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PROPER DESIGNING OF PASSIVE LCL FILTERS VIA IMPERIALIST COMPETITIVE ALGORITHM

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Abstract- Harmonics are one of the most important issues in electric power systems. A passive LCL filter is effectual equipment for impeding harmonic pollution and heightening power quality. A passive LCL filter is usually utilized to interconnect a power electronic converter to a system. The design of passive LCL filter is not simple because of high compensating bandwidth and variable frequency modulations involved in active filters. Conventional approaches for the design of passive filters depend on the experiences and single technology criterions, which are difficult to achieve the optimal solution. An optimal design technique based on Imperialist Competitive Algorithm (ICA) is proposed in this paper. The minimum Total Harmonics Distortion of voltage (*THD*) is used as constraint condition. The proposed method shows the application of ICA method to search optimal passive LCL filter parameters. The proposed method has different capability like, easy implementation and good computational efficiency. The results are compared with other evolutionary algorithm like PSO and the advantage of proposed method is revealed.

Keywords: Passive LCL Filter, Imperialist Competitive Algorithm (ICA), Particle Swarm Optimization (PSO), Optimal Design.

I. INTRODUCTION

With the wide use of power electronics equipment in the power systems, the harmonic pollution becomes more and more severe. This causes great disturbances to the quality of the power systems. Passive LCL filter is an effective equipment to suppress harmonics [1]. Conventionally, an inductance L connects the converter of the active filter to the grid network, thus acting like a passive filter. The bigger the inductance L, the higher the attenuation of high frequency components will be. Another reason for increased popularity of passive LCL filters is that they show higher harmonic performances compared to a single inductance. Improper design of LCL filters leads to some inefficient effects in active filters' performance and resonances [2].

Many approaches have been presented to analyze passive LCL filters for utilization as an interface between power electronic converters and the power systems [3]. A recursive method has been suggested in [4] by trial and error method to determine the LCL parameters of a grid-connected voltage source inverter. The method could not prevent the possible increase of both power losses and the ratings of the switches. Also, the selection of the initial values of the inductors is difficult at the start of the method. Later, a method has been proposed in [5] to select the initial values of inductors of the LCL filters, for the purpose of simplifying the proposed method in [4].

Further, LCL filters for the grid-connected distributed generations have been considered in [6] by focusing on the ratio of the two inductances on the two arms of the filter along with the relation of this ratio to the capacitance of the passive filter. Passive filters are alternative strategy to eliminate harmonics in the power distribution system. Although passive filters are economical, they may cause the resonance problem [7]. The harmonic distortion of voltage has become an important problem in power quality, especially after use of power electronic equipment and nonlinear loads.

A simple method for the limitation of the harmonic distortions is using the passive filters. As harmonics propagate through the power system, they result in increased losses and possible equipment loss-of-life. Also, over-currents or over-voltages resulting from resonances may damage equipment. Additionally, harmonics can interfere with control, communication, and protective equipment. With this reasons different research institutes have studied about the proper limitation of harmonic disturbance levels and released different standards. Among the several methods used to reduce these harmonic disturbances, the more employed are the tuned passive filters due to their simplicity and economical cost [8]. It is the purpose of this paper to find optimal passive filter parameters using Imperialist Competitive Algorithm (ICA). Finding optimal passive filter parameters problem is converted to an optimization problem an objective function including the desired Total Harmonics Distortion (*THD*) of voltage, which is solved by the ICA algorithm. In order to illustrate its strong performance, a comparative analysis is made between PSO method through some performance indices.

This paper is set out as follows: Problem statement is formulated in Section II. Heuristic optimization methods for solving the problem are presented in Section III. The application of the proposed model and simulation results are presented in Section IV and finally, the conclusion is presented in Section V.

II. PROBLEM FORMULATION

The optimal design of passive LCL filters is to meet requirement and to maximize overall efficiency. Optimal parameters should meet the following requirements:
1) Lower total harmonics distortion of voltage or current;
2) In the normal fluctuation of frequency, the filter meets the technology requirements;

In order to meet the above design requirements, we proposed the following objective function:

$$OF = \min\{THD_a(end) + THD_b(end) + THD_c(end)\} \quad (1)$$

where THD_a, THD_b and THD_c are the total harmonic distortion of phase voltages *a*, *b*, and *c*, respectively.

