I J C T A, 8(5), 2015, pp. 2013-2020

Multi-objective Optimal Design and Control of Auto-tuned Passive filter using Bacterial Foraging Algorithm to improve Power quality and to minimise Power losses

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Abstract: This paper presents a multi-objective optimization algorithm based design and control of harmonic filters in a practical system. The selected system is an interconnected system consisting of nonlinear loads. The harmonics injected by the nonlinear loads are propagated through the system and lead to deteriorated power quality at the terminals of all the connected loads. The proposed methodology is selected such as to minimize total harmonic current and voltage distortion introduced into point of couplings and losses and to improve the source power factor. The optimization of the objectives is achieved with bacterial foraging algorithm. Simulation and experimental results verify the performance of the algorithm.

Keywords: *Harmonic filter, power quality, reactive compensation, Bacterial foraging optimization.*

1. INTRODUCTION

Presently most of the consumer loads are nonlinear in nature, due to the solid state control circuits implemented for attaining smoothness in operation and flexibility in control. In addition, generators, transformers, arc-furnaces etc. also may contribute to distortions in large amounts. These distortions are propagated throughout the interconnected system and affects quality of source power at all the load terminals. Hence installation of harmonic filters is necessary in the system. The passive filter should provide least impedance path for least order harmonics. The overall system impedance should not generate series or parallel resonance. After harmonic and reactive compensation, source side harmonics, bus voltage, magnitude and angle should be within IEEE standard limits. The solution should be economical, with optimal cost of filters, optimum generation and minimum losses.

Multi objective optimization in power systems can be found in various fields such as reactive power optimization [1], design of compensators [1], design of harmonic filters [2], design of system reconfiguration. Many algorithms have been proposed for solution of complex multi objective optimization problems such as Genetic Algorithm [9], Simulated Annealing [9], Particle Swarm Optimization [9], Ant colony etc. The Bacterial Foraging optimization (BFO)[12,13] was proposed by Kevin Passino in the year 2002. The algorithm is based on the natural selection that eliminates participants with poor foraging strategy. BFO adopts the foraging strategy exhibited by E-coli bacteria. In many real time optimization problems, BFO has been found to perform efficiently in many powerful optimization algorithms with excellent convergence speed and final accuracy. Most of the existing methods in design and control of optimal passive filter follows deterministic methods for harmonic flow calculations [5]. However, deterministic approach may not consider the instantaneous variation in linear and nonlinear loads in the system. The probabilistic

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characteristics of harmonic currents and voltages are to be considered while designing filter components. This paper presents bacterial foraging optimization algorithm for optimal selection and control of passive filters in IEEE 5-bus system where passive filter is optimally allocated. Multi-objective optimization of selection of passive filter is carried out by framing a fitness function integrating all the objectives of problem. The formulation of objective function is explained in following selection.

2. FORMULATION OF MULTI-OBJECTIVE OPTIMIZATION ALGORITHM

For the selection, planning and control of passive filter in the system, the objective function is to minimize the filter installation cost, generation cost and power system losses. In addition, the system should satisfy IEEE-519 standard limits on individual harmonic voltages and current limits at each bus, improved power factor at each bus terminals, IEEE-1531 limits on capacitor voltage (rms) and inductor current (rms) limits.

2.1. Problem Formulation

Optimal selection and control of passive filters in this work is obtained by minimization of three operation costs – total cost of passive filter, power loss in all lines of the system and generation cost. Mathematical modeling of the cost function is as follows:

$$Cost(X) = \sum_{i=b} \sum_{h=H} TC_{hi} \times UC_F + \sum_{i=b} \sum_{j=b} loss_{i,j} \times U_L + \sum C_{Gi} \times U_G$$

where i, j varies from 1 to b, b = bus number, h = order of harmonics, TC = Total cost of the filter, UC_F = unit cost of the filter, Loss = Total losses in each line, U_L = cost for unit energy loss, C_{Gi} = cost of generation, U_G = unit cost of generation. Subjected to the following constraints of:

(1) Harmonic voltage and current distortion limits

According to IEEE 519 standards [8] individual harmonic voltage distortion limits (IHD_V) and total harmonic voltage distortion (THD_V) constraints imposed on any network is 1.5% and 5 % respectively.

According to IEEE 519 standards [8] total harmonic current distortion (THD_I) constraints imposed on any network is 5%.

(2) Voltage magnitude at each of the buses after filtering should be within the limits of 0.9 pu to 1.1 pu.

