

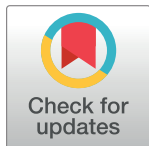
RESEARCH ARTICLE

A new flowchart for parameters calculation of Hybrid Active Power Filter with Injection Circuit

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Abstract

This paper presents a new flowchart for parameters calculation of Hybrid Active Power Filter with Injection Circuit (IHAPF). The first is the necessity to use the IHAPF model and the parameters of the IHAPF needed to search have been shown. Next, the constraints of the parameters to be searched and the objective function to be reached are given. Since then a flowchart is designed to look for parameters of IHAPF using the Jaya optimization algorithm. The Jaya algorithm has the advantage of simplicity, few parameters, and good performance. Therefore it reduces search time. Compared to the flowchart using the firefly algorithm, particle swarm optimization algorithm, and simulated annealing algorithm, the simulation results performed on an IHAPF 10kV-50Hz model have proven that: the proposed flowchart gives better results in minimizing the compensation errors, minimum phase shift angle between supply current, and source voltage, minimum total harmonic distortion of supply current.

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Introduction

As we all know, harmonics that exist on the power system will cause many very serious problems such as: overheating, overload, information interference, etc. Accordingly, to cancel harmonic problems and improve power factors in power systems, the Hybrid Active Power Filter with Injection Circuit (IHAPF) model is considered as one of the most effective solutions [1–5]. IHAPF also has many different structures to use for many different voltage levels, many different types of loads.

The problem here is that once the IHAPF structure is selected, the most important issue is the correct calculation of the parameters of an IHAPF system. The IHAPF is a hybrid of Active Power Filter (APF), and Passive Power Filters (PPF) [6–8]. Therefore, the parameters of an IHAPF usually include the parameters of the passive circuit part, and the parameters of the active circuit part. Passive circuit part parameters are parameters of a serial resonance circuit LR-C at a certain harmonic frequency, often resonating at high order harmonics 11th, and 13th. The parameters of the active circuit part include parameters of the injection circuit LR-C, the output filter of the inverter, the DC-link voltage of the inverter, and the parameters of the

Proportional–Integral (PI) controller. All IHAPF parameters shall be designed such that it satisfies all the constraints of the parameters, and minimum total harmonic distortion of the supply current, minimum the compensation error, and minimum phase shift angle between the supply current, and source voltage in steady state. This is a multi-objective optimization design problem.

Accordingly, to solve multi-objective optimization problems in general, the Genetic Algorithm (GA) [9, 10], and Particle Swarm Optimization (PSO) [11–13] algorithms are most often used. When applied to the IHAPF system, the GA algorithm is often used to design multi-objective optimizations for PPF parameters [14–17]. Meanwhile, the PSO algorithm is also used for designing PPF parameters but more than the GA algorithm because it usually gives better results [18–23]. However, the PSO algorithm also has the disadvantage that the search space is limited. Therefore, several studies have used a combination of PSO, and GA algorithms [24, 25]. A few studies have also applied Bat [26], and Ant Colony algorithms [27] to design multi-objective optimization of PPF parameters. The latest research, which is highly accurate, and efficient, has been applied to HAPF to find out PPF parameters to minimize the total harmonic distortion of source current, and source voltage [28, 29].

In summary, the multi-objective optimization methods applied to HAPF have largely found an optimal set of parameters PPFs for HAPF. However, the above methods are limited by the slow search speed, and especially only the parameters for the passive circuit part, and the parameters of the active circuit part are not mentioned. Therefore, this paper introduces a new multi-objective optimization design flowchart for the Hybrid Active Power Filter with Injection Circuit using the Jaya algorithm [30–32]. A firefly algorithm (FA) is proposed for Stochastic Test Functions and Design Optimisation in [33]. Jaya has been successful in solving a large range of optimization problems such as Optimal power flow, constrained Multi-objective optimization problem, optimize parameter for a neural network [34–37]. The advantage of this algorithm is simple, giving fast results. To prove the effectiveness of the proposed design flowchart, the simulation results were performed on the same model with the application of the Jaya, firefly algorithm, particle swarm optimization algorithm, and simulated annealing (SA) algorithm. The simulation results have proved that: the flowchart of applying Jaya algorithm give parameters set is better than that of applying firefly algorithm, particle swarm optimization algorithm, and simulated annealing algorithm in minimizing the total harmonic distortion of supply current, minimizing compensation error, minimize the phase shift angle between supply current, and source voltage, and especially, the calculation time is shorter.

The paper is structured in four parts: Part 1 presents the necessary of the problem to be studied, part 2 introduces the model, and the parameters needed to design, part 3 introduces the multi-objective optimization design flowchart for IHAPF using the Jaya algorithm, the simulation, and discussion results are presented in part 4, and finally the conclusions are drawn in part 5.

IHAPF model, and necessary design parameters

Let us consider a model IHAPF shown in Fig 1.

The parameters of the passive circuit part include: C_p , and L_p R_p are the capacitors, and inductors of passive power filters (R_p is the internal resistance of L_p), it used to filter high order harmonics. C_F is the injection capacitor, the L_1 , and C_1 are the fundamental resonance capacitor, and inductor, the $L_1 R_1 - C_1$ branch resonates at the fundamental frequency, (R_1 is the internal resistance of L_1). C_F combined with $L_1 R_1 - C_1$ forms an injection circuit that to filter harmonics, compensate reactive power. Furthermore, it reduces the voltage applied to the inverter. Therefore the capacity of the inverter is reduced. The coupling transformer is used to

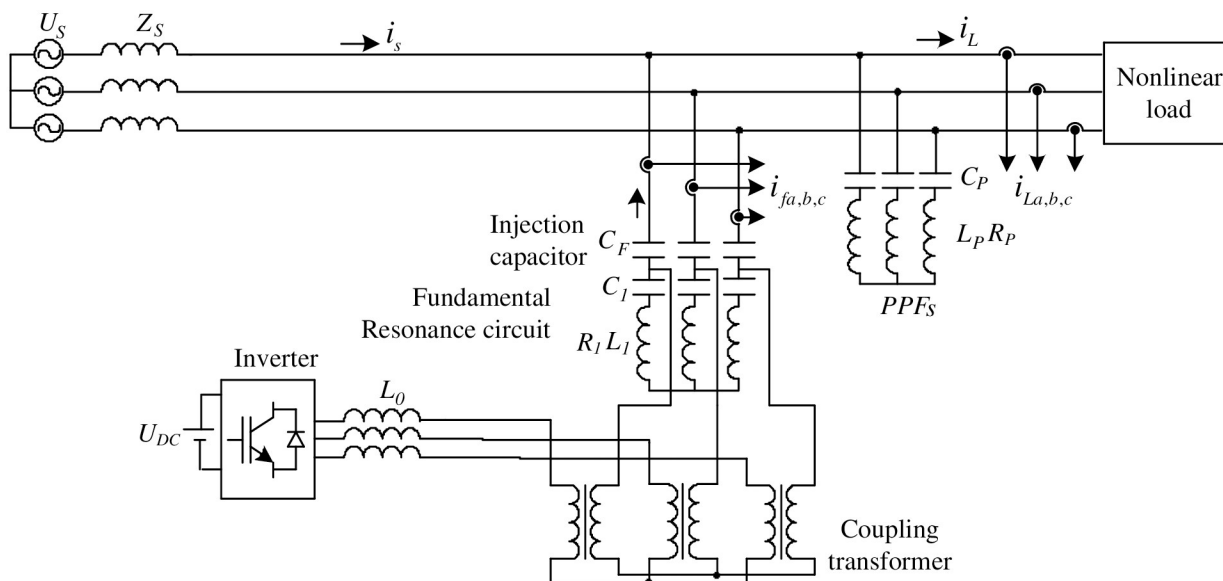


Fig 1. Structure of an IHAPF.

