Optimization Design of Single-Tuned Passive Filter Using Particle Swarm Optimization Algorithm in Industry

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ABSTRACT: In the industrial sector, the widespread use of non-linear loads such as inverters and variable speed drives has led to increased harmonic distortion, which negatively impacts power quality. These harmonics can cause equipment malfunctions, overheating, reduced system efficiency, and potential failures in power infrastructure. This study aims to optimize the design of a Single-Tuned Passive Filter (STPF) using the Particle Swarm Optimization (PSO) algorithm to minimize harmonic distortion in industrial electrical systems. Harmonic measurements in a representative system revealed Total Harmonic Distortion of current (THDi) values of 20.2%, 20.3%, and 18.6% for phases L1, L2, and L3, respectively, with the 5th and 7th harmonic orders being the most dominant. Initial simulation using standard filtering reduced THDi to 3.03%, 3.10%, and 2.89%, but significant residual harmonics were still present. By applying a PSO-optimized STPF, the THDi was further reduced to 2.42%, 2.43%, and 2.23%, indicating a marked improvement in harmonic mitigation. These findings confirm that the PSO-based design approach effectively enhances filter performance, resulting in improved power quality, increased system reliability, and better protection of electrical equipment. The implementation of the optimized STPF is particularly valuable in industrial environments such as the automotive sector, where power stability and equipment longevity are critical.

KEYWORDS: Single-Tuned Passive Filter (STPF), Particle Swarm Optimization (PSO), Total Harmonic Distortion (THDi), Individual Harmonic Distortion (IHDi), Filter Design Optimization, Industry

I. INTRODUCTION

In the Industry 4.0 era, energy supply faces significant challenges in maintaining the quality of electrical power delivered to consumers, particularly in industrial environments such as manufacturing, automotive, food processing, packaging, and others. The increasing use of non-linear electronic equipment, such as inverters, variable speed drives (VSDs), and other industrial devices, has led to the generation of harmonics in power systems [1][2][3][4].

Harmonics occur due to distortions in the sinusoidal wave of both current and voltage, which are among the primary causes of electrical system disturbances. These disturbances include increased power losses, reduced equipment efficiency, and operational failures in highly sensitive devices[5][6][7].

Uncontrolled harmonics can also cause serious issues for power system equipment such as transformers, generators, and cables, leading to overheating and insulation degradation, which can shorten the lifespan of these devices[8][9][10]. This is particularly critical for industries that rely on a stable and high-quality energy supply to maintain operational efficiency and production continuity. Harmonics standards refer to IEEE 519-2022, which regulates the allowable limits of harmonic distortion in power systems[11][12][13].

One widely used solution to address these issues is the implementation of Single-Tuned Passive Filters (STPFs) [14][15]. These filters are designed to mitigate harmonics at specific frequencies by absorbing the harmonic energy [16][17][18]. However, a suboptimal filter design may result in ineffective harmonic reduction, high installation costs, and potential resonance disturbances that could compromise the stability of the power system [19][20].

To overcome these limitations, a more advanced approach to filter design is required. Optimization algorithms, such as Particle Swarm Optimization (PSO), offer an innovative solution for designing STPFs optimally. PSO operates based on the simulation of social behavior, enabling the search for the best filter parameters through an iterative particle-based process. This approach [21][22].

II. METHOD

A. RESEARCH METHODS

The single-tuned passive filter design optimization using the Particle Swarm Optimization (PSO) algorithm begins with power quality measurement using a Power Quality Analyzer (PQA) to obtain parameters like THD and harmonics. Initial filter parameters are calculated based on IEEE standards and simulated to evaluate performance. If THD exceeds 8%, the PSO algorithm optimizes filter parameters (R, L, C) through iterative analysis. The final simulation confirms a significant THD reduction, demonstrating improved filter performance and effective optimization (See Fig. 1).

B. HARMONIC MEASUREMENT

Harmonic measurements were conducted at an automotive industry in South Tambun using a 630 kVA transformer on the secondary side. The measurement utilized the My eBox Power Quality Analyzer (PQA) integrated with the Internet of Things (IoT), enabling real-time monitoring through devices such as tablets or smartphones. The PQA was connected to the transformer's secondary side to record parameters such as voltage, current, active power, reactive power, power factor, and Total Harmonic Distortion (THD). The data was wirelessly transmitted to a cloud server, allowing remote access, historical trend analysis, and automatic anomaly notifications, one of which was the presence of a non-sinusoidal waveform.

