THE APPLICATION OF PSO TO HYBRID ACTIVE POWER FILTER DESIGN FOR 3 PHASE 4-WIRE SYSTEM WITH BALANCED & UNBALANCED LOADS

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ABSTRACT

This paper presents a application of PSO to Hybrid active power filter used to compensate for total harmonic distortion in three-phase four-wire systems. The shunt active filter employs a simple method for the calculation of the reference compensation current based on Fast Fourier Transform. The presented Shunt Active Power filter is able to operate in balanced, unbalanced and Variable load conditions. Classic filters may not have satisfactory performance in fast varying conditions. But auto tuned active power filter gives better results for harmonic minimization, reactive power compensation and power factor improvement. The proposed auto tuned shunt active filter maintains the THD well within IEEE-519 standards. The proposed methodology is extensively tested for wide range of different Loads with Improved dynamic behavior of shunt active power filter using PSO to Hybrid active power filter. The results are found to be quite satisfactory to mitigate harmonic Distortions, reactive power compensation and power factor correction thereby increase in Power Quality improvement and reduction in %THD.

KEYWORDS: *Hybrid active power filter (HAPF), Multiobjective optimization, particle swarm optimization (PSO), Total Harmonic distortion (THD), Power factor, Reactive power*

I. INTRODUCTION

Power Systems have to cope with a variety of nonlinear Loads which introduce significant amounts of harmonics. IEEE Standard 519-1992 provides a guideline for the limitation and mitigation of harmonics. Passive power filters (PPFs), Active power filters (APFs), and hybrid active power filters (HAPFs) can all be used to eliminate harmonics. For Medium- and high-voltage systems, PPFs and HAPFs appear to be better choices considering cost where the ratings are of several tens of megavolt–amperes. The design of such PPFs and HAPFs is a complicated nonlinear programming problem. Conventional trial-and-error Methods based on engineering experience are commonly used, but the results are not optimal in most cases.

In recent years, many studies have appeared involving optimal PPF design. A Method based on the sequential unconstrained minimization Technique has been used for PPF design because of its simplicity and versatility, but numerical instability can limit the application of this method. PPF design using simulated Annealing has been reported, but the major drawback is the repeated annealing.

Genetic algorithms (gas) have been widely used in PPF design, but the computing burden and convergence problems are disadvantages of this approach. A design method for PPFs using a hybrid

Differential evolution Algorithm has also been proposed, but the algorithm is Complex, involving mutation, crossover, migrant, and accelerated

Operations For the optimal design of HAPFs, a method based on gas has been proposed in order to minimize the rating of APF, but no other optimal design methods appear to have been suggested. Many methods treated the optimal design of PPFs and HAPFs as a single objective problem. In fact, filter Design should determine the optimal solution where there are multiple objectives. As these objectives generally conflict with One another, they must be cautiously coordinated to derive a Good compromise solution.

In this paper, optimal multi objective designs for both PPFs and HAPFs using an advanced particle swarm optimization (PSO) algorithm are reported. The objectives and constraints were developed from the viewpoint of practicality and the Filtering characteristics.

For the optimal design of PPFs, the capacity of reactive Power compensation, the original investment cost, and the total Harmonic distortion (THD) were taken as the three objectives. The constraints included individual harmonic distortion, fundamental Reactive power compensation, THD, and parallel and Series resonance with the system. For the optimal design of HAPFs, the capacity of the APF, The reactive power compensation, and the THD were taken as the three objectives; the constraints were as for the PPFs.

The Uncertainties of the filter and system parameters, which will Cause detuning, were also considered as constraints during the optimal design process. A PSO-based algorithm was developed to search for the optimal solution. The numerical results of case Studies comparing the PSO method and the conventional trial and- Error method are reported. From which, the superiority and Availability of the PSO method and the designed filters are certified.

II. SYSTEM UNDER STUDY

A typical 10-kV 50-Hz system with nonlinear loads, as shown in Fig. 1, was studied to determine the optimal design for both PPFs and HAPFs. The nonlinear loads are the medium frequency furnaces commonly found in steel plants with abundant harmonic currents, particularly the fifth and seventh orders, as shown in Table I. The utility harmonic tolerances given in IEEE Standard 519-1992 and the Chinese National Standard GB/T14549-93 are listed in Table I as percentages of the fundamental current.