III. HEURISTIC OPTIMIZATION METHOD

A. Imperialist Competitive Algorithm

The ICA was first proposed in [9]. It is inspired by the imperialistic competition. It starts with an initial population called colonies. The colonies are then categorized into two groups, namely, imperialists (best solutions) and colonies (rest of the solutions). The imperialists try to absorb more colonies to their empire [10-12]. The colonies will change according to the policies of imperialists. The colonies may take the place of their imperialist if they become stronger than it (propose a better solution). The flowchart of the proposed algorithm is shown in Figure 1. The steps of the proposed ICA are described as follows:

Step 1. Generate an initial colonies set with a size of N_c.
Step 2. Set iteration equal to 1.
Step 3. Calculate the objective function for each colony and set the power of each colony as follows:

$$CP_c = OF \quad (2)$$

Step 4. Keep the best N_{imp} colonies as the imperialists and set the power of each imperialist as follows:

$$IP_i = OF \quad (3)$$

Step 5. Assign the colonies to each imperialist according to the calculated IP_i. This means the number of colonies owned by each imperialist $(IP_i / \sum_{j=1}^{N_{imp}} IP_j) \times (N_c - N_{imp})$ is proportional to its power, IP_i.
Step 6. Move the colonies towards their relevant imperialist using crossover and mutation operators.
Step 7. Exchange the position of a colony and the imperialist if it is stronger $CP_c > IP_i$.
Step 8. Compute the empire's power, that is, EP_i for all empires as follows:

$$EP_i = \frac{1}{N_{E_i}}(\chi_1 \times IP_i + \chi_2 \times \sum_{c \in E_i} CP_c) \quad (4)$$

where χ_1 and χ_2 are weighting factors that are adaptively selected.
Step 9. Pick the weakest colony and give it to one of the best empires (select the destination empire probabilistically based on its power, EP_i).
Step 10. Eliminate the empire that has no colony.
Step 11. If more than one empire remained then go to Step 6.
Step 12. End.

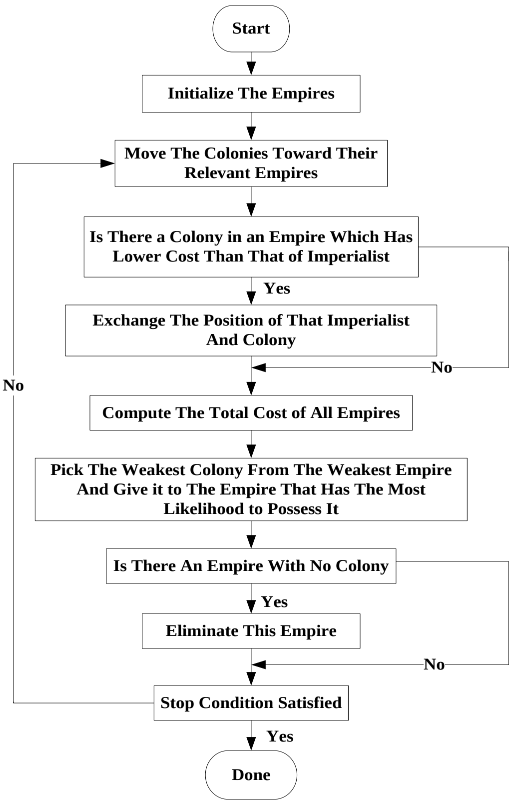


Figure 1. ICA flowchart

B. Particle Swarm Optimization

The PSO is a population based stochastic optimization technique developed by Eberhart and Kennedy in 1995 [13, 14]. The PSO algorithm is inspired by social behavior of bird flocking or fish schooling. The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. Compared to GA, the advantages of PSO are that PSO is easy to implement and there are few parameters to adjust. PSO has been successfully applied in many areas [13]. The standard PSO algorithm employs a population of particles. The particles fly through the *n*-dimensional domain space of the function to be optimized. The state of each particle is represented by its position $x_i = \left(x_{i1},\ x_{i2},\ ...,\ x_{in}\right)$ and velocity $v_i = \left(v_{i1},\ v_{i2},\ ...,\ v_{in}\right)$, the states of the particles are updated. The three key parameters to PSO are in the velocity update Equation (5). First is the momentum component, where the inertial constant w, controls how much the particle remembers its previous velocity [15].