A non-sinusoidal waveform detected by a Power Quality Analyzer (PQA) indicates harmonic distortion in the electrical system. Harmonics are sinusoidal waves with frequencies that are multiples of the system's fundamental frequency (50 Hz or 60 Hz). This distortion is caused by non-linear loads such as inverters, VFDs, switching devices, and LED lighting, which transform pure sinusoidal waveforms into complex shapes (see Fig. 2)

Measurement results showed THD values of 20.2% on L1, 20.3% on L2, and 18.6% on L3. Individual Harmonic Distortion (IHD) values indicated third-order harmonics of 4.1% (L1 and L2) and 3.9% (L3), fifth-order harmonics of 15.2% (L1), 15.3% (L2), and 14.1% (L3), and seventh-order harmonics of 12.9% (L1), 12.8% (L2), and 11.8% (L3), with smaller values for higher harmonics (see Fig. 3). These results indicate the presence of dominant low-order harmonics, requiring corrective actions to maintain power quality in compliance with the IEEE 519 2022 standard (See Tbl 1.)

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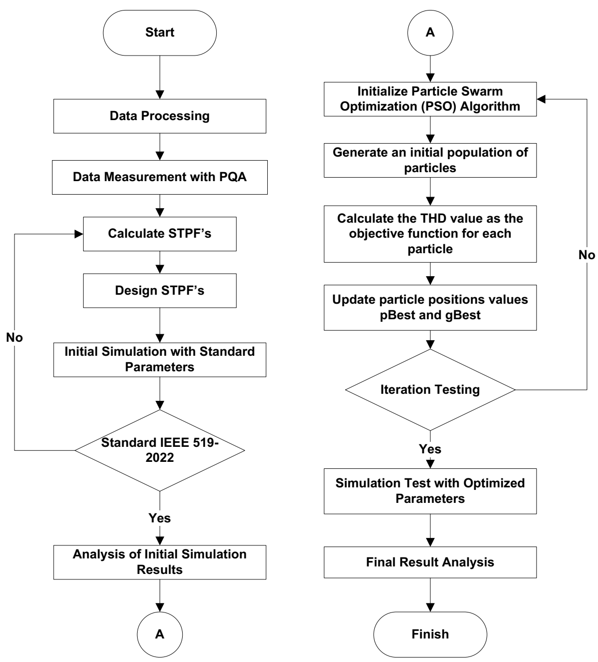


Fig 1. Research Flowchart

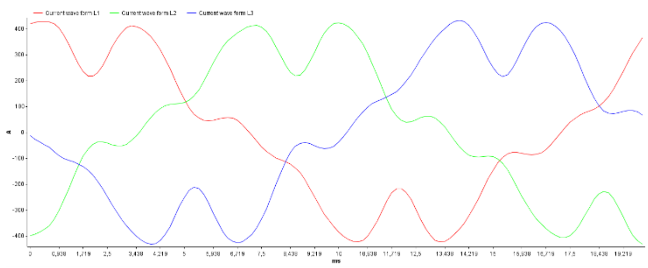


Fig 2. IHDi Waveform

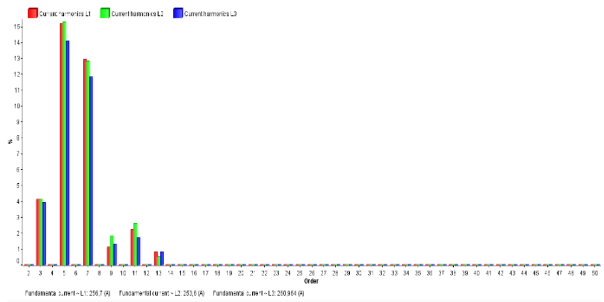


Fig 3. IHDi Measurement Results

Tbl 1. Harmonic Measurement

IHDi Order	Measurement			IEEE 519-2022 Standard
	L1	L2	L3	
3	4.1	4.1	3.9	7.0
5	15.2	15.3	14.1	7.0
7	12.9	12.8	11.8	7.0
9	1.1	1.8	1.3	7.0
11	2.2	2.6	1.7	3.5
13	0.8	0.5	0.8	3.5
15	0	0	0	3.5
Total THD	20.2	20.3	18.6	

