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Research Article

BBO ALGORITHM FOR ECONOMICALLY OPTIMUM HARMONIC POWER FLOW IN RADIAL DISTRIBUTION SYSTEMS WITH LINEAR AND NONLINEAR LOADS

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ABSTRACT

For optimizing LC passive power filters harmonic tuning orders setting in the distribution system, objective function includes the reduction of power losses and investment cost of passive power filters. At the same time, constraints include voltage limits, number/size of installed LC passive filters, limit candidate buses for LC installation and the voltage total harmonic distortion (THDv) in all buses. The harmonic levels of system are obtained by current injections method and the load flow is solved by the iterative method of power sum, which is suitable for the accuracy requirements of this type of study. It is shown that through an economical placement and sizing of LC passive filters the total voltage harmonic distortion and active power losses could be minimized simultaneously.

Biogeography based optimization is a novel evolutionary algorithm that is based on the mathematics of biogeography. In the BBO model, problem solutions are represented as islands, and the sharing of features between solutions is represented as immigration and emigration between the islands. The simulation results for a 34-bus radial systems show that the proposed method is efficient for solving the presented problem.

Keywords: *Nonlinear Load, Passive LC Filters, Harmonic Distortion, Distribution Feeders, Biogeography-Based Optimization*

INTRODUCTION

The results of related investigations show that the most of voltage and current distortions in distribution networks are arose to harmonics of third, fifth and seventh orders (Kawam and Emuel 1996). Due to that, in this case the implantation of three single tuned passive filters could solve this problem and therefore the sitting and sizing of filters is quite simple. However, because of distributed linear and nonlinear loads in distribution system, the passive filter planning is much difficult (Omneyer and Hiyama, 1996). In (Verma and Singh, 2010) the genetic-algorithm-based design of passive filters for offshore application is presented and discussed. In (Chen, 2003) a new genetic algorithm based approach to design a passive LC filter fora full-bridge rectifier with aim of finding maximum power factor of the ac mains is presented. In (Ram *et al.*, 1988) the calculation of the R-L-C parameters for a typical passive harmonic filter used in the customers' house is analyzed. In (Henderson and Rose, 1994), the harmonic passive filter planning in radial distribution systems using micro genetic algorithms with aim of voltage harmonic reduction is addressed. In this reference, the input parameters of programmed software include the number and the relevant order of these filters. Optimum location and sizing of two passive harmonic filters, whose harmonic tuning orders are 5 and 7 in distribution networks using genetic algorithm is analyzed by (Messey, 1994). Power loss reduction and minimization of total voltage harmonic distortion are considered as objective function in this reference.

In this research, sitting and sizing of harmonic passive filters in 34-bus test distribution systems using biogeography based optimization (BBO) algorithm is presented. In this work, the objective function to be minimized is value of investment cost of filters and active power loss. Voltage total harmonic distortion is considered as a constraint in optimization problem. In this research, the problem consists of planning passive filters in distribution system with distributed linear and nonlinear loads. In this work for each candidate buses for installing passive filter, the between one to three filter branches whose harmonic tuning orders are 4.7 (for 5th harmonic), 6.7 (for 7th harmonic) and 10.7 (for 11th harmonic), are considered. Locating, sizing of filter capacity in terms of KVar and detection of harmonic tuning orders with aim of minimizing power loss and investment cost is addressed in this paper.

Effects of Harmonic Distortion on Power Systems

Once the harmonic sources are clearly defined, they must be interpreted in terms of their effects on the rest of the system and on personnel and equipment external to the power system. Each element of the power system must be examined for its sensitivity to harmonics as a basis for recommendations on the allowable levels. The main effects of voltage and current harmonics within the power system are (Akagi, 2006):

- Amplification of harmonic levels resulting from series and parallel resonances.
- Reduction in the efficiency of the generation, transmission and utilization of electrical energy.
- Ageing of the insulation of electrical plant components with consequent shortening of their useful life.
- Malfunction of system or plant components.
- Thermal stress
- Insulation stress
- Load disruption

Harmonics increase the equipment losses and thus the thermal stress. Triplen harmonics result in the neutral carrying a current which might equal or exceed the phase currents even if the loads are balanced. This dictates the derating or over sizing of neutral wires. Moreover, harmonics caused resonance might damage the equipment. Harmonics further interfere with protective relays, metering devices, control and communication circuits, and customer electronic equipment. Sensitive equipment would experience maloperation or component failure (Seyed *et al.*, 2011).