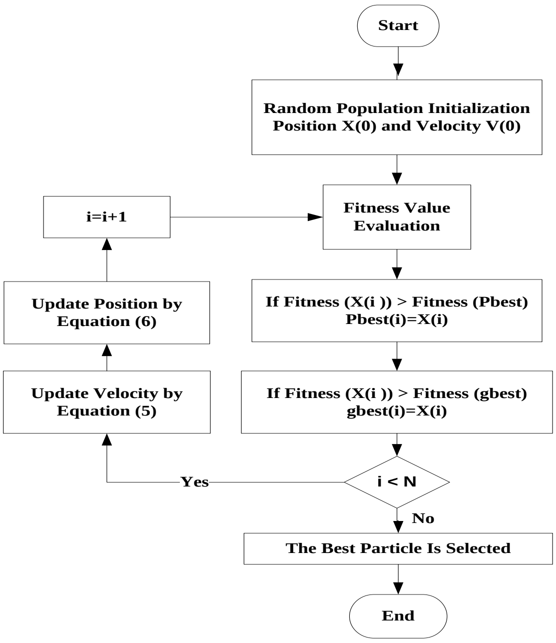


Figure 2. PSO flowchart

The second component is the cognitive component. Here the acceleration constant c_1, controls how much the particle heads toward its personal best position. The third component, referred to as the social component, draws the particle toward swarm's best ever position; the acceleration constant c_2 controls this tendency. The flowchart of the procedure is shown in Figure 2. Each particle is updated by two "best" values during every iteration. The first one is the position vector of the best solution (fitness) this particle has achieved so far. The fitness value $p_i = \left(p_{i1},\ p_{i2},\ ...,\ p_{in}\right)$ is also stored. This position is called *pbest*. Another "best" position that is tracked by the particle swarm optimizer is the best position, obtained so far, by any particle in the population. This best position is the current global best $p_g = \left(p_{g1},\ p_{g2},\ ...,\ p_{gn}\right)$ and is called *gbest*. At each time step, after finding the two best values, the particle updates its velocity and position according to (5) and (6).

$$v_i^{k+1} = wv_i^k + c_1 r_1 (pbest_i - x_i^k) + c_2 r_2 (gbest_k - x_i^k) \qquad (5)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \qquad (6)$$

IV. SIMULATION RESULT

A. Case Study

This section presents the application and study of the proposed method for optimal designing of passive LCL filters. The system of the case is shown in Figure 3. The system's parameters are shown in the Table 1. An active filter is also connected across the load terminal to eliminate the load harmonics. The load consists of a three-phase inductors and resistors.

Table 1. CPU time required to find the optimal PMU locations

Source voltage (kV)	Input power (W)	Damping resistor (Ω)	Switching frequency (Hz)
0.38	4100	10	5 to 8

Also the inductances of filter are considered as L_1=L_2=L. The L_1 and L_2 are defined as the converter-end inductance of the LCL filter and the network-end inductance of the LCL filter, respectively. This power system is simulated with Matlab-Simulink to investigate the suitability of the designed passive LCL filter. Two heuristic algorithms are applied to optimal design of passive LCL filters.