C. SINGLE-TUNED PASSIVE FILTER DESIGN

The design of a single-tuned filter utilizes an LC circuit (inductor and capacitor) tuned to the target harmonic resonance frequency. This frequency is determined based on harmonic analysis using a Power Quality Analyzer (PQA) [1][10]. The inductance (L) and capacitance (C) values are calculated as needed, while the resistance (R) is adjusted to control the quality factor of the resonance (See Fig. 4). The filter functions by directing harmonic currents to the ground, preventing disturbances to the main load and reducing Total Harmonic Distortion (THD) in compliance with IEEE 519 standards [20][23]. Optimization of R, L, and C parameters. When designing a filter, the first step is to determine the quality of the capacitor (Qc), which can be calculated using the following formula:

$$Q_c = P\ (\tan(cos^{-1}Pf_1) - (\tan(cos^{-1}Pf_2) \quad (1)$$

After that, we determine the reactance of the capacitor, which can be calculated using the following formula :

$$X_c = \frac{V^2}{Q_c} \quad (2)$$

After obtaining the value of the capacitive reactance, the capacitance of the capacitor (C) can be determined using the formula , where ω=2πf.

$$C = \frac{1}{\omega X_c} \quad (3)$$

After that, determine the inductive reactance (X_L) using the following formula:

$$X_L = \frac{X_C}{H_0^2} \quad (4)$$

Next, determine the value of the inductor (L), which is obtained as :

$$\mathrm{L} = \frac{\mathrm{X_L}}{\omega} \quad (5)$$

After that, to determine the characteristics of the filter's reactance, the following is obtained:

$$X_n = \sqrt{\frac{L}{C}} \quad (6)$$

Then, to determine the resistor (R) value, where the quality factor (Q) lies within the range 20 < Q < 100, the following is obtained:

$$R = X_n . Q_{Filter} \quad (7)$$

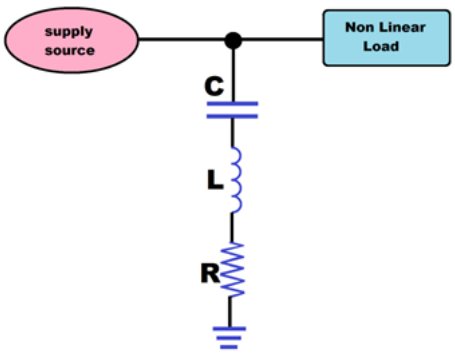


Fig 4. STPF's Design

D. OPTIMAZITATION DESIGN WITH PSO

Particle Swarm Optimization (PSO) is a metaheuristic technique inspired by the social behavior of bird flocks or fish schools to find the best solution within a search space. In PSO, each particle represents a potential solution and moves through the search space based on its velocity and position, which are iteratively updated by considering the individual's best experience (local best) and the swarm's best experience (global best). PSO is well-suited for non-linear problems, such as harmonic filter optimization, as it can handle complex objective functions without requiring function derivatives. In single-tuned filter applications, PSO is used to determine the optimal values of inductance (L), capacitance (C), and resistance (R) to minimize Total Harmonic Distortion (THD) and system power losses [21]. To determine the optimal Particle Swarm Optimization (PSO) [22], we first calculate the particle's velocity using the following equation:

$$V_i^{k+1} = \omega V_i^k + c1.rand().P_{Best_i} - X_i^k + C2.rand().(G_{Best} - X_i^k) \quad (8)$$

After determining the particle's velocity, the next step is to update the particle's position using the following equation:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (9)$$

Then, to find the maximum allowed velocity (Vmax) to determine the granularity of the search space, the following equation is obtained:

$$V_{max} = k\ x\ X_{max} \quad (10)$$

Therefore, for the iteration value, the following equation is obtained:

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iteration_{max}}\ x\ iteration \quad (11)$$

III. RESULTS AND DISCUSSION

In the 20 kV distribution system, a 555 kVA power supply from PLN feeds an automotive industry through a 630 kVA step-down transformer. Measurement results indicated harmonic levels that do not comply with the IEEE 519 standard, particularly with a significant increase in the 5th and 7th harmonic orders. To further analyze this, a simulation was conducted using MATLAB/Simulink to assess the harmonic magnitude and plan mitigation using a Single-Tuned Passive Filter (see Fig. 5).