(3) Voltage angles should be maintained above 0.95.

(4) After the installation of passive filter, the system should not be either over compensated or under compensated. Hence condition on reactive power is set as $Q_{imin} \leq Q_i \leq Q_{imax}$

where $Q_{i\,min}$ and $Q_{i\,max}$ are lower and upper limits of fundamental reactive power provided by passive filter.

(1) RMS Value of capacitor voltage should be less than 110% of the rated value.

(2) RMS value of inductor current should be less than 180% of the rated value.

(3) Detuning of passive filter: During manufacturing process or due to environmental variations, filter inductor value and capacitor value may have deviations in the standard range of -3% to 3% and -7% to 12% from their nominal values. Hence standard limits on detuning factor (d) is kept as $0.92 \leq d \leq 1.06$.

Methodology for implementation of BFO algorithm is explained in next section.

2.2. Methodolgy

The solution technique of BFO algorithm for optimal allocation and control typically includes steps such as chemotaxis, swarming, reproduction, and elimination and dispersal.

Following algorithm summarizes the significant steps of proposed solution procedure [7].

Step I: Initialise the parameters.

Dimension of the search space (p), Number of bacteria(s) in the population, Swimming length (N_s), N_c the number of iterations in the chemotactic loop ($N_c > N_s$), N_{re} the number of reproduction steps, N_{ed} the number of elimination and dispersal events, P_{ed} the elimination-dispersion probability, The location of each bacterium $P(1\text{-}p,1\text{-}s,1)$ specified by the random numbers on [-1,1], $C(i)$ is assumed to be constant for all bacterium in order to make the design simple

Step II: Iterative algorithm for optimization.

This section models the bacterial population chemotaxis, swarming, reproduction and elimination and dispersal (initially, $c = r = e = 0$).

(1) Elimination-dispersal loop, $e = e + 1$

(2) Reproduction loop, $r = r + 1$

(3) Chemotaxis loop, $c = c + 1$

  (a) For $i = 1, 2, \ldots.s$, obtain the cost function value for each bacterium i.

  (b) For $i = 1, 2, \ldots s$ take the swimming decision.

  (c) Go to the next bacterium ($i + 1$). If $i \neq s$ (i.e go to b) in order to process the next bacterium.

(4) If $c < N_c$, go to (3). Then, continue chemotaxis since the life of the bacteria is not over.

(5) Reproduction

  (a) For the given r an e and for each $i = 1, 2, \ldots s$, let $J^i_{\text{health}} = \min_{j\in\{1\ldots Nc\}}\{Jsw(i, c, r, e)\}$ be the health of the bacterium i. Sort the bacteria in the ascending order of cost $J_{\text{health.}}$

  (b) The $S_r = s/2$ bacteria with the highest J_{health} values die and other S_r bacteria with the best value split.

(6) If $r < N_{re}$, go to (2). In this case, the number of specified reproduction steps has not reached, so start the next generation in the chemotactic loop.

(7) Elimination dispersal: For $i = 1, 2,\ldots s$ with probability P_{ed}, eliminate and disperse each bacterium (this keeps the number of bacteria in the population constant) to a random location on the optimization domain[7].

3. CASE STUDY

The proposed technique is implemented on the test system shown in figure 2 which is an extension of IEEE 5 bus transmission system[10].

The load harmonics are assumed to be time-invariant quantities and the selected nonlinear loads have much higher harmonic components compared to many research works in this area[10].

The nonlinear loads connected in 4th and 5th bus injects current harmonics into the system. This harmonic current propagates throughout the system. The effect of current harmonic propagation in IEEE 5 bus system is studied as follows:

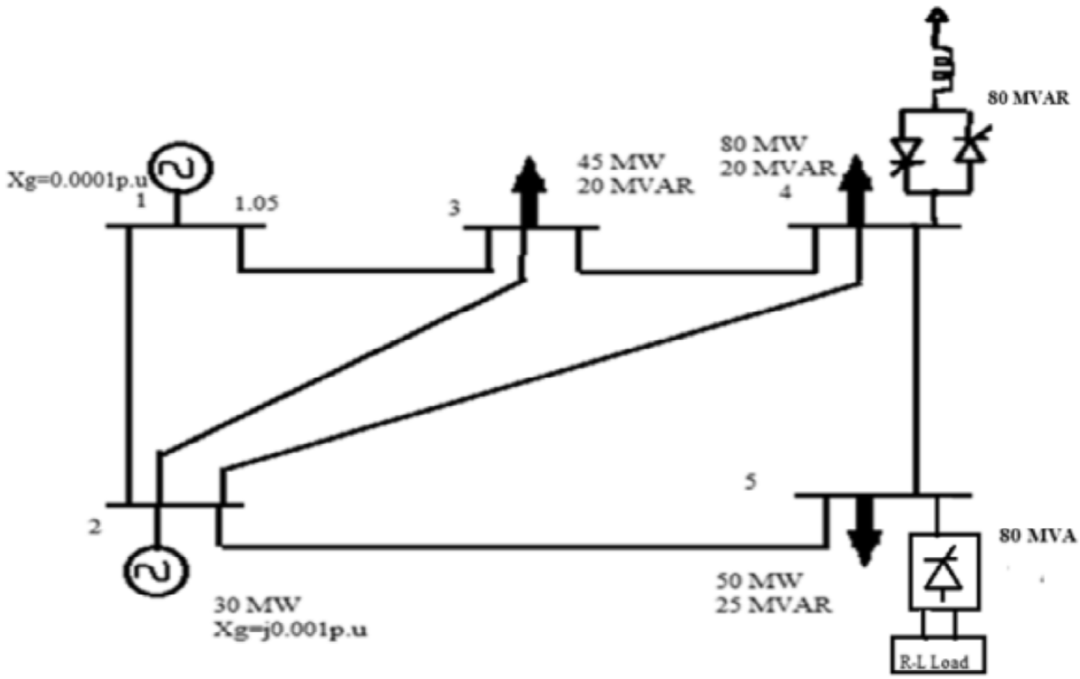

Figure 1: IEEE 5 bus system

Table 1
System Parameters

Line, p-q	*Impedence, Z_{pq}*	*Line charging, $Y_{pq}/2$*
1-2	0.02+j0.06	0.0+j0.030
1-3	0.08+j0.24	0.0+j0.025
2-3	0.06+j0.18	0.0+j0.020
2-4	0.06+j0.18	0.0+j0.020
2-5	0.04+j0.12	0.0+j0.015
3-4	0.01+j0.03	0.0+j0.010
4-5	0.08+j0.24	0.0+j0.025

Table 2
Fundamental load flow results

Node	|V|	q	P_g	Q_g	P_d	Q_d
1	1.0500	0	1.52	0.6584	0.00	0.00
2	1.0000	-2.69	0.30	-0.651	0	0
3	0.9796	-6.21	0	0	0.45	0.20
4	0.9776	-6.92	0	0	0.80	0.30
5	0.9922	-6.69	0	0	0.50	0.25

Table 3
Ratings of the non linear Loads

Bus number	*Type of non linear load*	*Rating*
4	Thyristor controlled reactor (TCR)	80 MVAR
5	Thyristor converter	80 MW

Table 4
% of harmonic currents injected by nonlinear load (TCR) connected in 4th bus (α = 30°)

Harmonic order	*% of fundamental*	*Harmonic order*	*% of fundamental*	*THD*
5	29.56	17	0.85	
7	5.15	19	0.84	30.17%
11	2.58	23	0.42	
13	1.31	25	0.27	

Table 5
% of harmonic currents injected by non linear load (Thyristor converter) in 5th bus (α = 45°)

Harmonic order	*% of fundamental*	*Harmonic order*	*% of fundamental*	*THD*
5	22.55	17	5.55	
7	11.28	19	4.56	30.53%
11	8.94	23	4.01	
13	6.48	25	3.52	

(1) All the *P*-*Q* loads connected in system are modeled as passive loads.

The passive equivalent circuit of the system is derived using the CIGRE standard[10].The capacitor banks are considered to be passive elements where,

$$X_c(h) = -j\frac{{V_{LL}}^2}{h \times Q_{3\Phi}} \tag{1}$$

The linear loads are represented by parallel R-X_L in series with X_s, where

$$R = \frac{{V_{LL}}^2}{P_{3\Phi}} \tag{2}$$

$$X_s(h) = j0.073 \times h \times R \tag{3}$$

$$X_{sh}(h) = j\frac{h \times R}{6.7(\frac{Q_{3\Phi}}{P_{3\Phi}} - 0.74)} \tag{4}$$

Non–linear loads are represented by either a harmonic current injection source or by a harmonic voltage source. Harmonic load in bus 4 is represented by harmonic current injection given by I_h = harmonic as % of fundamental current × $I_{1,}$ where fundamental current I_1 given

$$I_1 = \frac{Q_{3\Phi}}{\sqrt{3} \times V_{LL}} e^{j(\theta \pm \frac{\pi}{2})} \tag{5}$$

θ = angle of respective bus voltage and π/2 is the phase shift since current lags or leads by 90°.