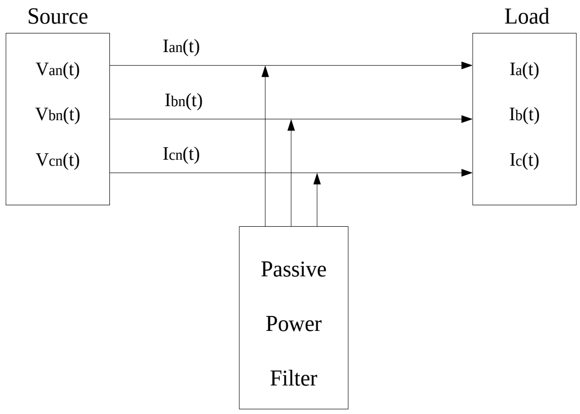


Figure 3. System under study

B. Determination of ICA Parameters

In this section the effect of ICA parameters on average total (THD) of voltage is investigated (after 100 trials). The following procedure has been adopted to calculate optimum value of the mutation and crossover probabilities. Different colony sizes, that is, N_c, tried were 50 and 100.

For each colony size the crossover and mutation probabilities are increased from 0.1 to 0.9 in steps of 0.1 as described in Table 2. The performance of the proposed ICA is evaluated for all the above-mentioned combinations. Hundred independent trials have been made with 100 iterations per trial. The performance of the ICA also depends on the number of colonies.

In Table 2 the performance of the ICA is also checked for different number of colonies. The parameters of ICA are selected based on the average total (*THD*) obtained for different values of parameters given in Table 2. After a number of careful experimentation, following optimum values of ICA parameters have finally been settled: $N_c = 100$; crossover probability = 0.4, mutation probability = 0.3. The other simulation parameters of ICA and PSO are shown in Table 3.

Table 2. Influence of ICA parameters on average total *THD* (after 100 trials)

N_c	Mutation Probability	Crossover Probability								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
50	0.1	1.7510	1.7523	1.7467	1.7448	1.7516	1.7485	1.7893	1.7483	1.7479
	0.2	1.7536	1.7521	1.7495	1.7439	1.7560	1.7899	1.7586	1.7526	1.7593
	0.3	1.7498	1.7466	1.7496	1.7422	1.7985	1.7428	1.7519	1.7534	1.7562
	0.4	1.7472	1.7457	1.7575	1.7568	1.7490	1.7494	1.7555	1.7528	1. 7646
	0.5	1.7630	1.7564	1.7581	1.7650	1.7443	1.7469	1.7582	1.7436	1. 7511
	0.6	1.7468	1.7482	1.7483	1.7439	1.7506	1.7473	1.7577	1.7487	1.7533
	0.7	1.7421	1.7434	1.7487	1.7406	1.7519	1.7532	1.7624	1.7484	1.7610
	0.8	1.7434	1.7646	1.7669	1.7526	1.7562	1.7564	1.7561	1.7497	1.7618
	0.9	1.7560	1.7439	1.7478	1.7498	1.7497	1.7582	1.7497	1.7469	1.7566
100	0.1	1.7320	1.7301	1.7286	1.7277	1.7312	1.7278	1.8463	1.728	1.7275
	0.2	1.7350	1.7210	1.7290	1.7299	1.7306	1.8023	1.7343	1.7322	1.7311
	0.3	1.7262	1.7279	1.7259	1.7099	1.7281	1.7262	1.7314	1.7313	1.7333
	0.4	1.7429	1.7344	1.7318	1.740	1.7293	1.7256	1.7338	1.7253	1. 7291
	0.5	1.7272	1.7280	1.7288	1.7277	1.7310	1.7287	1.7317	1.7273	1.7323
	0.6	1.7254	1.7253	1.7268	1.7260	1.7332	1.7330	1.7264	1.7238	1.7422
	0.7	1.7274	1.7256	1.7286	1.7312	1.7342	1.7354	1.7301	1.7289	1.7388
	0.8	1.7320	1.7301	1.7286	1.7277	1.7312	1.7278	1.8463	1.7283	1.7275
	0.9	1.7199	1.7279	1.7259	1.7262	1.7281	1.7262	1.7314	1.7313	1.7333

Table 3. ICA and PSO simulation parameters

Method	Fixed Parameters
ICA	N_{imp}=3; χ_1 =0.85; χ_2 =0.25; V_{max}=1.05; V_{min}=0.95
PSO	N_c = 100; c_1=2; c_2=2; r_1=1.1; r_2=1.1