A. SIMULATION BEFORE USING PSO

In this test, the values of C, L, and R were calculated to determine the magnitude of the components in the STPF, then simulated using MATLAB/Simulink and analyzed with Fast Fourier Transform (FFT) to evaluate the minimized harmonics. The analysis results show that for the 5th-order harmonics, the initial IHDi values of 15.2 (L1), 15.3 (L2), and 14.1 (L3) were reduced to 2.42 (L1), 2.48 (L2), and 2.31 (L3). Meanwhile, for the 7th-order harmonics, the initial IHDi values of 12.9 (L1), 12.8 (L2), and 11.8 (L3) decreased to 1.58 (L1), 1.60 (L2), and 1.50 (L3) (See Fig. 5). Overall, the Total Harmonic Distortion (THDi) was lowered to 3.03 (L1), 3.10 (L2), and 2.89 (L3), demonstrating the effectiveness of the implemented harmonic mitigation strategy (See Tbl 2.).

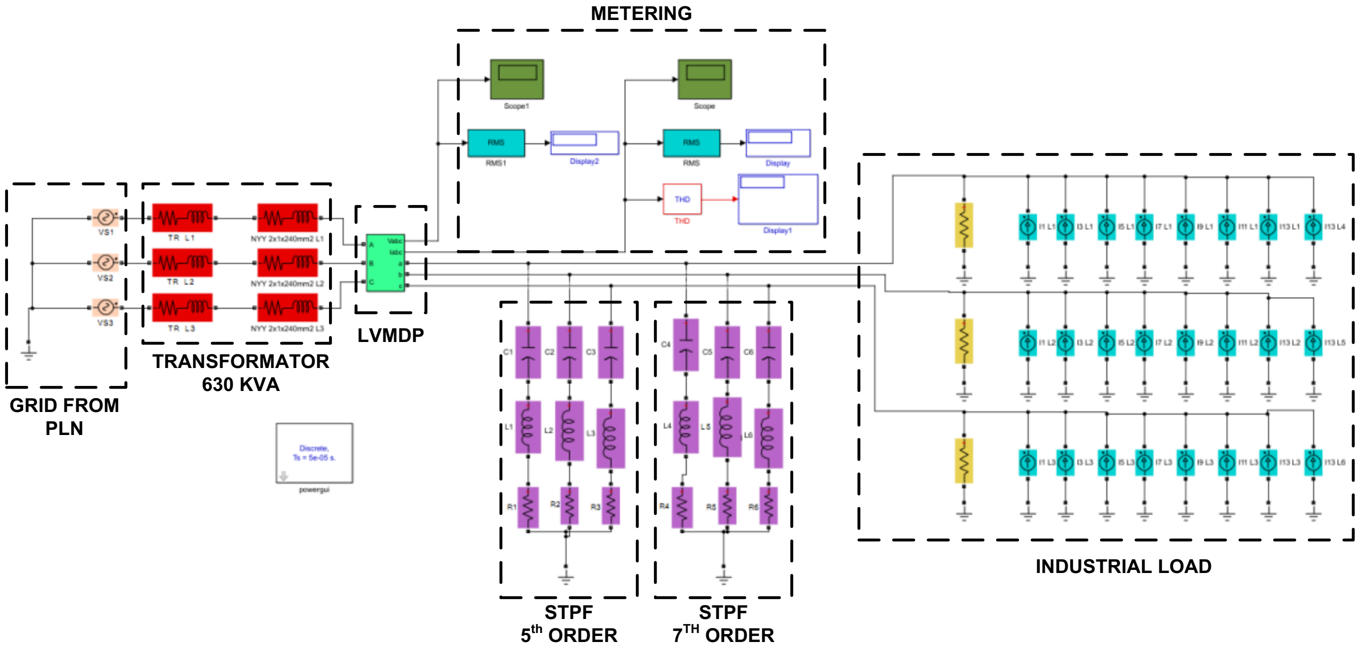


Fig 5. Industrial Network System with STPF's

Tbl 2. Harmonic Before PSO

IHDi Order	Simulation Before PSO			IEEE 519-2022 Standard
	L1	L2	L3	
3	0.89	0.91	0.87	7.0
5	2.42	2.48	2.31	7.0
7	1.58	1.60	1.50	7.0
9	0.11	0.18	0.13	7.0
11	0.18	0.22	0.15	3.5
13	0.06	0.04	0.06	3.5
15	0	0	0	3.5
Total THD	3.03	3.10	2.89	

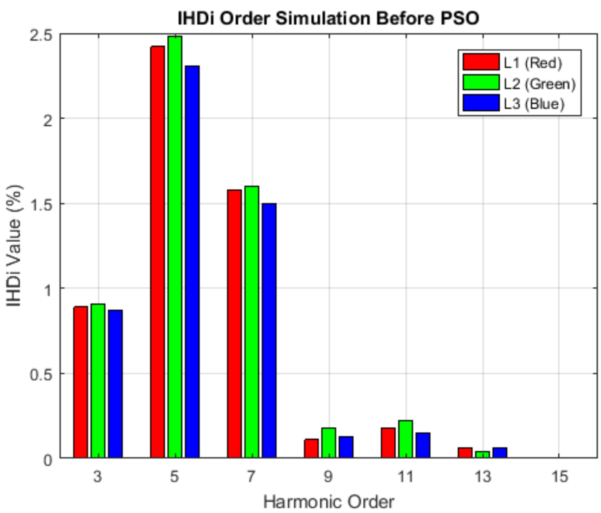


Fig 6. IHDi Graph Before Simulation

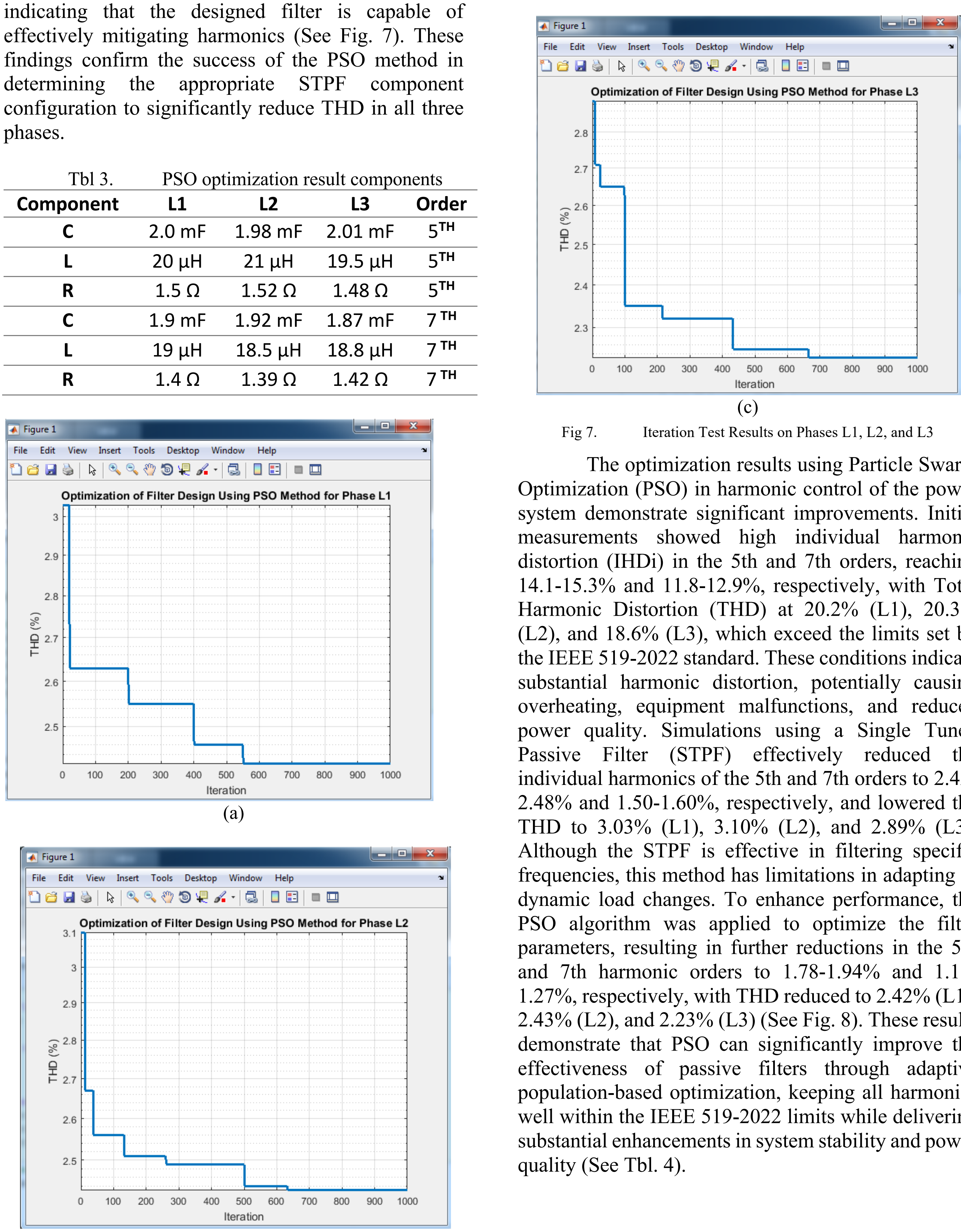
B. Simulation Using the Particle Swarm Optimization (PSO) Method