Harmonic Power Flow Equations:

The most of the distribution feeders are radial. As shown in Figure1 the details of one section of this feeder is illustrated. Generically, each bus can have linear and nonlinear loads, and shunt capacitor banks.

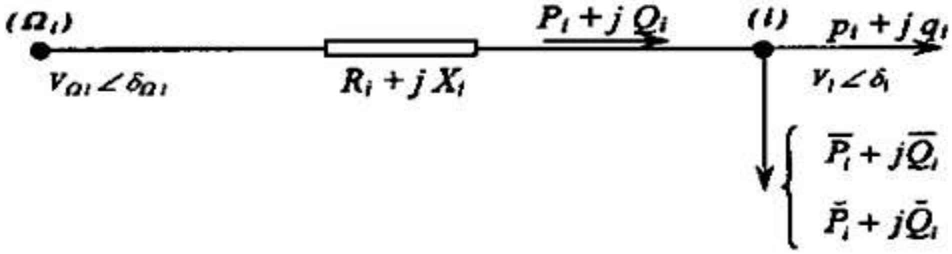


Figure 1: Section i of a radial distribution feeder

To determine the harmonic flow in a radial distribution feeder, the current injection method can be used (Rao *et al.*, 2011). The advantages of this method are that solution can be obtained directly, it is able to handle several harmonic sources simultaneously, and it is computationally efficient. In this method, the network harmonic voltages are calculated by frequency-domain matrix:

$$Y^h V^h = I^h \qquad 1$$

Where I^h is the harmonic current injection vector. V^h is the harmonic voltage vector to be calculated, and Y^h is the admittance matrix of the system. In the adopted notation, the superscript b assumes all values of harmonic orders of interest. The superscript 1 (h=1) corresponds to parameters in fundamental frequency.

The elements of admittance matrix should use models whose parameters are frequency dependent. However, there is some disagreement regarding which harmonic models are best for each component of system (Chis *et al.*, 1997).

The admittances of each line feeder section and capacitor banks in end of each section are:

$$y_i^h = \frac{1}{R_i + jhX_i} \qquad 2$$

and

$$y_{Ci}^h = hy_{Ci}^1 \qquad 3$$

Where, R_i and X_i the resistance and the inductive reactance of feeder section ***i*** and y_{Ci}^1, it is the shunt admittance of the capacitor bank in the bus ***i***, in the fundamental frequency.

The linear loads are represented by a parallel combination of resistance and inductive reactance. These parameters are obtained through the load data in fundamental frequency. The harmonic admittance of these loads is given by the expression:

$$y_{Li}^h = \frac{\overline{P}_i}{\left|V_i^1\right|^2} - j\frac{\overline{Q}_i}{h\left|V_i^1\right|^2} \qquad 4$$

In that $\overline{P}_i$ and $\overline{Q}_i$ they are the active and reactive powers of the linear loads in the bus i.

The non linear loads are represented by harmonic currents sources whose nominal values to the fundamental frequency are:

$$\bar{I}_i^1 = \left(\frac{\tilde{\mathrm{P}}_\mathrm{i} + \mathrm{j}\tilde{\mathrm{Q}}_\mathrm{i}}{\mathrm{V}_\mathrm{i}^1}\right)^* \qquad 5$$

Where $\tilde{P}_i$ and $\tilde{Q}_i$ are the active and reactive power of the nonlinear load in the i^{th} bus. In harmonic frequencies, the current source has nominal values:

$$\bar{I}_i^h = C^h \bar{I}_i^1 \qquad 6$$

Where C^h the percentile value of the current, in the h^{th} harmonic order.

Assuming that the resistance of the harmonic filter is despicable, the admittance of j^{th} harmonic filter, installed in bus *i*, is given for:

$$y_{F_j}^h = -j\left[\frac{h\left(h_{rj}^2 - 1\right)}{\left(h^2 - h_{rj}^2\right)}\right]\frac{k_j Q_C}{\left|V_i^1\right|^2} \qquad 7$$

In that, h_{rj} is the absolute value of tuning frequency of j^{th} harmonic filter installed in bus i; k_j is the number of capacitive modules of j^{th} filter, and Q_C the size of the capacitive modules available for installation.