C. Comparing Result

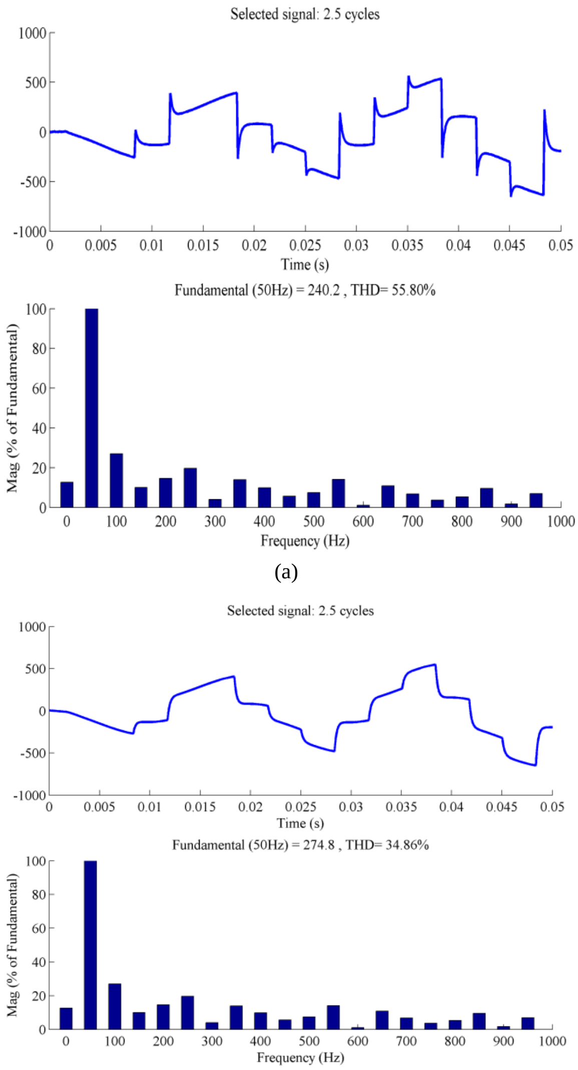
The passive LCL filter is designed using ICA and PSO algorithms for different conditions and the best results reported in this paper. The simulation results about three-phase current waveforms before and after compensating are shown in Figures 4 and 5. It is important to mention that *THD* is influenced by load which means by changing the load, *THD* also changes. For this purpose, a load consists of a three-phase inductive and resistive is considered here.

It can be seen from above figures that the lower order harmonics have more amplitude than the higher ones. The spectrums are analyzed and the harmonic ratios of current before and after compensating and also the filter's parameters obtained by of each method are given in Table 4. According to the figures, it can be simply found that the higher percentage of total harmonics distortion (*THD*) can be compensated by proposed method in comparison with PSO. Execution time complexity of each optimization method is very important for its application to real systems. The execution time of the proposed ICA compared with other method is given in the last column of Table 4.

Table 4. Comparative analysis between Proposed ICA and PSO

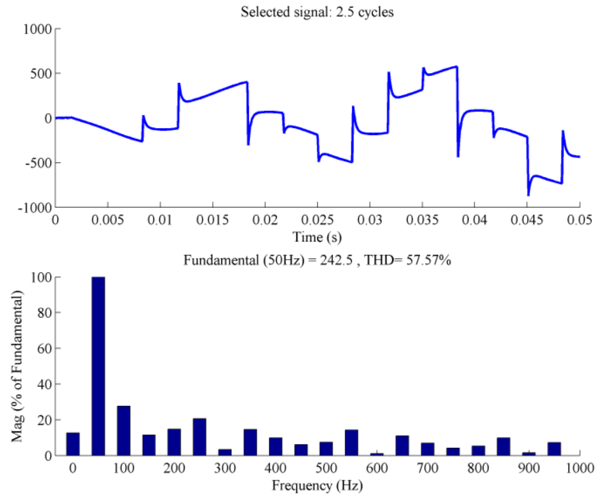
Method	Before compensation (%)	After compensation (%)
0.2	55.08	31.86
0.3	57.57	37.85