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isolate the system, and the inverter. The output filter L_0 has the effect of reducing the voltage spikes at the output of the inverter when the inverter is switching at high frequency. The inverter used in this model is a voltage source inverter with a U_{DC} power supply. Parameters of the active circuit part include: K_p , and K_i of the PI controller.

Control block diagram for IHAPF is described in Fig 2. The three-phase load current i_{Labc} through the $i_p - i_q$ harmonic detection circuit [20] to separate harmonic components i_{Lhabc} . These are reference signals. The compensation current i_{fabc} is also connected to the $i_p - i_q$ harmonic detection circuit to separate harmonic components i_{fhabc} , which are considered as actual signals. The error between the actual signals, and the reference signals will be passed through the PI controllers (including the parameters K_p , and K_i) to minimize this error. The output of the PI controller will be compared with the high frequency carrier wave to create pulse into inverter. Thus, the parameters to be determined for the IHAPF system include: C_F (F), R_I (Ω), L_I (H), C_I (F), R_{I1} (Ω), L_{I1} (H), C_{I1} (F), R_{I3} (Ω), L_{I3} (H), C_{I3} (F), L_0 (H), U_{DC} (V), K_p , and K_i .

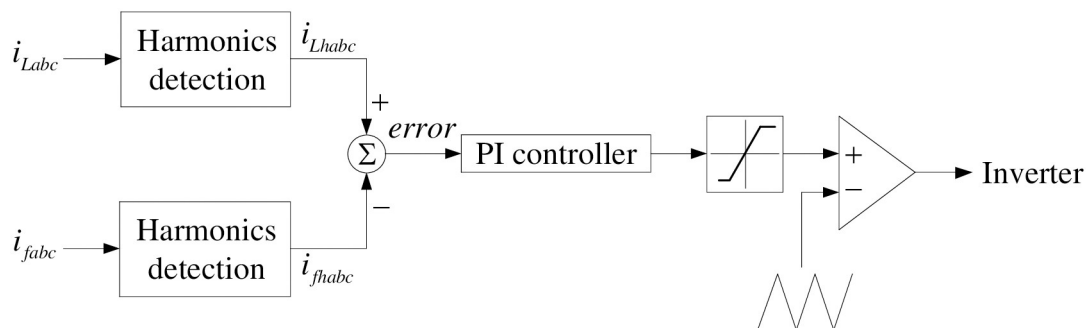


Fig 2. IHAPF control block diagram.

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Multi-objective optimization design for parameters of IHAPF using Jaya algorithm

Constraints, and objective functions

- Constraint on parameters of R_i , L_i , C_i : values of R_i , L_i , C_i must be positive and must be ensured to compensate a minimum amount of reactive power and not exceed the maximum limit to be compensated. Therefore:

$$0 < R_i < R_{i-\max} \quad (1)$$

$$0 < L_i < L_{i-\max} \quad (2)$$

$$0 < C_i < C_{i-\max} \quad (3)$$

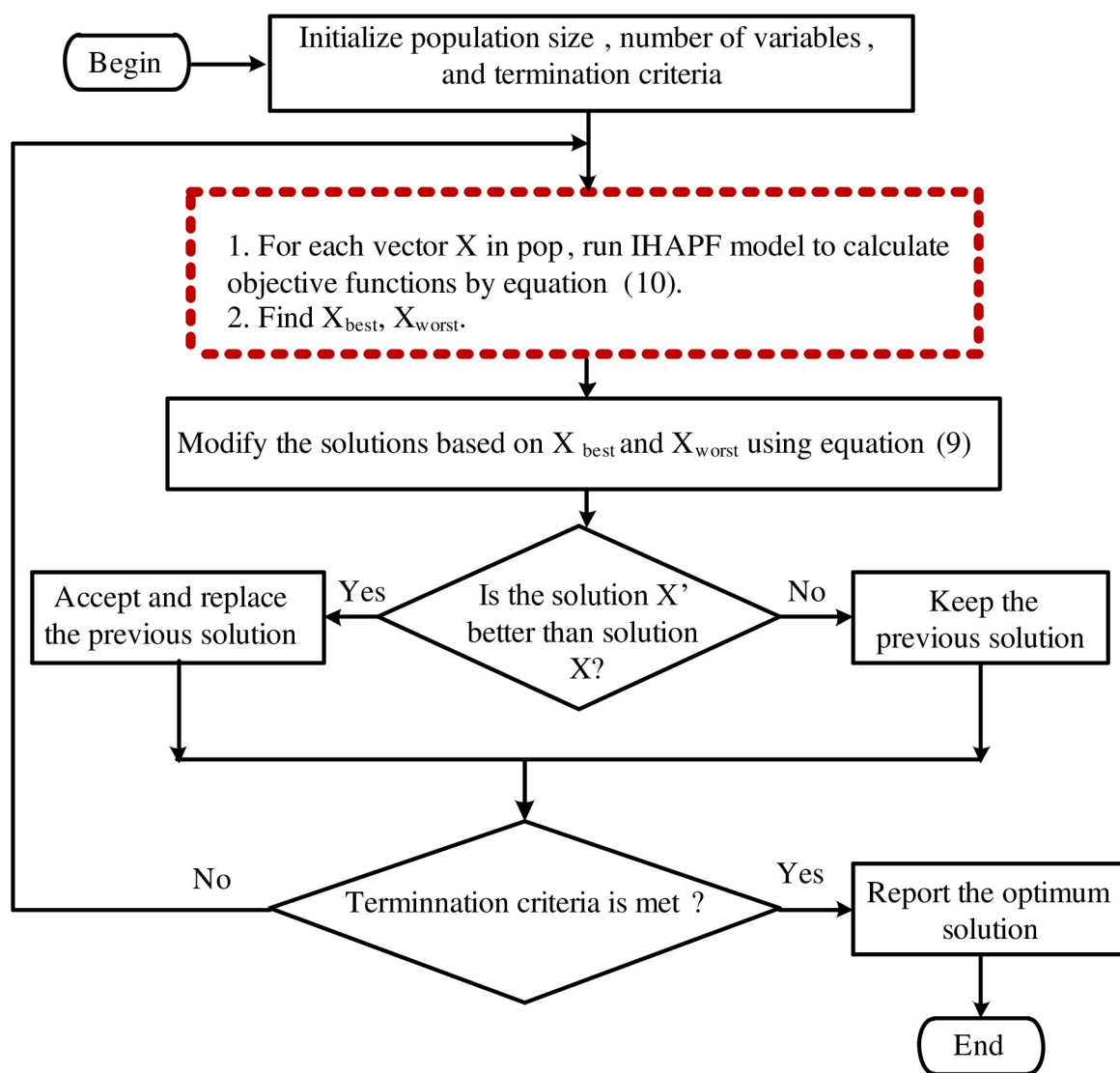


Fig 3. Flowchart for parameters calculation design for IHAPF using Jaya algorithm.