The reactivate power supplied by j^{th} harmonic filter it is expressed for:

$$Q_{F_j}^h = \frac{h_{rj}^2}{\left(h_{rj}^2 - 1\right)} k_j Q_C \qquad 8$$

Optimization Algorithm

Biogeography Theory

Biogeography Based Optimization (BBO) approach has been developed based on the theory of biogeography. The idea of BBO was first proposed in 2008 by Dan Simon. It is an example of natural process that can be modeled to solve general optimization problems. In BBO, each individual is considered as an island (or a habitat), and the sharing of features between individuals are represented as emigration and immigration in Figure 2. Each solution feature is called a suitability index variable (SIV).

Geographical areas that are well suited as residences for biological species are said to have a high habitat suitability index (HSI) (Simon, 2008).

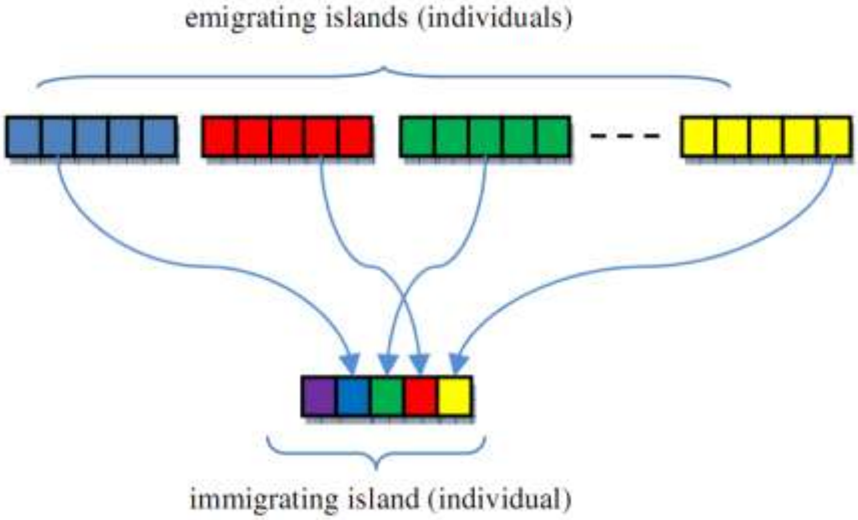


Figure 2: Emmigration of species and new island

Where a high HSI of an island means good performance on the optimization problem and a low HSI means bad performance on the optimization problem. Intensification the population is the way to solve problems in heuristic algorithms. The method to generate the next generation in BBO is by immigrating solution features to other islands, and receiving solution features by emigration from other islands. Then mutation is performed for the whole population in a manner similar to mutation in GAs.
In BBO, each individual has its own immigration rate, denoted by λ, and emigration rate, denoted by μ and are functions of the number of species in the habitat.Figure3 illustrates a model of specie abundance in a single habitat.

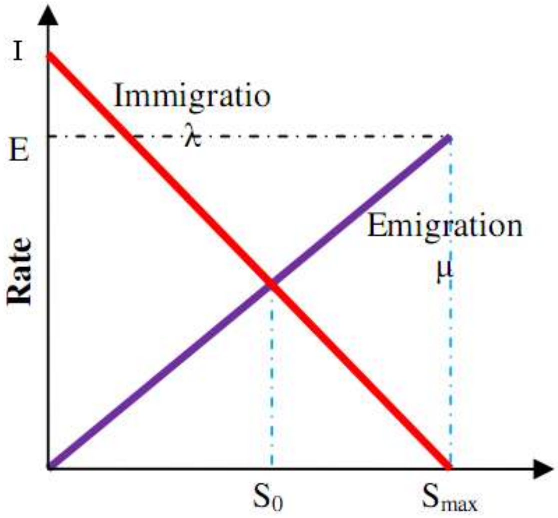


Figure 3: Species model of a single habitat

The maximum possible immigration rate to the habitat is ***I***, which occurs when there are zero species in the habitat. The largest possible number of species that the habitat can support is S_{max}, at which point the immigration rate becomes zero. The maximum emigration rate is ***E***, which occurs when the habitat contains the largest number of species that it can support. The equilibrium number of species is S_0, at which point the immigration and emigration rates are equal.