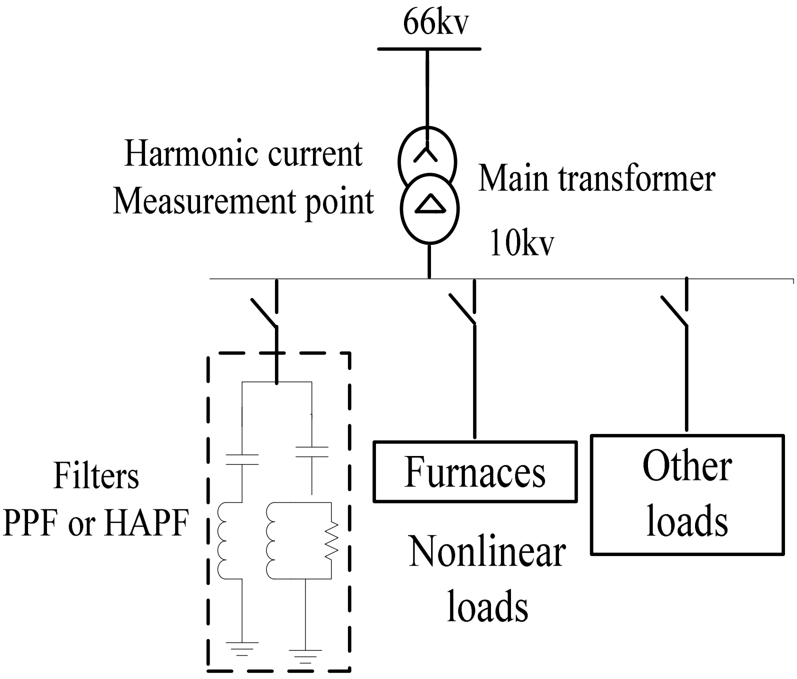

Fig 1. Single diagram of system for case studies.

Table I : Harmonic Current distributions in phase A and utility tolerances

Harmonic Order	Measured Value (%)	National Standard (%)	IEEE standard 519-1992 (%)
5	6.14	2.61	4
7	2.77	1.96	4
11	1.54	1.21	2
13	0.8	1.03	2
17	0.6	0.78	1.5
19	0.46	0.7	1.5
23	0.95	0.59	0.6
25	0.93	0.53	0.6
THD	7.12	5	5

Table I shows that current THD, and the 5th, 23rd, and 25th order harmonic currents exceed the tolerances based on both standards. In addition, the 7th and 11th order harmonics exceed the tolerance based on the National standard.

Filters must therefore be installed to mitigate the harmonics sufficiently to satisfy both standards. Both PPF and HAPF are suitable and economical for harmonic mitigation in such systems. For this system with nonlinear loads as medium frequency furnaces, the even and triple harmonics are very small and far below the standard values, so these harmonics are not considered. In addition, the harmonic voltages are in fact very small, so the voltages are assumed to be ideal.

The fundamental current and reactive power demands are 1012 A and 3–4 MVar, respectively. The short circuit capacity is 132 MVA, and the equivalent source inductance of the system is 2.4 mH

III. HAPF DESIGN BASED ON PSO

A. HAPF Structure and Performance:

In order to demonstrate the optimal design method of HAPFs based on PSO, an HAPF was designed and is shown in Fig. 2; it is supposed to be used in the same situation as that shown in Fig. 1. In this HAPF, PPFs are mainly used to compensate for harmonics and reactive power, and an APF is used to improve the filtering performance .The PPF consists of the fifth and seventh single-tuned filters and a high-pass damped filter. The APF is implemented with a three-phase voltage-source inverter. Fig. 3(a) shows the single-phase equivalent circuits of the HAPF, assuming that the APF is an ideal controllable voltage *V*AF and that the load is an ideal current source *IL*. *ZS* is the source impedance, *ZF* is the total impedance of the PPF, *V*pcc is the voltage of the injected point, and *K* is the controlling gain of the APF.