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- Constraints on DC-link voltage values: a small value of DC bus voltage will not provide enough power to the inverter output, a large value of DC bus voltage will contribute to increased losses during switching. Therefore:

$$U_{DC-\min} < U_{DC} < U_{DC-\max} \quad (4)$$

- Constraints on reactive power capacity to be compensated: The total compensation capacity $Q_{b\Sigma}$ must be maximum but not exceeding the maximum capacity to be compensated, which is based on the desired $\cos\phi$ min-max value. Here, the value $\cos\phi$ is usually chosen as the smallest is 0.85, and the largest is 1.0. When $\cos\phi = 1$, that mean phase shift angle between supply current, and the source voltage is zero. Therefore the total compensation capacity is limited by:

$$Q_{b\Sigma-\min} < Q_{b\Sigma} < Q_{b\Sigma-\max} \quad (5)$$

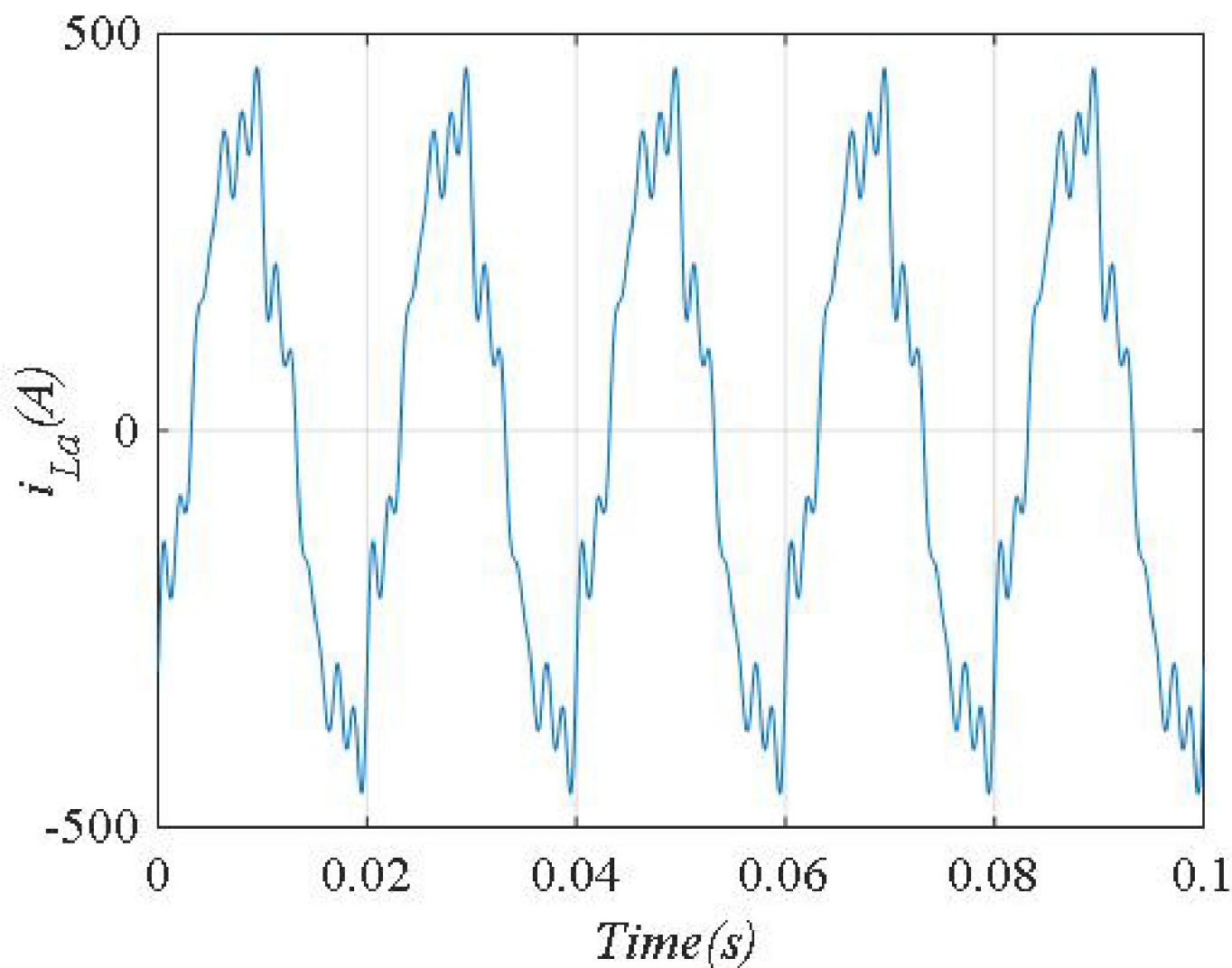


Fig 4. Load current waveform.

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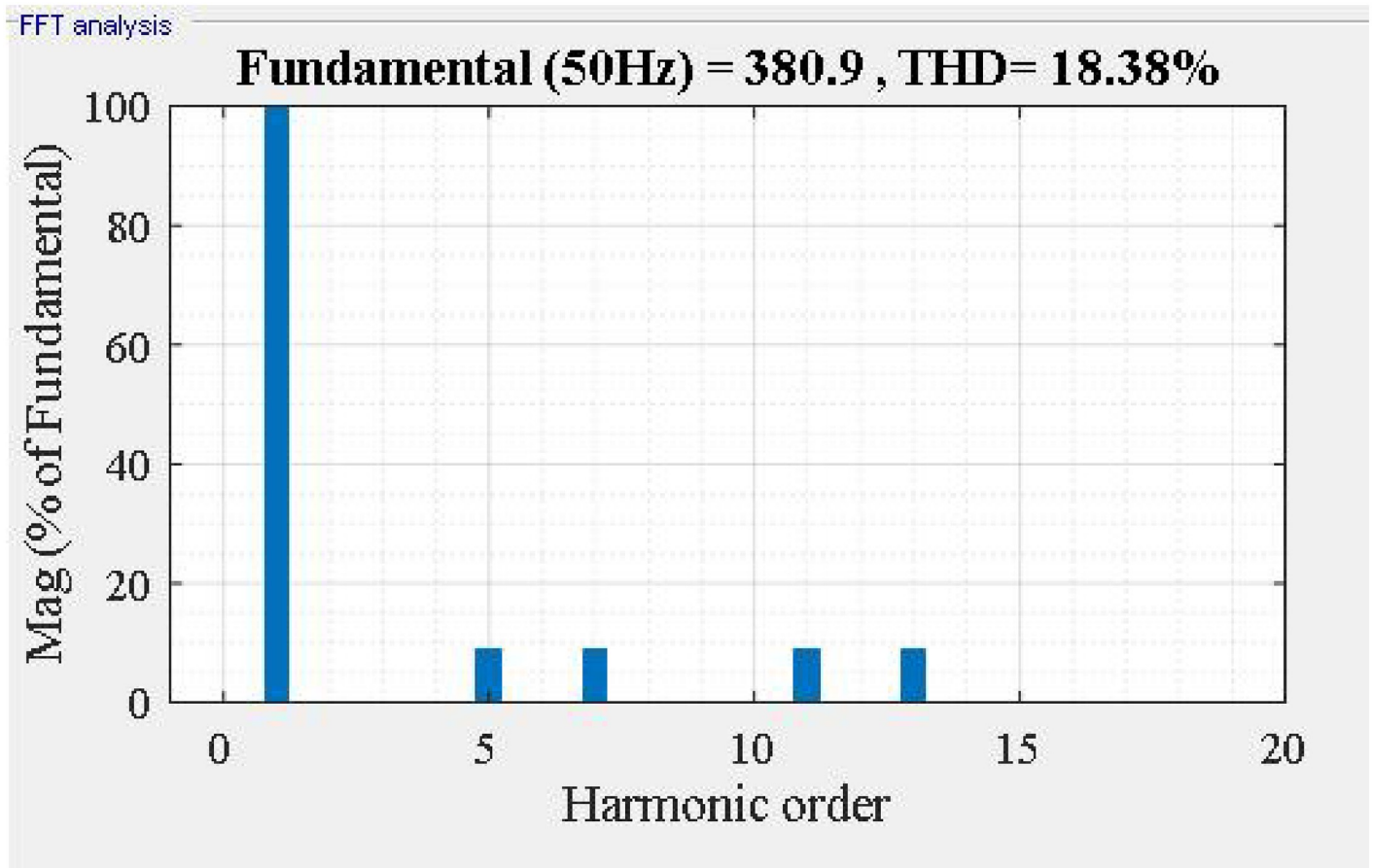


Fig 5. Frequency spectrum of i_{La} .