A good solution has higher μ; hence, it has a very high chance of borrowing features from other solutions, helping it to improve for the next generation.

Note that emigration in BBO does not mean that the emigrating island loses a feature.

Mathematically the concept of emigration and immigration can be represented by a probabilistic model. Further suppose that, consider the probability P_s that the habitat contains exactly ***S*** species at ***t***. P_S changes from time t to time $t+\Delta t$ as follows:

$$P_S(t+\Delta t) = P_S(t)(1-\lambda_S\,\Delta t-\mu_S\Delta t\,)+P_{S-1}\lambda_{S-1}\,\Delta t P_{S+1}\lambda_{S+1}\,\Delta t \qquad 9$$

If time Δt is small enough so that equation (17) as $\Delta t \to 0$ gives the following equation;

$$\begin{cases} -(\lambda_S+\mu_S\,)P_S+\mu_{S+1}\,P_{S+1} & S=0 \\ -(\lambda_S+\mu_S\,)P_S+\mu_{S-1}\,P_{S-1}+\mu_{S+1}\,P_{S+1} & 0\le S\le S_{max}-1 \\ -(\lambda_S+\mu_S\,)P_S+\mu_{S-1}\,P_{S-1} & S=S_{max} \end{cases} \qquad 10$$

As these relationships are shown in Figure 3 as straight lines but, in general, they might be more complicated curves. The values of emigration and immigration rates are given as:

$$\mu_k = \frac{E_k}{n} \qquad 11$$

$$\lambda_k = I\,(1-\frac{k}{n}) \qquad 12$$

Where ***I*** is the maximum possible immigration rate; ***E*** is the maximum possible emigration rate; ***K*** is the number of species of the ***kth*** individual and ***n*** is the number of species. Now, consider the special case ***E=I*** in Figure 4.

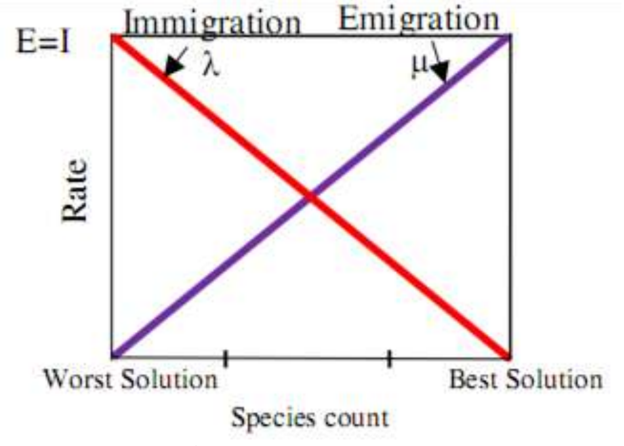


Figure 4: Illustration of two candidate solutions to some problem

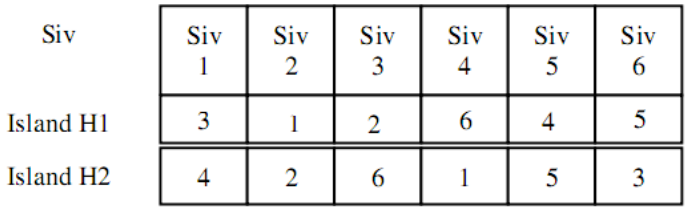
In this case;

$$\lambda_k+\mu_k = \mathrm{E} \qquad 13$$

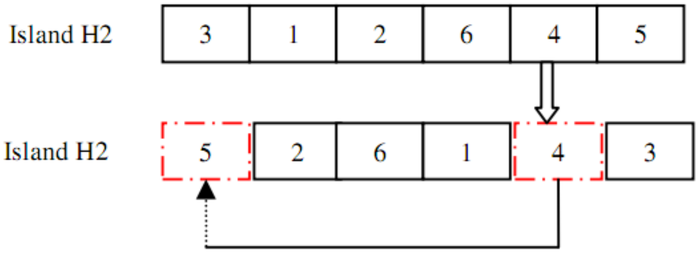
Biogeography-Based Optimization

Suppose that we have a problem and a population of candidate solutions that are represented as vectors.