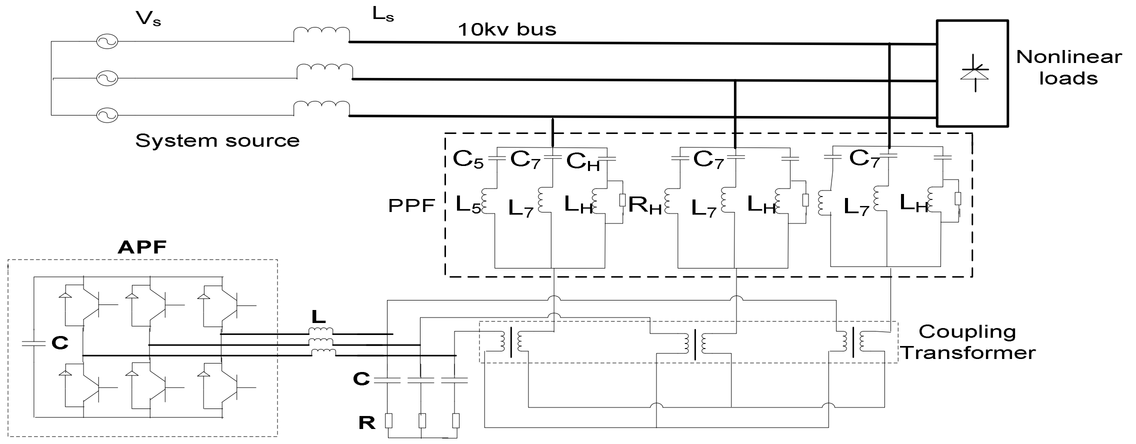

Fig.2. Shunt HAPF.

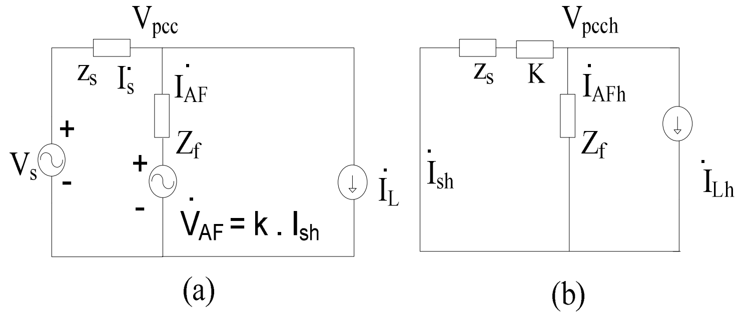

Fig 3.Single-phase equivalent circuits of the HAPF (a) Equivalent circuit.
(b) Equivalent harmonic circuit.

The equivalent harmonic circuit is redrawn as in Fig. 3(b). The harmonic current *Ish* into the system source and the harmonic attenuation factor *γ* are given in the following equations:

$$I_{sh} = \left| \frac{Z_F}{K + Z_F + Z_S} \right| I_{Lh} \rightarrow (1)$$

$$\gamma = \frac{I_{Sh}}{I_{Lh}} = \left| \frac{Z_F}{K + Z_F + Z_S} \right| \rightarrow (2)$$

Assuming that the fundamental component of the supply voltage is fully dropped across the PPF, the voltage and current of APF can be derived as follows [24]:

$$V'_{AF} = \sum_h V'_{AFh} = \sum_h -Z_{Fh}.I'_{AFh} = \sum_h Z_{Fh}.I'_{Lh} \rightarrow (3)$$

$$I'_{AF} = I'_{AF1} + \sum_h I'_{AFh} \rightarrow (4)$$

The rms value of ˙*V*AF is defined as

$$V_{AF} = \sqrt{\sum_{h=5,7,11,13,17,19,23,25} V^2_{AFh}} \rightarrow (5)$$

The capacity of the APF is determined by the current *I*˙AF and the voltage ˙*V*AF. It is obvious that the low VA rating of APF can be achieved by decreasing ˙ *I*AF and ˙*V*AF. In this shunt hybrid topology, the current *I*˙AF is almost constant, so the only way to reduce the VA rating of APF is to decrease the voltage *V*AF.

B. Multi objective Optimal Design Model for HAPF:

As mentioned earlier, when designing an HAPF, it is very important to minimize the capacity of the APF component, and there are some other objectives and constraints to be considered when the APF of the HAPF is cut off due to faults, the PPF part keeps work in to mitigate harmonics until the APF is restored. It follows that some additional constraints should be included in respect of such occasions. The constructions of objective functions and constraints are described next.

Three important objective functions are defined as follows.

1) Minimize the capacity of the APF, which is mainly determined by the harmonic voltage across it

$$\min V_{AF} = \sqrt{\sum_{h=5,7,11,13,17,19,23,25} V^2_{AFh}} \rightarrow (6)$$

2) Minimize the current THD with HAPF

$$\min THDI_{HAPF} = \sqrt{\sum_{h=2}^{N} \left(\frac{I_{sh}}{I_1} \right)^2} \rightarrow (7)$$

where *THDI*HAPF is the current THD with the HAPF in place; and the definitions of *Ish*, *I*1, and *N* are the same as those in (7).