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Table 1. The results when using PSO algorithm.

	Iteration No. = 1	Iteration No. = 2	Iteration No. = 3	Iteration No. = 4	Iteration No. = 5
f_1	2.924038e-05	2.924038e-05	2.924038e-05	4.914723e-05	4.914723e-05
f_2	0.01048602	0.01048602	0.01048602	0.01712694	0.01712694
f_3	0.01258446	0.01258446	0.01258446	0.01500472	0.01500472
f_4	0.0004634158	0.0004634158	0.0004634158	0.000382653	0.000382653
f_5	0.01810615	0.01810615	0.01810615	0.01059619	0.01059619
f_6	0.001708113	0.001708113	0.001708113	0.001681972	0.001681972
f_7	4.124338e-05	4.124338e-05	4.124338e-05	4.680448e-05	4.680448e-05
f_8	0.01993343	0.01993343	0.01993343	0.01042431	0.01042431
f_9	0.001650619	0.001650619	0.001650619	0.001071445	0.001071445
f_{10}	1.975492e-05	1.975492e-05	1.975492e-05	3.086599e-05	3.086599e-05
f_{11}	0.0005561522	0.0005561522	0.0005561522	0.000374114	0.000374114
f_{12}	785.2274	785.2274	785.2274	745.4446	745.4446
f_{13}	62.60184	62.60184	62.60184	84.5074	84.5074
f_{14}	0.7431786	0.7431786	0.7431786	0.7604024	0.7604024
Best Cost	1.9142	1.9142	1.9142	1.5843	1.5843

<https://doi.org/10.1371/journal.pone.0253275.t001>

Table 2. The results when using PSO algorithm (continued).

	Iteration No. = 6	Iteration No. = 7	Iteration No. = 8	Iteration No. = 9	Iteration No. = 10
f_1	4.144803e-05	4.377235e-05	4.377235e-05	4.263329e-05	4.263329e-05
f_2	0.01993759	0.01045568	0.01045568	0.01534102	0.01534102
f_3	0.01933229	0.01290587	0.01290587	0.01542507	0.01542507
f_4	0.0006829551	0.0001927401	0.0001927401	0.0003625335	0.0003625335
f_5	0.01360928	0.01561335	0.01561335	0.01937979	0.01937979
f_6	0.001644205	0.001633333	0.001633333	0.001945282	0.001945282
f_7	1.271789e-05	3.496854e-05	3.496854e-05	3.873805e-05	3.873805e-05
f_8	0.01207912	0.01930776	0.01930776	0.01219119	0.01219119
f_9	0.00187596	0.001977769	0.001977769	0.001882403	0.001882403
f_{10}	2.798992e-05	2.359759e-05	2.359759e-05	2.091486e-05	2.091486e-05
f_{11}	0.0002712869	0.0003684738	0.0003684738	0.0002357758	0.0002357758
f_{12}	640.8078	698.5205	698.5205	602.5295	602.5295
f_{13}	36.87138	64.24956	64.24956	63.69255	63.69255
f_{14}	0.2350871	0.1970984	0.1970984	0.2389422	0.2389422
Best Cost	1.4197	1.129	1.129	0.91005	0.91005

<https://doi.org/10.1371/journal.pone.0253275.t002>

- Constraints on PI controller parameters: in this study, we chose PI controller, so the parameters we need to know are K_p , and K_i . Small K_p parameters will have a slow response but less overshoot, whereas too large K_p will cause instability, and overshoot. The small K_i parameter usually gives a small overshoot at the set, and the large K_i will not minimize the error in steady-state. Therefore, when controlling we often combine two parameters K_p and K_i together, usually, K_p is big, and K_i is small.

$$0 < K_p < K_{pmax} \quad (6)$$

$$0 < K_i < K_{imax} \quad (7)$$

- Objective Functions: The main objective functions considered here are minimum the compensation errors, minimum the phase shift angle between supply current, and source voltage, minimum the total harmonic distortion of supply current.

$$\begin{cases} \min THD_{i_s} \\ \min error \\ \min(\angle(u_s, i_s)) \end{cases} \quad (8)$$

Flowchart for parameters calculation design for IHAPF using Jaya algorithm

We call $f(x)$ is the objective function of a minimized problem. n is the dimensional of the problem. There are $popsize$ candidate in each iteration are update.

Each iteration, each new solution X'_i candidate is calculated by formula (9):

$$X'_i = X_i + r_1(X_{best} - |X_i|) - r_2(X_{worst} - |X_i|) \quad (9)$$

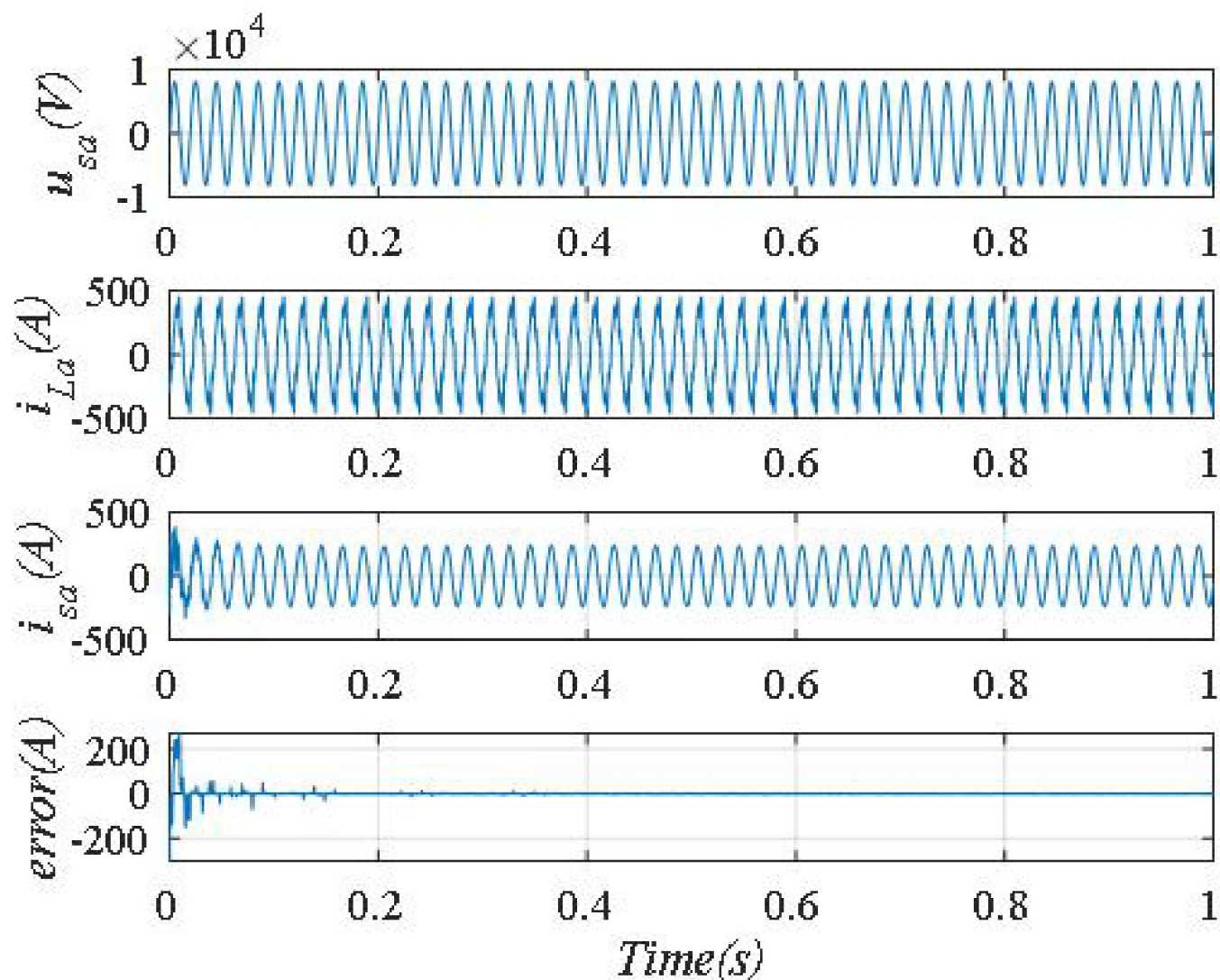


Fig 6. The waveforms corresponding to the best parameter set using the PSO algorithm.