Further suppose that we have some way of assessing the goodness of the solutions. Good solutions are analogous to islands with a high island suitability index (***ISI***), and poor solutions are analogous to islands with a low ***ISI.*** Note that ***ISI*** is the same as "fitness" in other population based optimization algorithms. BBO mainly works based on the two mechanisms. These are migration and mutation Figures 5, 6.

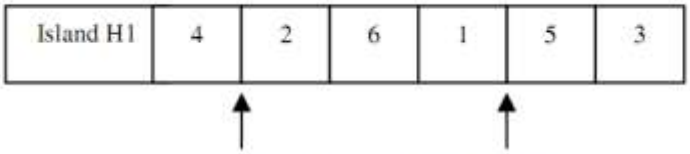


a) Before migration

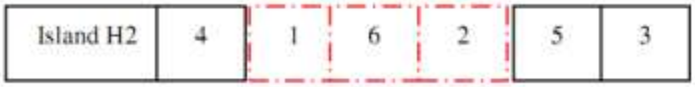


b) After migration

Figure 5: The migration operator in BBO



a) Before inverse mutation



b) After inverse mutation

Figure 6: The mutation operator in BBO

Migration

With probability P_{mod}, known as habitat modification probability each solution can be modified based on other solutions. If a given solution ***Si*** is selected to be modified, then its immigration rate λ is used to probabilistically decide whether or not to modify each suitability index variable ***(SIV)*** in that solution. After selecting the ***SIV*** for modification, emigration rates μ of other solutions are used to select which solutions among the population set will migrate randomly chosen ***SIV***s to the selected solution ***Si***.

Mutation

In BBO species count probabilities are used to determine mutation rates. The probabilities of each species count can be calculated using the differential equation as mentioned in equation (17). Each population member has an associated probability, which indicates the likelihood that it exists as a solution for a given problem. If the probability of a given solution is very low then that solution likely to mutate to some other solution. Similarly if the probability of some other solution is higher than that solution set has very little chance to mutate. Mutation rate of each set of solution can be calculated in terms of species count probability using the equation;

$$m(S) = m_{max}\left(\frac{1-P_S}{P_{max}}\right) \qquad 22$$

Where m_{max} is a user defined parameter.

RESULTS AND DISCUSSION

Simulation and Results

In practice, the available values of capacitance for filters design are discrete, because they correspond to commercially standardized values of capacitive modules available. As described in section 4.3, L and C values of passive filters are mutually dependent, so the size of filter is discrete in the same way as the capacitors. These values also depend on the localization of filter on feeder. On the other hand, the points of possible installation are the buses of the feeder and therefore, they can also be considered as a discrete variable and form a finite group. In that way, the problem is especially of combinatory optimization. This problem should also take in consideration the distributed nature and variable of linear loads and harmonic sources of system.

In this example, the problem consists of planning three passive harmonic filters, whose harmonic tuning orders are 4.7 (for 5th harmonic), 6.7 (for 7th harmonic) and 10.7 (for 11th harmonic), respectively.

As presented, the reactive power capacity of passive filter is a function of harmonic tuning orders and the reactive capacity of pre-installed fixed shunt capacitors in busses of system. On the other hand the investment cost of filter is related to filter capacity, so the proposed algorithm must calculate the optimum harmonic tuning orders until the objective function is minimized. At the same time, constraints include voltage limits, number/size of installed LC passive filters, limit candidate buses for LC installation and the minimum harmonic voltage distortion must satisfied by this procedure. In this section the proposed method for LC passive filter sizing and sitting in the presence of linear and nonlinear loads has been applied on the11 kV, 34-bus radial distribution test system (Figure 7).