3) Maximize the reactive power compensation

$$\max \sum_{i=5,7,H} Q_i \rightarrow (8)$$

Where *Qi* is same with that in (9)

***Constraints are defined as follows*.**

The tolerated values quoted hereinafter are also based on the National standard.

1) Requirements of total harmonic filtering with the HAPF

$$THDI_{HAPF} \le THDI_{MAX} \rightarrow (9)$$

Where *THDI*MAX is defined in (10)

When PPF runs individually with the APF cutoff, an additional constraint is added as follows:

$$THDI_{PPF} \le THDI_{MAX} \rightarrow (10)$$

Where *THDI*PPF is the THD with the PPF alone

2) Requirements of individual harmonic filtering with HAPF and PPF alone: Each order harmonic should satisfy the standards, so the following constraints are included:

$$I_{HAPF_{sh}} \le I_{h_{\max}}, h=5,7,11,13,17,19,23,25 \rightarrow (11)$$

$$I_{PPF_{sh}} \le I_{h_{\max}}, h=5,7,11,13,17,19,23,25 \rightarrow (12)$$

Where $IHAPF_{sh}$ and $IPPF_{sh}$ are, respectively, the rms values of the h_{th} order harmonic current into the system source with the HAPF and the PPF alone $Ih_{\max}$ is defined by (11).

3) Fundamental reactive power compensation limits: The fundamental reactive power must be restricted as

$$Q_{\min} \le \sum_{i=5,7,H} Q_i \le Q_{\max} \rightarrow (13)$$

Where $Q_{\min}$ and $Q_{\max}$ are as defined in (12).

4) Parallel and series resonance restrictions: Parallel and series resonance with system source will rarely happen for the HAPF due to the active damping function of the APF. Nevertheless, it is necessary to consider, during the HAPF design, parallel and series resonance restrictions when PPF works alone with the APF cutoff. Therefore, constraints are constructed, which are the same as those constructed during the PPF optimal design in (13)–(16).

5) Consideration of the detuning constraints: The HAPF system is not sensitive to detuning effects because of the APF damping function. In the worst case, that the system impedance decreases by 20%, the system frequency changes to 50.5 Hz, the capacitance of each branch increases by 5%, and the reactance also increases by 2%, then the filtering performance of the PPF alone should still satisfy all the standards and limit described earlier, as set out in (10), (12), and (13).

***C. Optimal Design for HAPF Based on PSO* Based** on the objectives and constraints constructed earlier for HAPF, the multi objective optimization task is carried out using an advanced PSO algorithm. The capacitance in each branch of the PPF and the characteristic frequency of the high-pass damped filter are chosen as optimal variables

Xi = (*C*5, *C*7, *CH, fH*)T, while the tuning frequencies of the fifth and seventh single-tuned filters are predetermined as 242 and 342 Hz, respectively. According to the optimization objectives, the corresponding fitness functions are defined as

$$F_1'(X) = V_{AF} \rightarrow (14)$$

$$F_2'(X) = THDI_{HAPF} \rightarrow (15)$$

$$F_3'(X) = \sum_{i=5,7,H} Q_i \rightarrow (16)$$

Similar methods were adopted to solve this multi objective optimization problem. The objective of minimizing the APF capacity is chosen as the final objective, while the other two objectives are solved by using acceptable level constraints, as shown in the following equations:

$$\min F_1' \rightarrow (17)$$

$$F_2' \le \alpha_1' \rightarrow (18)$$

$$\alpha_2' \le F_3' \le \alpha_3' \rightarrow (19)$$

Whereα'_1, *α'3, and* α'_2 are the highest and lowest acceptable levels for the secondary objectives, respectively. The overall optimization process for the HAPF based on PSO is similar to that of the PPF in Fig. 4.