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where, $X_i = (x_1, x_2, \dots, x_n)$ is i^{th} candidate. X_{best} and X_{worst} are the best, and worst candidate respectively. r_1 , and r_2 are two random numbers in $[0, 1]$.

X'_i is the updated value of X_i . The term $r_1 (X_{best} - |X_i|)$ guide potential solution to move closer to the best solution, and the term $r_2 (X_{worst} - |X_i|)$ guide potential solution to avoid the worst solution. X_i is replaced by X'_i if X'_i gives better function value. Fig 3 shows the flowchart of the proposed algorithm. According two these factors, the algorithm performs the explore, and exploit functions.

The pseudo-code of JAYA algorithm for IHAPF is shown in Algorithm 1.

Algorithm 1: The pseudo-code of Jaya algorithm for IHAPF

1. Initialize population size (*Popsize*), number of variables, and terminated criteria (*Max_Iteration*)
2. **While** Termination criteria is not met **do**
3. For each solution X_i in pop, run IHAPF model;

4. Evaluate fitness functions based on the outputs of IHAPF model and Eq (10);
5. Calculate the X_{best} and X_{worst} ;
6. **For** $i = 1$ to $popsize$ **do**
7. Calculate solution X'_i by Eq (9);
8. If X'_i is better, replace X_i by X'_i .
9. **End for**
10. Increase iteration number by one;
11. **End while**.
12. **End Algorithm**

Solution presentation. The parameters to search for IHAPF model include: C_F (F), R_1 (Ω), L_1 (H), C_1 (F), R_{11} (Ω), L_{11} (H), C_{11} (F), R_{13} (Ω), L_{13} (H), C_{13} (F), L_0 (H), U_{DC} (V), K_p , and K_i corresponding to the values $f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8, f_9, f_{10}, f_{11}, f_{12}, f_{13}$, and f_{14} .

A vector $X = (f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8, f_9, f_{10}, f_{11}, f_{12}, f_{13}, f_{14})$ is used to present the solution of the optimization problem.

Fitness function. When applied Jaya for IHAPF, the evaluate fitness function is calculated using the output of IHAPF model and Eq 10. For each X_i in pop, the simulation IHAPF model is called. After running the model, $THDi_s$, $error$, and $\angle(u_s, i_s)$ are produced. In this research, multi-objective problem is converted to single-objective problem. Finally, the fitness function is calculated by Eq 10.

$$\text{Min } f(X) = THDi_s + error + \angle(u_s, i_s) \quad (10)$$

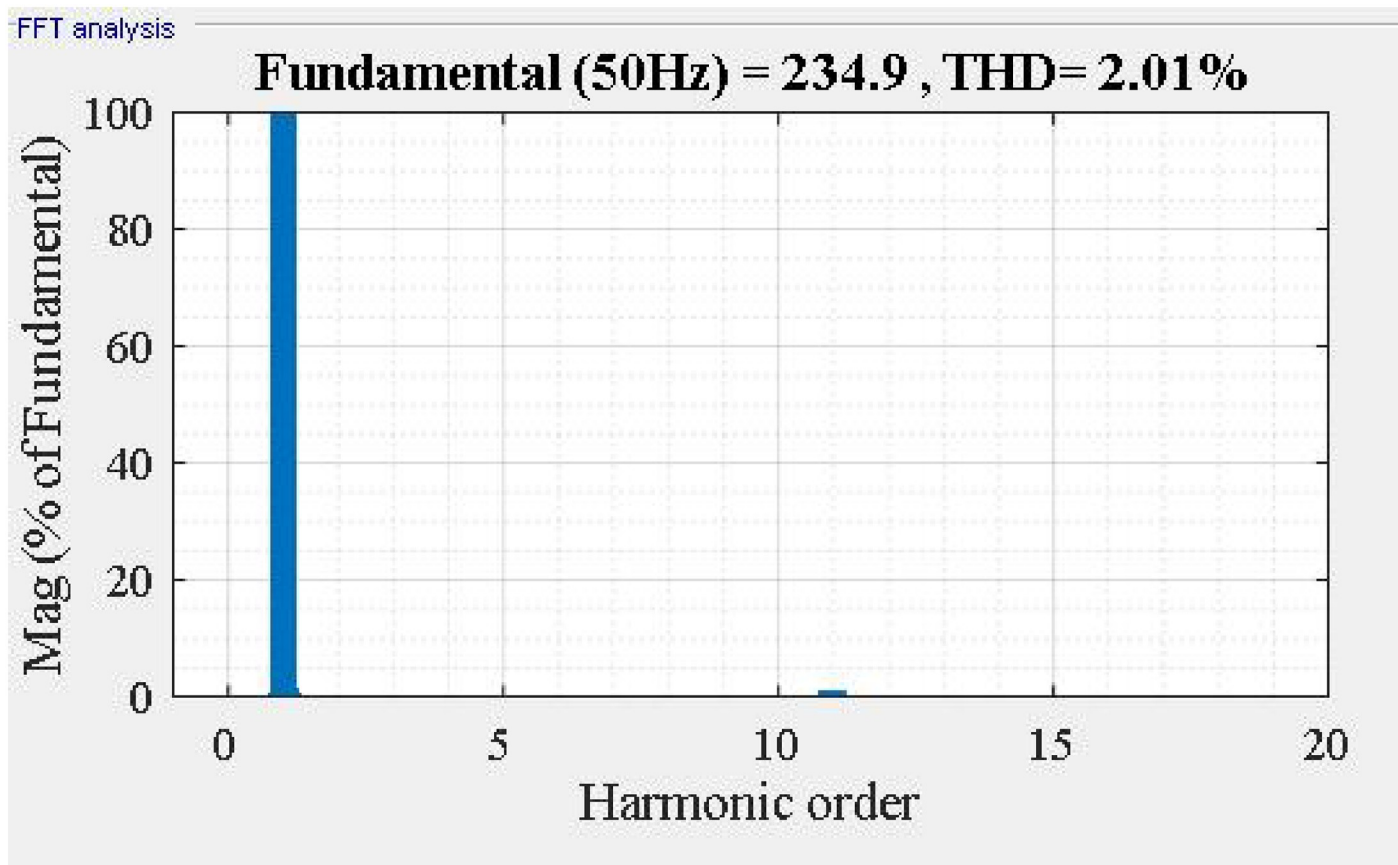


Fig 7. Frequency spectrum of supply current i_{sa} .