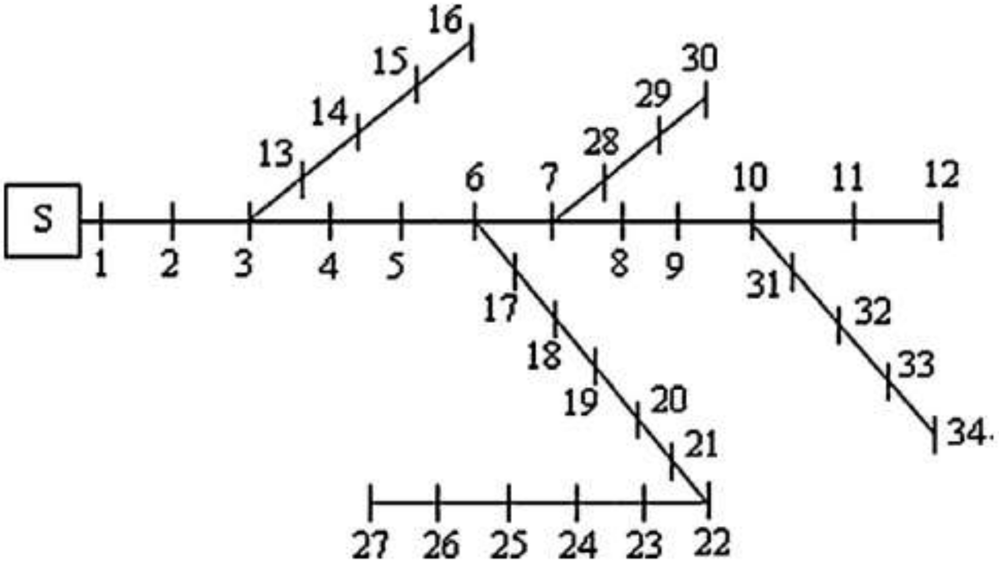


Figure 7: Single-line diagram of the 34-bus radial distribution test system

Specification of this system is given in Tables 1 and 2. Table 4 lists the harmonic current spectrum data in 34-bus test system.

Table 1: Line data in 34-bus test system

From Bus	To Bus	R (p.u)	X (p.u)	From Bus	To Bus	R (p.u)	X (p.u)
1	2	0.03076	0.01567	18	19	0.09385	0.08457
2	3	0.02284	0.01163	19	20	0.02555	0.02985
3	4	0.02378	0.01211	20	21	0.04423	0.05848
4	5	0.05114	0.04411	21	22	0.02815	0.01924
5	6	0.01168	0.03861	22	23	0.05603	0.04424
6	7	0.04439	0.01467	23	24	0.05591	0.04374
7	8	0.06514	0.04617	24	25	0.01267	0.00645
8	9	0.01227	0.00406	25	26	0.01773	0.00903
9	10	0.02336	0.00772	26	27	0.06607	0.05826
10	11	0.09159	0.07206	7	28	0.05018	0.04371
11	12	0.03379	0.04448	28	29	0.03166	0.01613
3	13	0.03687	0.03282	29	30	0.06083	0.06008
13	14	0.04656	0.03410	10	31	0.01937	0.02258
14	15	0.08042	0.10738	31	32	0.02128	0.03319
15	16	0.04567	0.03581	32	33	0.00575	0.00293
6	17	0.01023	0.00976	33	34	0.02336	0.00772
17	18	0.08042	0.10738				

Table 2: Load data in 34-bus test system

Bus number	P Liner Load (kW)	Q Liner Load (kVar)	P Nonlinear Load (kW)	Q Nonlinear Load (kVar)	Nonlinear Devicetype
1	0	0	--	--	------
2	150	120	700	400	6puls
3	0	0	--	--	------
4	250	530	270	190	6puls
5	600	450	50	80	12puls
6	0	0	--	--	------
7	0	0	--	--	------
8	250	180	--	--	------
9	600	300	800	400	6puls
10	0	0	--	--	------
11	200	150	--	--	------
12	300	220	90	30	6puls
13	400	250	--	--	------
14	150	640	350	230	6puls
15	800	500	300	450	12puls
16	500	390	250	110	6puls
17	500	310	800	450	6puls
18	250	180	--	--	------
19	600	300	800	400	6puls
20	150	240	110	80	12puls
21	0	0	--	--	------
22	300	220	400	100	6puls
23	400	250	--	--	------
24	450	520	350	330	6puls
25	800	400	300	750	6puls
26	400	280	--	--	-----
27	650	300	540	670	6puls
28	250	180	--	--	------
29	250	320	120	80	6puls
31	150	240	--	--	-----
32	500	390	450	310	6puls
33	380	260	100	50	6puls
34	400	250	--	--	------

Simulation results are shown in Tables 3. Passive filters locations, harmonic tuning orders, filter capacity, fundamental harmonic voltages, rms voltages and total harmonic distortion of voltages in all buses, have been listed in this table.