Table II : Design results of HAPFs based on PSO and conventional methods

Design parameters	Pso-method	Conventional method
The 5th Single-tuned filter	C_5=59.76uF L_5=7.24mH Q_5=60	C_5=80.6uF L_5=5.37mH Q_5=60
The 7th single - tuned filter	C_7=12.32uF L_7=17.58mH Q_7=60	C_7=23.76uF L_7=9.11mH Q_7=60
High-pass damped filter	C_H=52.06uF L_H=1.20mH m=0.5	C_H=15.28uF L_H=3.32mH m=0.5

Table III : Harmonic current distributions with HAPFs based on PSO and conventional methods

Harmonic orders	PSO Method (%)	Conventional Method (%)
5	0.24	0.17
7	0.24	0.11
11	0.25	0.71
13	0.1	0.3
17	0.07	0.16
19	0.06	0.12
23	0.13	0.26
25	0.13	0.26
THD	0.48	0.91
V_{AF}	116.64 V	340.82 V
Reactive Power Compensation	4MVar	3.88MVar

The design results of HAPFs using PSO and conventional trial-and-error methods are listed in Table II. The design results based on the conventional method in Table II .It can be seen that the harmonic currents and reactive power are well compensated by both HAPFs and that the HAPF designed using the method based on PSO can obtain better filtering performance with lower THD (0.48%) and larger reactive power compensation (4MVar). Moreover, the voltage *V*AF of the APF, in this case, was much smaller than that based on conventional method. Therefore, the investment cost of the whole system is much reduced. Table IV shows the harmonic current distributions when the PPF is working alone, without the APF.

A comparison is made between the PSO method and conventional method, and it can be seen that all the harmonic currents and the THD are still within the standards, and the filtering performance of PPF based on PSO is a little better.

Table IV: Harmonic current distributions with PPFs alone Based on PSO and conventional methods

Harmonic orders	PSO Method (%)	Conventional Method (%)
5	1.1	0.82
7	0.76	0.39
11	0.94	1.13
13	0.26	0.60
17	0.14	0.29
19	0.11	0.21
23	0.21	0.40
25	0.20	0.38
THD	1.68	1.71

Table V: Harmonic current distributions with HAPFs alone considering detuning effects

Harmonic Orders	PSO Method HAPF (%)	Conventional Method HAPF (%)
5	0.65	0.44
7	0.75	0.27
11	0.23	0.71
13	0.1	0.27
17	0.08	0.16
19	0.06	0.13
23	0.14	0.28
25	0.14	0.28
THD	1.05	1.02

In order to verify the filtering performances of HAPF alone under the worst detuning situations, comparisons are shown in Table V. It is clear that both HAPFs, using PSO method and conventional method, can obtain excellent filtering performance in spite of detuning effects.

Fig. 4 shows the harmonic attenuation factors of HAPF alone using the PSO design method and considering detuning effects. It can be seen that the harmonic currents are still well attenuated, and no resonance point can be found. Furthermore, the attenuation factor of HAPF is much smaller than that of PPF, which shows the excellent harmonic mitigation performance of HAPF.

The simulation using the MATLAB/SIMULINK software has been run based on field measurement data. The compensated source current with the HAPF is shown in Fig. 5. From Fig. 5, we can see that the source current is very close to a pure sine wave, with the current THD decreasing to 0.48%.

Fig. 6 shows the convergence characteristics of the PSO algorithm developed in this paper for optimal design of HAPF. In this paper, the PSO algorithm is run 200 times, and every time, it can converge within 360 iterations. All those can demonstrate the efficiency and validity of PSO for the optimal HAPF design.

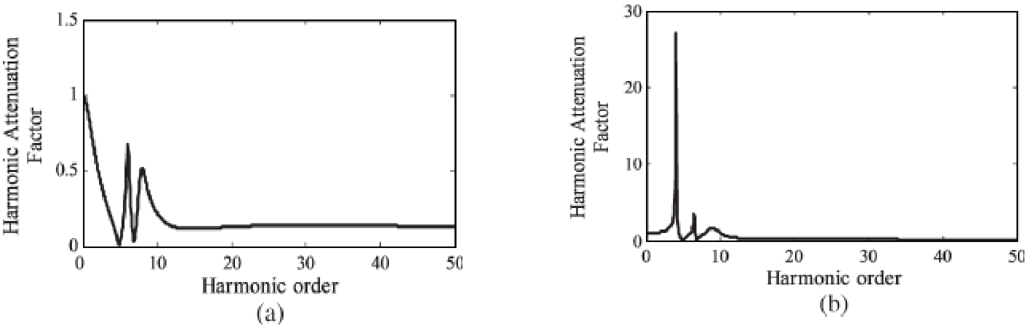

Fig 4. Harmonic attenuation factors of the HAPF and its PPF alone based on the PSO method.
(a) Harmonic attenuation factor of the HAPF based on the PSO method.
(b) Harmonic attenuation of the PPF alone based on the PSO method.