An iterative approach based on Particle Swarm Optimization (PSO) is applied to optimize the component parameters in the design of STPF with the aim of reducing harmonic distortion in the 5th and 7th orders. The iterative test is carried out by systematically varying the values of the capacitor, inductor and resistor to obtain optimal values. For the 5th order the optimal values are a capacitor of 2.0 mF on L1, 1.98 mF on L2 and 2.01 mF on L3, an inductor of 20 µH on L1, 21 µH on L2 and 19.5 µH on L3, as well as a resistor of 1.5 Ω on L1, 1.52 Ω on L2 and 1.48 Ω on L3. Meanwhile for the 7th order the obtained optimal values consist of a capacitor of 1.9 mF on L1, 1.92 mF on L2 and 1.87 mF on L3, an inductor of 19 µH on L1, 18.5 µH on L2 and 18.8 µH on L3, as well as a resistor of 1.4 Ω on L1, 1.39 Ω on L2 and 1.42 Ω on L3 (See Tbl. 3). The results of the iterative test, which are verified through simulation using MATLAB Simulink, demonstrate the consistency and validity of the optimal parameters so that they can be effectively implemented in automotive industry applications.

The PSO iterative test results for phases L1, L2, and L3 show that the THD value consistently decreases as the number of iterations increases, until it reaches a convergence point. Each phase exhibits a similar pattern of THD reduction, where initially the THD is relatively high and gradually decreases as the particles in the PSO population share information about the best positions. This process yields an optimal solution, marked by a stable THD value at the final iteration, indicating that the designed filter is capable of effectively mitigating harmonics (See Fig. 7). These findings confirm the success of the PSO method in determining the appropriate STPF component configuration to significantly reduce THD in all three phases.

Tbl 3. PSO optimization result components

Component	L1	L2	L3	Order
C	2.0 mF	1.98 mF	2.01 mF	5TH
L	20 µH	21 µH	19.5 µH	5TH
R	1.5 Ω	1.52 Ω	1.48 Ω	5TH
C	1.9 mF	1.92 mF	1.87 mF	7 TH
L	19 µH	18.5 µH	18.8 µH	7 TH
R	1.4 Ω	1.39 Ω	1.42 Ω	7 TH



(a)
(b)
(c)