Table 3: Results of LC passive filter sitting and sizing in 34-bus test system

Bus number	Pre-installed Qc (Kvar)	Filter Capacity QF (Kvar)	Harmonic tuning orders	V1 (p.u)	Vrms (p.u)	THDv (%)
1	--	--	--	1.0810	1.0832	3.94
2	--	--	--	1.0821	1.0841	3.11
3	600	810/740	5th / 11th	1.0832	1.0855	3.01
4	--	--	--	1.0811	1.0831	3.44
5	1100	1600/1900	5th / 7th	1.0810	1.0824	3.22
6	--	--	--	1.0705	1.0725	3.65
7	700	650/780	5th / 7th	1.0611	1.0627	3.10
8	--	--	--	1.0513	1.0545	3.31
9	--	--	--	1.0640	1.0663	3.25
10	1000	1100	11th	1.0751	1.0784	3.15
11	--	--	--	1.0812	1.0834	3.00
12	800	1100/1340	5th / 7th	1.0825	1.0845	3.03
13	520	450/510/640	5th / 7th /11th	1.0817	1.0879	3.15
14	--	--	--	1.0822	1.0834	3.23
15	1200	1380	5th	1.0812	1.0819	3.10
16	--	--	--	1.0712	1.0721	3.31
17	700	650/780	7th/ 11th	1.0629	1.0645	3.33
18	--	--	--	1.0624	1.0678	3.88
19	800	1100/1340	5th / 7th	1.0611	1.0631	3.98
20	250	370	5th	1.0731	1.0787	3.73
21	--	--	--	1.0822	1.0835	3.78
22	--	--	--	1.0835	1.0847	3.43
23	--	--	--	1.0817	1.0856	3.44
24	--	--	--	1.0822	1.0837	3.12
25	800	980/1100	5th / 7th	1.0812	1.0818	3.32
26	--	--	--	1.0732	1.0743	3.43
27	700	650/780	7th/ 11th	1.0539	1.0545	3.54
28	--	--	--	1.0624	1.0678	3.23
29	--	--	--	1.0631	1.0677	3.22
30	150	200/280/360	5th / 7th /11th	1.0711	1.0787	3.32
31	--	--	--	1.0842	1.0867	3.28
32	--	--	--	1.0845	1.0849	3.19
33	600	740	7th	1.0837	1.0856	3.10
34	--	--	--	1.0822	1.0831	3.34

In table 4 the comparison results of proposed method based on power loss, maximum total harmonic distortion, minimum bus voltage and system cost is shown.

Table 4: Comparison results of proposed method for 34-bus test system

Results	Before Optimization	After Optimization
Power loss [kW]	624	278
THDmax (%)	10.39	3.98
Vmax (p.u)	1.0021	1.0879
Vmin (p.u)	0.9661	1.0513
Total Cost ($/year)	214412	153828

Conclusion

This study deals with optimizing the placement and size of passive filters by BBO algorithm, economically. The algorithm constrains are number/size of installed LC passive filters, limit candidate buses for LC installation, the limitation voltage limits and the voltage total harmonic distortion (THDv) in all buses define by standard IEEE-519.

In this example, the problem consists of planning three passive harmonic filters, whose harmonic tuning orders are 4.7 (for 5th harmonic), 6.7 (for 7th harmonic) and 10.7 (for 11th harmonic), respectively.

Due to dependency of reactive capacity of passive filter to harmonic tuning orders and the reactive capacity of shunt capacitors and on the other hand because of dependency the investment cost of filter to filter capacity, so the proposed algorithm optimize the optimum location, size and harmonic tuning orders. Results of simulation before and after optimizations are compared, which indicate power loss, maximum THD and annual cost after optimization using proposed method, decreased to 55.45%, 61.7% and 28.25% in 34-bus system, respectively. Results show that the proposed method issue table for optimal passive filter placement and sizing in presence of voltage and current harmonic in distribution network.

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