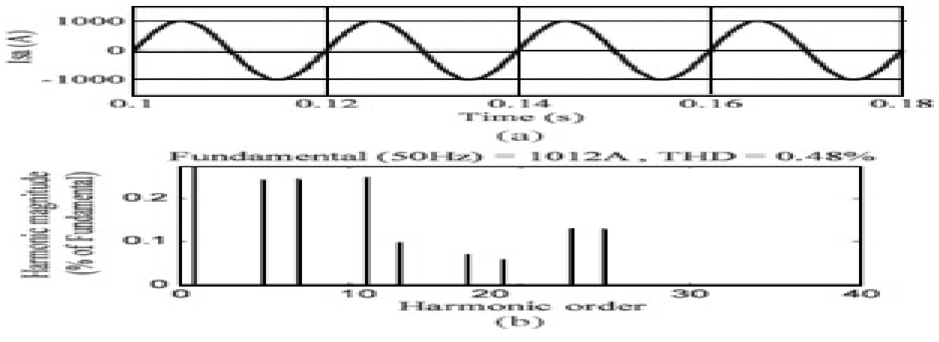

Fig 5. Compensated source current and its THD analysis with HAPF based on the PSO method
(a) Compensated source currents of phase A with HAPF.
(b) THD analysis of compensated source current.

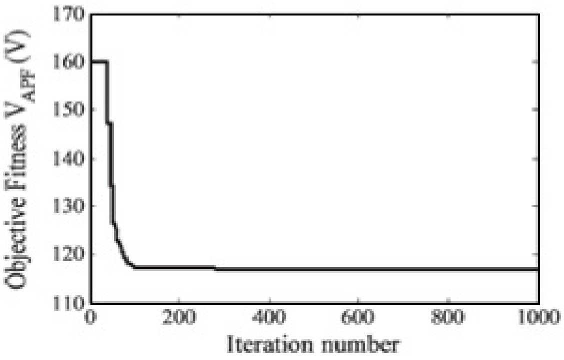

Fig.6. Convergence characteristics of PSO for HAPF design.

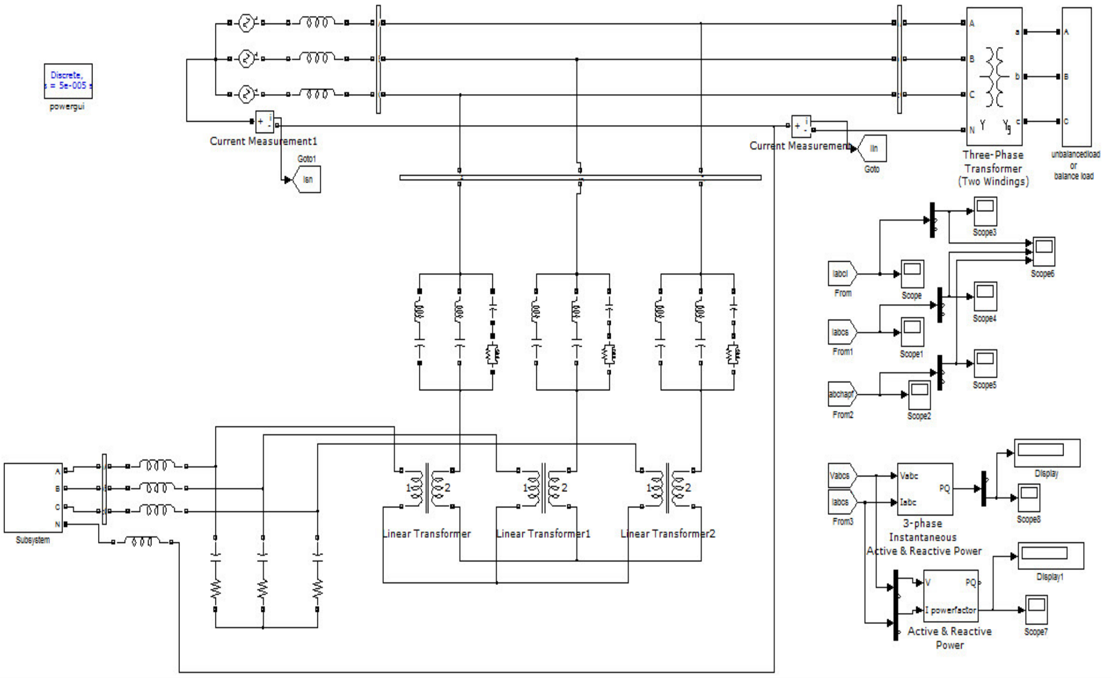

Fig.7. Simulink model of HAPF using PSO & without PSO with balanced,& unbalanced models