C	*L*	Average fitness	Mean time (sec)
0.0043	0.0995	1.7099	8537
0.0042	0.0813	1.8139	10 816

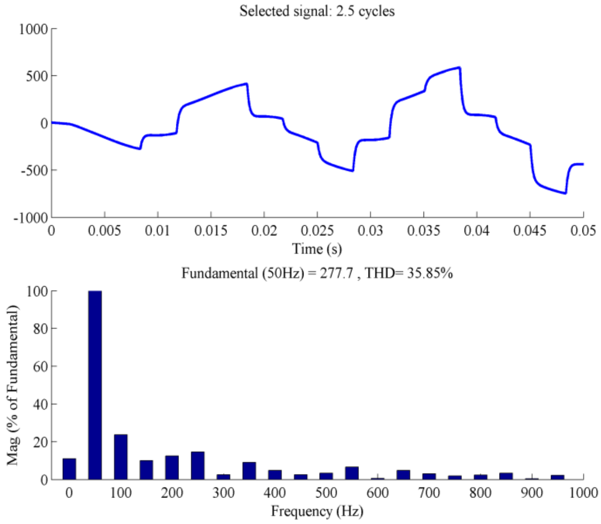


(b)

Figure 4. Current waveform
(a) before and (b) after compensating using ICA



(a)



(b)

Figure 5. Current waveform
(a) before and (b) after compensating using PSO

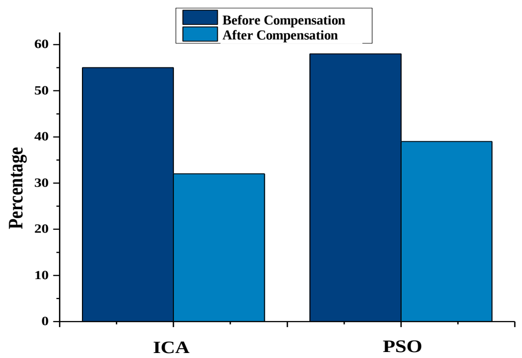


Figure 6. Comparative analysis between ICA and PSO with respect to compensate the total harmonics distortion (*THD*)

One of the main advantages of the proposed method is that the convergence of ICA algorithm is faster and less time consuming (Table 4) as compared to the case where either method is applied alone. Because the proposed algorithm (ICA) provides the correct answers with high accuracy in the initial iterations which make the responding time of this algorithm extremely fast. As seen in Table 4, the average value of fitness function in the proposed ICA method is less than other analyzed method. This means that the ICA is more robust compared to other heuristic methods such as PSO. This would show the convergence characteristics of the proposed ICA compared with other methods.

The major disadvantage of the proposed method is that there is no evidence for finding the global optimum solution in a given problem. This can also be seen in classical methods because of their sensitivity to the starting point of the decision variables (initial values). The output current waveforms after compensating for ICA and PSO are at 0.3186 and 0.3785, respectively. Therefore, the preference of proposed scheme is demonstrated by having more compensation variance in comparison with the other one. This fact is also drawn in the bar chart of the Figure 6.

V. CONCLUSIONS

Passive LCL filters are effective equipment for preventing harmonic pollution and enhancing power quality. But some inefficiency in active filters' performance, resonance, and instability amongst other possible consequences can be appeared by improper designing of passive filter. Therefore, in order to achieve these goals, proper design of LCL filters is important. This paper is focused on optimal designing of the parameters of passive LCL filter using Imperialist Competitive Algorithm (ICA). The minimum total harmonics distortion of voltage (*THD*) is deduced as objective function. By adopting ICA, the parameters of filters are achieved. The proposed scheme is testified by simulation in a practical case and is compared with the other evolutional algorithm like PSO. The effectiveness of proposed scheme Compared with other two ones can be summarized as follow:

- The higher percentage of total harmonics distortion (*THD*) compensation which shows its preference than other method;
- The faster convergence and less time consuming;
- The ability to jump out the local optima;
- Providing the correct answers with high accuracy in the initial iterations;
- Superiority in computational simplicity, success rate and solution quality.

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