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Simulation results, and discussion

To prove the effectiveness of the proposed design flowchart, the parameters needed to search for IHAPF 10kV-50Hz model in Fig 1 will be implemented in turn with four algorithms, the search algorithm using the Jaya, FA, PSO and SA. The parameters to search for IHAPF model include: C_F (F), R_1 (Ω), L_1 (H), C_1 (F), R_{11} (Ω), L_{11} (H), C_{11} (F), R_{13} (Ω), L_{13} (H), C_{13} (F), L_0 (H), U_{DC} (V), K_p , and K_i corresponding to the values $f_1, f_2, f_3, f_4, f_5, f_6, f_7, f_8, f_9, f_{10}, f_{11}, f_{12}, f_{13}$, and f_{14} .

Initially, the nonlinear load current, and its frequency spectrum are shown in Figs 4 and 5. The nonlinear load current is lag compared to the source voltage, and the power factor before compensation is 0.64 (lag).

When PSO algorithm is used we have the results as in Tables 1 and 2.

Elapsed time is 2049.0846 seconds, and the best cost value in steady-state is 0.91005 in iteration No. 10.

The waveforms corresponding to the best parameter set using the PSO algorithm are shown in Fig 6.

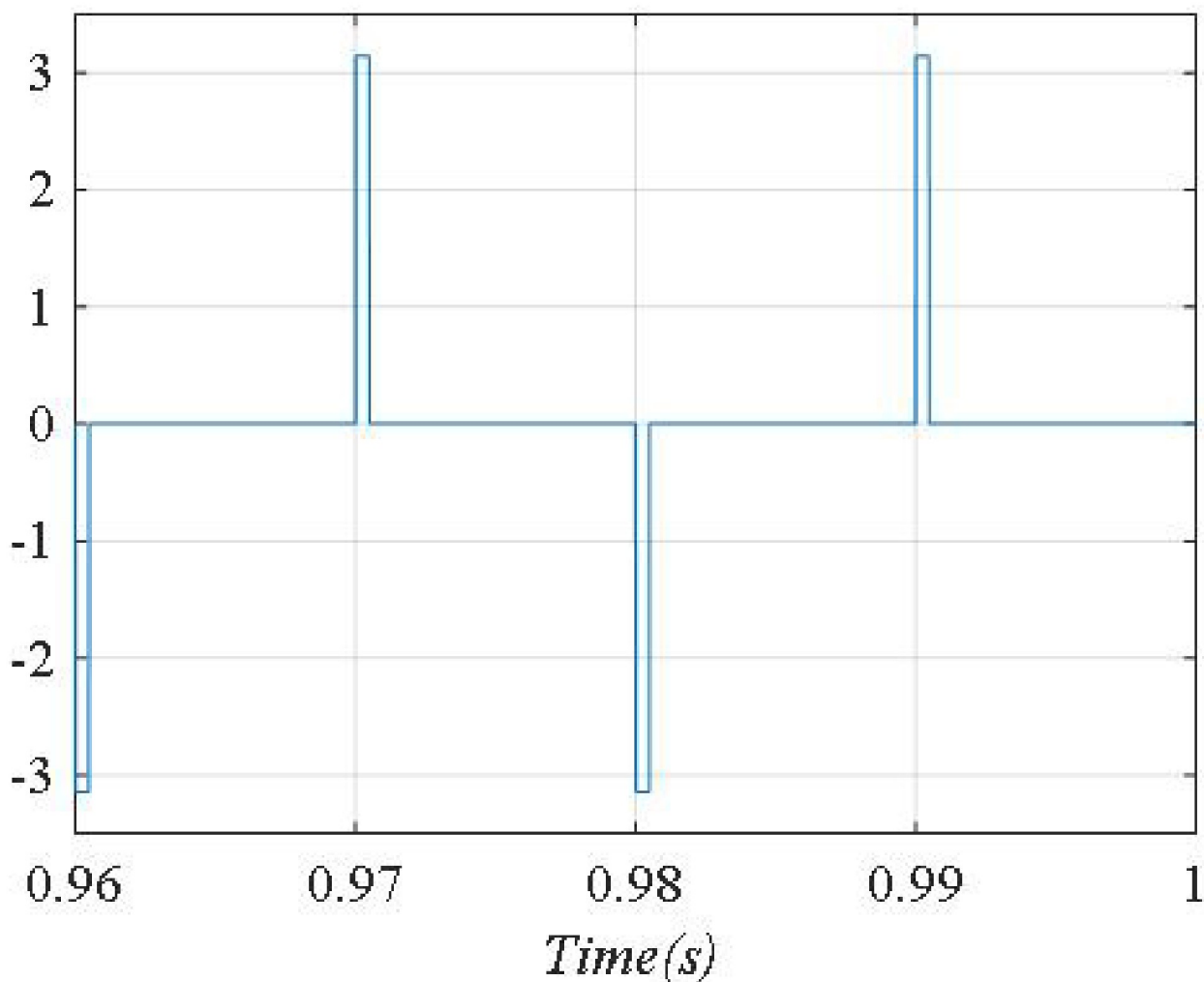


Fig 8. Phase shift angle between u_{sa} and i_{sa} .

<https://doi.org/10.1371/journal.pone.0253275.g008>

Table 3. The achieved results when using the Jaya algorithm.

	Iteration No. = 1	Iteration No. = 2	Iteration No. = 3	Iteration No. = 4	Iteration No. = 5
f_1	5e-5	5e-5	5e-5	5e-5	2.482436e-05
f_2	0.02	0.02	0.02	0.02	0.01185758
f_3	0.01580929	0.01580929	0.01580929	0.01729594	0.0197449
f_4	0.0001	0.0001	0.0001	0.0001	0.0006872732
f_5	0.01046266	0.01046266	0.01046266	0.01092533	0.01519984
f_6	0.001	0.001	0.001	0.001	0.001380426
f_7	3.836756e-05	3.836756e-05	3.836756e-05	5e-5	5e-5
f_8	0.02	0.02	0.02	0.02	0.0181462
f_9	0.002	0.002	0.002	0.002	0.001268174
f_{10}	4.72922e-05	4.72922e-05	4.72922e-05	5e-5	2.084714e-05
f_{11}	0.0002	0.0002	0.0002	0.0002	0.0002404516
f_{12}	500	500	500	500	630.5891
f_{13}	39.11946	39.11946	39.11946	44.83766	60.01977
f_{14}	0.3905476	0.3905476	0.3905476	0.1	0.1
Best Cost	2.1933	2.1933	2.1933	2.0895	1.7277

<https://doi.org/10.1371/journal.pone.0253275.t003>

Fast Fourier Transform analysis of the supply current i_{sa} as shown in Fig 6, we found that THD_{i_s} % decreased from 18.38% to 2.01%. The frequency spectrum of supply current i_{sa} shown in Fig 7.

The phase shift angle between u_{sa} and i_{sa} is shown in Fig 8. From Fig 8, we can see that i_{sa} is lag compared to u_{sa} by an angle of about 10° , corresponding to the value of the power factor is 0.98(lag). The compensation error at steady state is $\pm 5A$.

When the Jaya algorithm is used we have the results as in Tables 3 and 4.

Elapsed time is 1764.328972 seconds, and the best cost is 0.73731 in iteration No. 10.

The waveforms corresponding to the best parameter set when using the Jaya algorithm are shown in Fig 9.

Table 4. The achieved results when using the Jaya algorithm (continued).