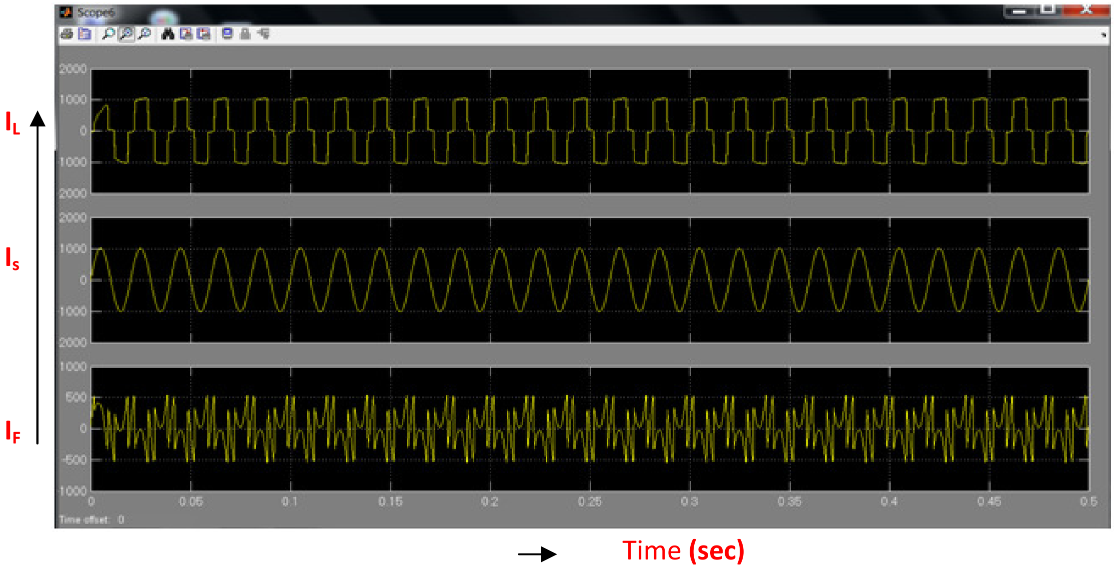

Fig 8. Wave form of balanced load for HAPF-Conventional Method

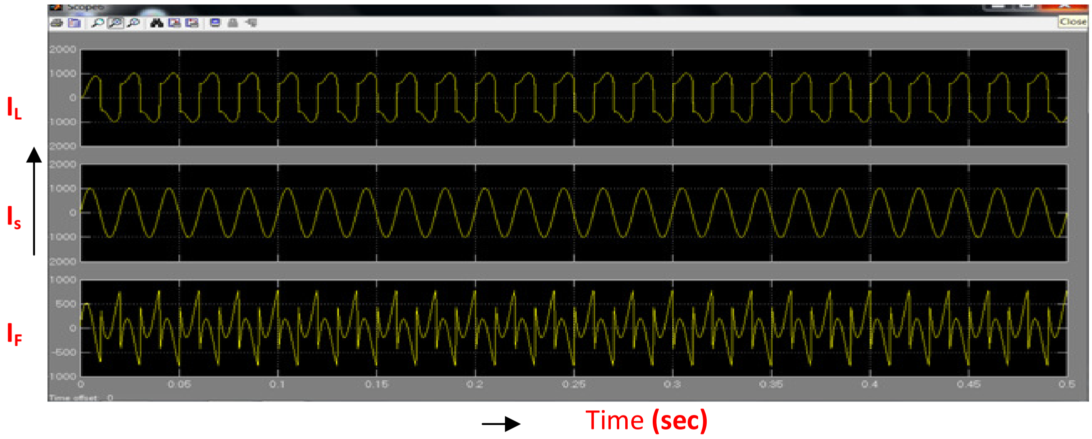

Fig.9. Wave form of Unbalanced load for HAPF-Conventional Method

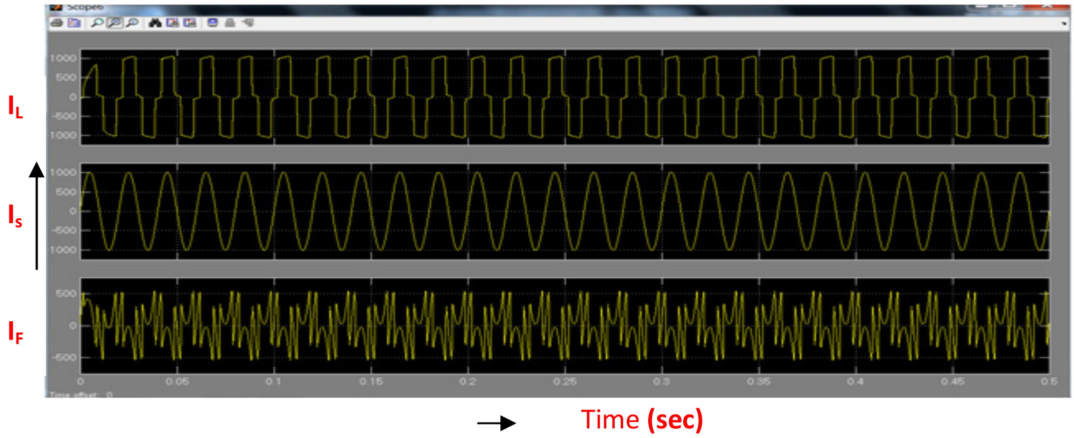

Fig.10. Wave form of Balanced load for HAPF-PSO Method

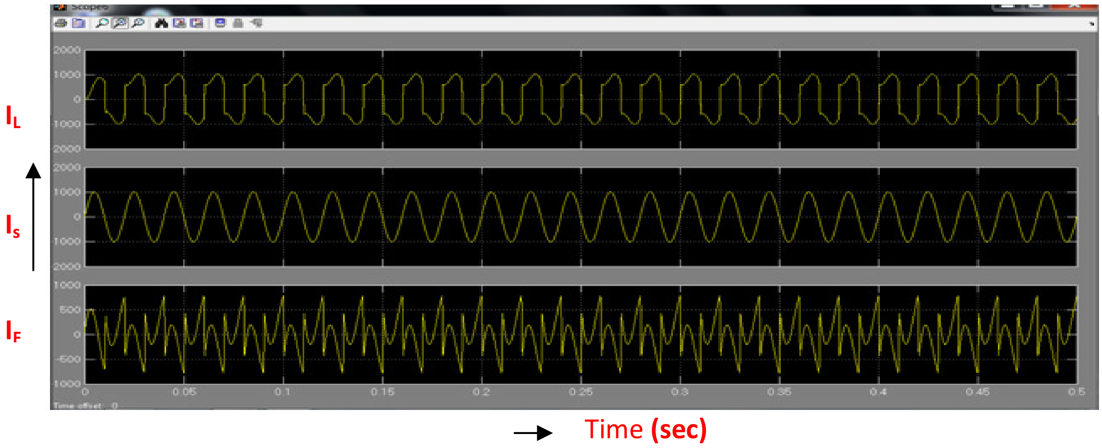

Fig.11. Wave form of Unbalanced load for HAPF-PSO Method

Table: VI. Results with Balanced Load

SCHEME	With PSO			With PSO		
	% THD	**P.F**	**Reactive Power (VAR)**	**% THD**	**P.F**	**Reactive Power (VAR)**
HAPF	0.47	0.9929	6.665	26.54	0.599	2.887

Table: VII. Results with Unbalanced Load

SCHEME	With PSO			With PSO		
	% THD	P.F	Reactive Power (VAR)	% THD	P.F	Reactive Power (VAR)
HAPF	0.49	0.9933	6.663	33.68	0.764	-8.0257

IV. CONCLUSION

The application of PSO to Hybrid active power filter is designed. The proposed control technique is found satisfactory to mitigate harmonics from utility current especially under balanced and unbalanced loading conditions. Thus, the resulting total current drawn from the ac mains is sinusoidal. The proposed design of SAF improves the overall control system performance over other conventional controller. The validity of the presented controllers was proved by simulation of a three phase four wire test system under balanced and unbalanced loading conditions. The proposed Hybrid shunt active filter compensate for balance and unbalanced nonlinear load currents, adapt itself to compensate variations in non linear load currents, and correct power factor of the supply side near to unity. Proposed APF topology limits THD percentage of source current under limits of IEEE-519 standard. It has also been observed that reactive power compensation has improved leading to power factor improvement with the PSO Technique.

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