Fig 7. Iteration Test Results on Phases L1, L2, and L3

The optimization results using Particle Swarm Optimization (PSO) in harmonic control of the power system demonstrate significant improvements. Initial measurements showed high individual harmonic distortion (IHDi) in the 5th and 7th orders, reaching 14.1-15.3% and 11.8-12.9%, respectively, with Total Harmonic Distortion (THD) at 20.2% (L1), 20.3% (L2), and 18.6% (L3), which exceed the limits set by the IEEE 519-2022 standard. These conditions indicate substantial harmonic distortion, potentially causing overheating, equipment malfunctions, and reduced power quality. Simulations using a Single Tuned Passive Filter (STPF) effectively reduced the individual harmonics of the 5th and 7th orders to 2.42-2.48% and 1.50-1.60%, respectively, and lowered the THD to 3.03% (L1), 3.10% (L2), and 2.89% (L3). Although the STPF is effective in filtering specific frequencies, this method has limitations in adapting to dynamic load changes. To enhance performance, the PSO algorithm was applied to optimize the filter parameters, resulting in further reductions in the 5th and 7th harmonic orders to 1.78-1.94% and 1.16-1.27%, respectively, with THD reduced to 2.42% (L1), 2.43% (L2), and 2.23% (L3) (See Fig. 8). These results demonstrate that PSO can significantly improve the effectiveness of passive filters through adaptive population-based optimization, keeping all harmonics well within the IEEE 519-2022 limits while delivering substantial enhancements in system stability and power quality (See Tbl. 4).

Tbl 4. Harmonic Using PSO

IHDi Order	Simulation Using PSO			IEEE 519-2022 Standard
	L1	L2	L3	
3	0.70	0.70	0.66	7.0
5	1.93	1.94	1.78	7.0
7	1.27	1.27	1.16	7.0
9	0.09	0.14	0.10	7.0
11	0.15	0.17	0.11	3.5
13	0.05	0.03	0.05	3.5
15	0	0	0	3.5
Total THD	2.42	2.43	2.23	

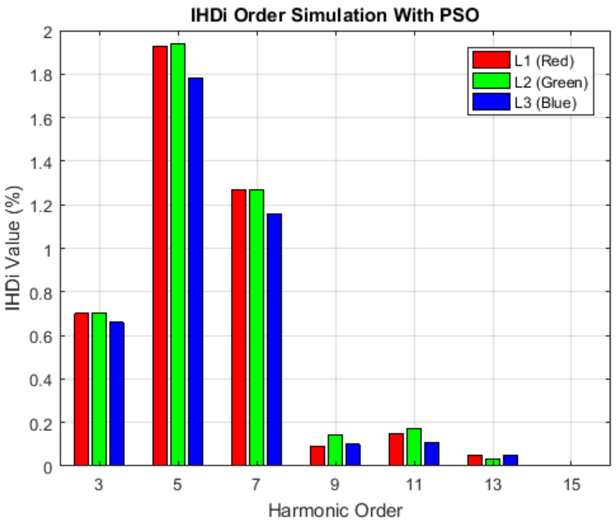


Fig 8. IHDi Graph Simulation Using PSO

IV. CONCLUSION

The optimization results using Particle Swarm Optimization (PSO) for harmonic control in the power system show substantial improvements. Initial measurements revealed high Total Harmonic Distortion (THD) values of 20.2% on L1, 20.3% on L2, and 18.6% on L3, with individual harmonic distortion (IHDi) for the 5th and 7th orders reaching 14.1-15.3% and 11.8-12.9%, respectively. These figures significantly exceeded the IEEE 519-2022 standard limits, indicating a critical need for harmonic mitigation. Implementing a Single Tuned Passive Filter (STPF) effectively reduced IHDi in the 5th and 7th orders to 2.42-2.48% and 1.50-1.60%, with THD decreased to 3.03% (L1), 3.10% (L2), and 2.89% (L3). However, due to the STPF's limited adaptability to dynamic load changes, the PSO algorithm was introduced for filter parameter optimization. This approach further reduced the 5th and 7th order harmonics to 1.78-1.94% and 1.16-1.27%, achieving lower THD values of 2.42% (L1), 2.43% (L2), and 2.23% (L3). The PSO-based optimization demonstrated a consistent decrease in harmonic levels, maintaining all harmonics within the IEEE 519-2022 thresholds, thereby enhancing power quality and system stability effectively

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