	Iteration No. = 6	Iteration No. = 7	Iteration No. = 8	Iteration No. = 9	Iteration No. = 10
f_1	3.238689e-05	3.285666e-05	3.285666e-05	4.116398e-05	4.116398e-05
f_2	0.01	0.01	0.01	0.01367639	0.01367639
f_3	0.02	0.02	0.02	0.02	0.02
f_4	0.0007	0.0007	0.0007	0.0001	0.0001
f_5	0.01796313	0.02	0.02	0.01709288	0.01709288
f_6	0.002	0.002	0.002	0.002	0.002
f_7	5e-5	5e-5	5e-5	4.280462e-05	4.280462e-05
f_8	0.01	0.01	0.01	0.01	0.01
f_9	0.002	0.002	0.002	0.001761725	0.001761725
f_{10}	2.552435e-05	1e-5	1e-5	2.73808e-05	2.73808e-05
f_{11}	0.0002264428	0.0002528856	0.0002528856	0.0003568722	0.0003568722
f_{12}	800	800	800	659.9763	659.9763
f_{13}	56.80504	100	100	100	100
f_{14}	1	1	1	0.6063943	0.6063943
Best Cost	1.1001	0.93592	0.93592	0.73731	0.73731

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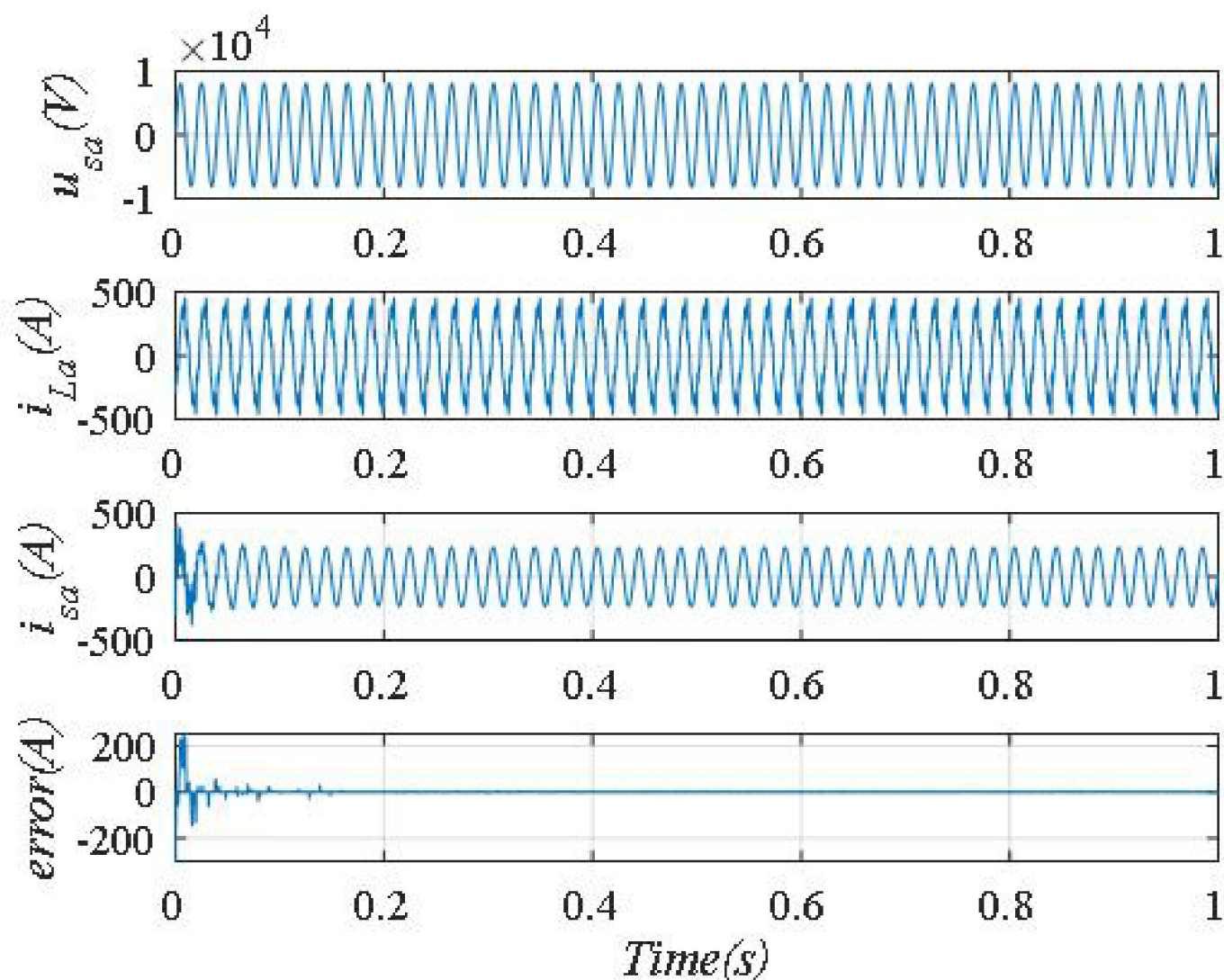


Fig 9. The waveforms corresponding to the best parameter set using the Jaya algorithm.

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To do a comparison, the experiment is run and demonstrated in Table 5. The parameters for the algorithms in Table 5 are setting as following: In three algorithms, population size is 3, and Iteration is 25. For PSO, c_1 equal to 1.2, c_2 equal to 1.2. For simulated annealing, all other parameters are set as [38]. For FA, $\alpha = 1.0$, $\beta_0 = 1.0$, $\gamma = 0.01$, $\theta = 0.97$. Each algorithm is run 15 times. In Table 5, Mean, best, worst, and stdEV are average, best, worst, and standard deviation of 15 runs. The results conducted by the Jaya algorithm are better than the others.

Table 5. The comparison results of FA, PSO, SA and Jaya algorithms.

	Best	Worst	Mean	stdEV
Jaya	0.0023	0.0162	0.0042	0.003
FA	0.0067	0.0823	0.0238	0.023
PSO	0.0032	0.0060	0.0038	0.001
SA	0.004	0.1095	0.0565	0.040

