reference Current

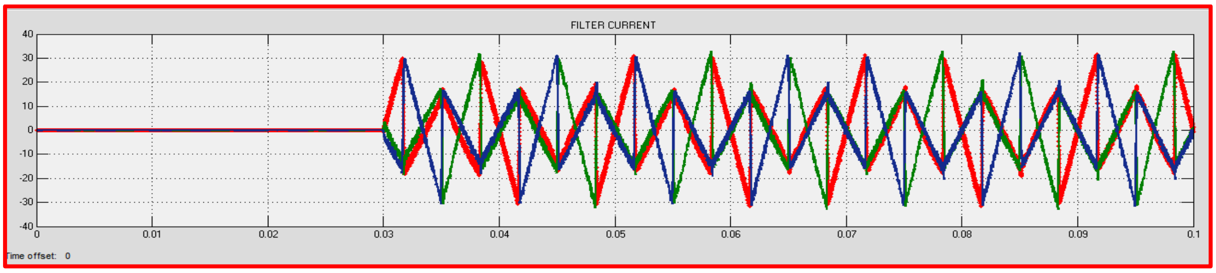

Fig. 6 Filter compensation Current

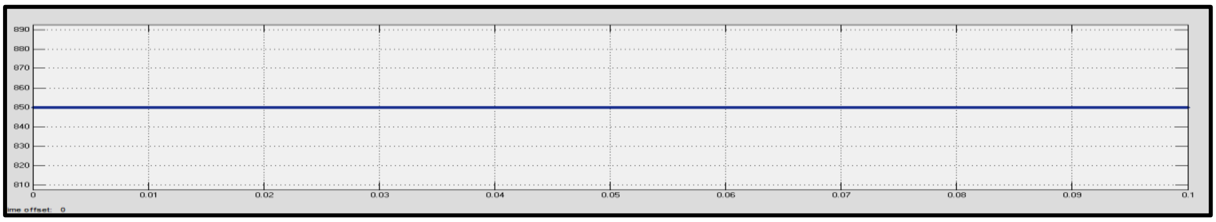

Fig. 7 DC capacitor Simulation Voltage waveform

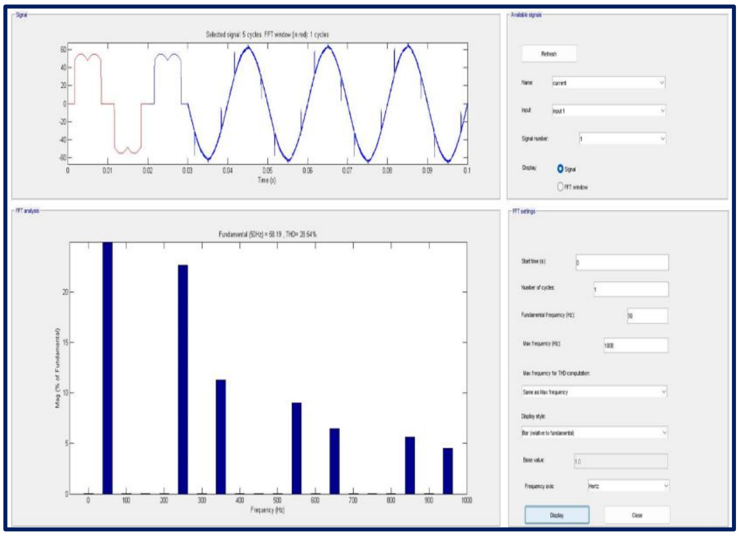

Fig. 7 THD Analysis without Filter

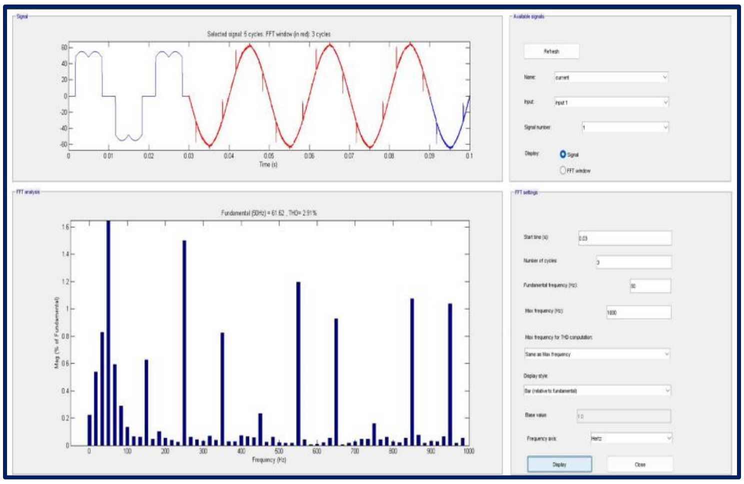

Fig.8 THD Analysis with Filter

Figures 3 and figure 4 showing the source current waveform without and with SAPF with proposed method. Figure 5 represents reference current .Figure 6 illustrate compensation current and with proposed method and the harmonic spectrum of the source current with and without SAPF, and with tuning methods shown in figure 7 and figure 8

The results demonstrate the effectiveness of the proposed LMO-based SAPF in mitigating harmonic distortion, compensating reactive power, and improving overall power quality.

7. Conclusion

This paper has presented an optimal design of a shunt active power filter (SAPF) offers a robust solution for improving power quality in electrical networks. The integration of a TID-FOPID controller with Lemur Optimization significantly enhances SAPF performance, The LMO algorithm is used to optimally tune the parameters of the SAPF controller, including the PI gains and the DC-link voltage, to minimize total harmonic distortion (THD) and improve power factor. The simulation results show that the proposed LMO-based SAPF significantly reduces the THD of the source current and improves the power factor compared to conventional PI controller tuning methods. The proposed LMO-based SAPF offers a robust and efficient solution for mitigating power quality problems and improving the performance of power systems. Future work will focus on extending the proposed approach to multi-objective optimization and exploring its application to other power quality devices.

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