<https://doi.org/10.1371/journal.pone.0253275.t005>

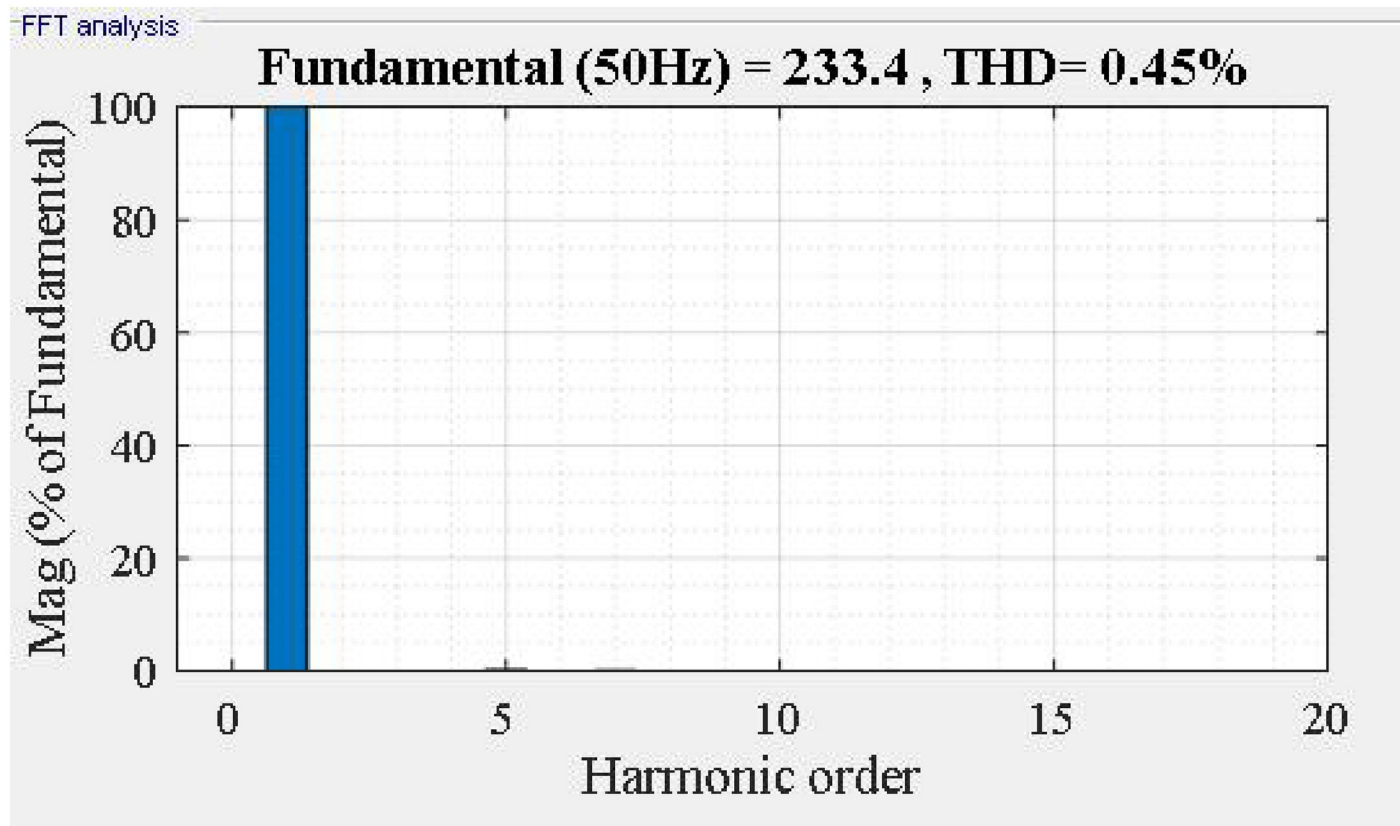


Fig 10. Frequency spectrum of supply current i_{sa} with Jaya algorithm.

<https://doi.org/10.1371/journal.pone.0253275.g010>

Fast Fourier Transform analysis of the supply current i_{sa} in Fig 9, we can see that the total harmonic distortion of i_s decreased from 18.38% to 0.45%. The frequency spectrum of supply current i_{sa} shown in Fig 10.

The phase shift angle between u_{sa} and i_{sa} is shown in Fig 11. From Fig 11, we can see that phase shift angle between u_{sa} and i_{sa} is almost zero, corresponding to the value of the power factor $\cos\phi = 1$. The compensation error is $\pm 3A$.

Wilcoxon rank-sum test

With the observable measure, you'll be able to prove beyond a shadow of a doubt that the results aren't random. The non-parametric Wilcoxon statistical test is applied, and the resulting p-values are also presented as significance metrics. When comparing Jaya to FA, PSO, and SA, any p-values less than 0.05 indicate statistically significant superiority of the outcomes. p values are presented in Table 6.

In summary, from the above analysis results, we realize that the Jaya search algorithm is more effective than firefly algorithm, PSO search algorithm, and the simulated annealing algorithm in minimizing the total harmonic distortion of supply current, minimum phase shift angle between source voltage, and supply current, and minimum compensation error in steady-state. Moreover, Jaya algorithm also has computing time faster than PSO algorithm.

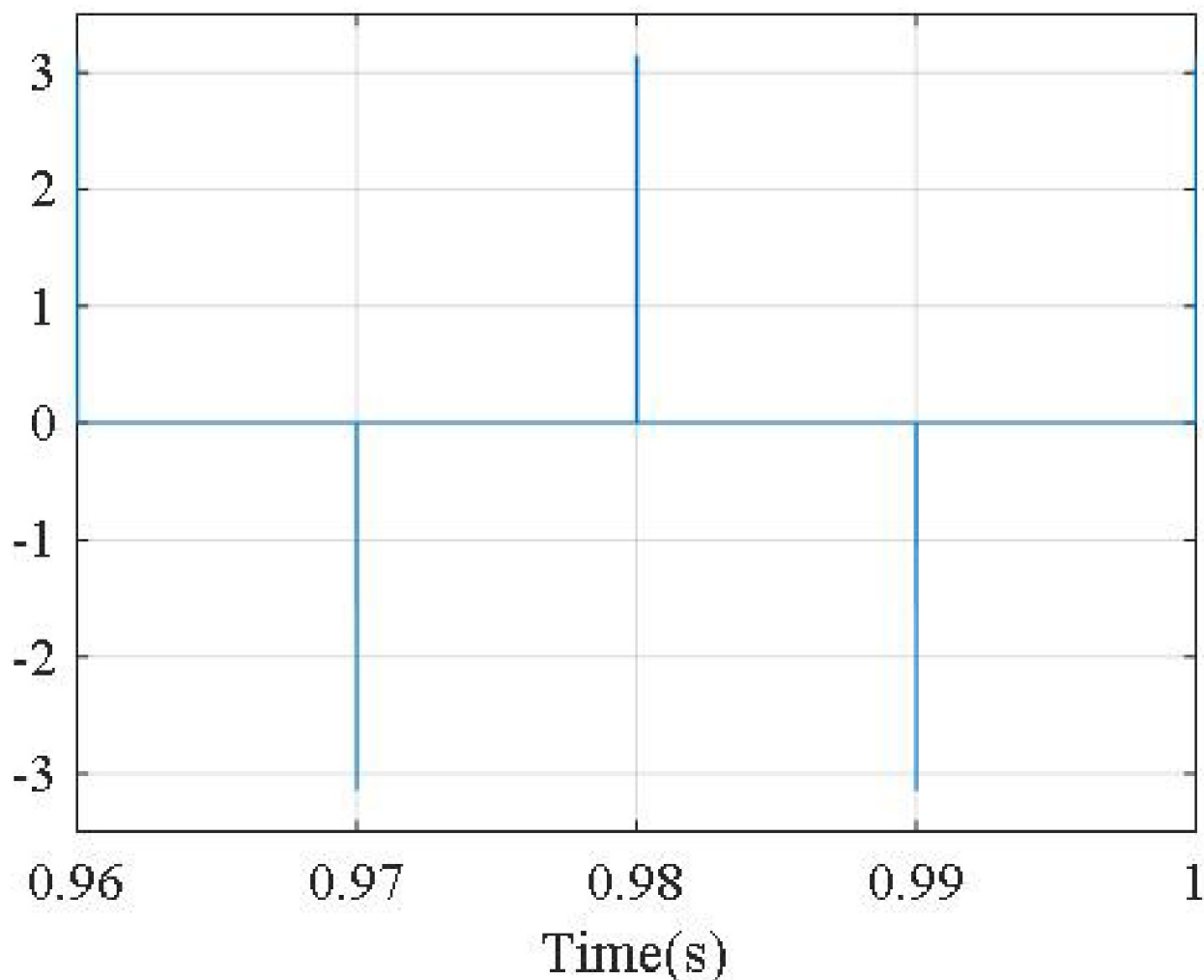


Fig 11. Phase shift angle between u_{sa} and i_{sa} .

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Conclusion

The paper introduced a new multi-objective optimization design flowchart using the Jaya algorithm for IHAPF. The highlight of the proposed algorithm flowchart is that it can determine all the parameters of the IHAPF system with a short search time, and very good results. Compared with the Firefly Algorithm, PSO algorithm, and the Simulated Annealing algorithm, the simulation results have proved that: Jaya algorithm is better at minimizing compensation errors, minimum phase shift angle between source voltage, and supply current, minimum total harmonic distortion of supply current, and less search time.

Table 6. p values of the Wilcoxon rank-sum test over 15 runs.

FA	PSO	SA
2.30E-05	2.74E-02	2.30E-05

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