(2) Determination of harmonic bus admittance matrix

Diagonal elements of YBUS are modified with inclusion of harmonic modeling of loads.

(3) Obtain the Harmonic voltage components at each bus using the following equation

$$[V_h] = [Y_h]^{-1}[I_h]$$

Table 6
Harmonic voltages and angles in each bus

hV, θ	5(%)	7(%)	11(%)	13(%)	17(%)	19(%)	23(%)	THD (%)
V1 (pu)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
θ1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
V2 (pu)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
θ2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-
V3 (pu)	3.16	1.67	0.76	0.23	0.26	0.014	0.09	3.67
θ3	20.3°	12.5°	0.3°	9.3°	-13°	-17.8°	-33°	-
V4 (pu)	3.86	2.24	1.07	0.61	0.39	0.23	0.16	4.65
θ4	26.2°	20.6°	12.3°	23.5°	8.4°	-6.9°	3.3°	-
V5 (pu)	3.10	3.22	2.57	1.19	0.19	0.14	0.09	5.29
θ5	38.2°	41.1°	37.1°	33.4°	9.91°	10.9°	-0.2°	-

(4) Obtain the Total Harmonic Distortion in voltage and current in the system.

Table 7
System parameters without compensation

Bus	1	2	3	4	5
THD_I	3.76%	14.1%	10.02%	33.2%	50.98%
THD_V	0	0	3.67%	4.65%	5.2%
Voltage magnitude (pu)	1.049	0.998	0.9	0.88	0.758
Angle	0	-2.73°	-6.62°	-6.10°	-5.98°
Source power factor	0.99	0.99	0.994	0.77	0.622

(5) The THD_I, THD_V, voltage magnitude, angle, source power factor are also noted in Table 8. Results in table shows that:

1. The Total Harmonic Distortion in current should be less than 5% as per IEEE standard[8]. All buses except bus 1 exceeds the limit.
2. The Total Harmonic Distortion in voltage should be less than 2.5% and individual harmonic distortion should be less than 1.5% for a 100kV system. Some of the buses are exceeding both the limits.
3. The voltage magnitude should be maintained in limits as $0.9 < V < 1.1$. Bus 4 and Bus 5 are found to be not in the limits.
4. The source power factor has to be maintained above 0.9 which is not satisfied by bus 4 and bus 5.

Hence it is necessary to install optimal harmonic filter of adequate rating at optimal location.

3.1. Optimal selection of passive filter using BFO in IEEE 5 bus system

(1) Initial values selected for case study are:

The parameters initialized in the optimization problem are as follows

$$Ne = 8,\ Nr = 8,\ Nc = 8,\ Np = 8,\ Ns = 4,\ D = 4,\ C = 0.01,\ P_{ed} = 0.9$$

The Table 3 shows that maximum reactive power demand in the system is 80 MVAR. Hence capacitor sizes upper and lower bounds are selected in the range 20 MVAR to 100MVAR. If the selected value of capacitor is too high, it provides over compensation or power factor will be leading. If the capacitor selected is too low, it provides under compensation or power factor will be lagging. The optimal capacitor size should be such that power factor at the bus is 0.9-0.95.

The initial value of filter inductor is obtained using

$$L = \frac{1}{4\pi^2 f_r^2 C} \tag{6}$$

(2) Harmonic modeling of the passive filter is done as per CIGRE standard.

(3) The harmonic bus admittance matrix is modified including harmonic filter.

(4) The propagation of remaining harmonic currents into the system is determined.

(5) Apply operators of bacterial foraging optimization technique. The algorithm will stop when a feasible point is reached or when the stop criterion is arrived. The global optimum solution is obtained by scanning the obtained results. The system performance with obtained filter parameters is verified as shown in Table 9.

Table 9
System parameters with passive filter installed

Bus	1	2	3	4	5
Voltage Magnitude(pu)	1.05	1.0	1.1	1.1	0.9
THD in current(%)	3	13.4	8.5	10.8	23.3
THD in voltage(%)	0	0.2	2.35	2.91	4.32
Source power factor	1	0.997	0.993	0.929	0.88

The global optimum solution is obtained using BFO algorithm where the filter cost is minimum by keeping all the system parameters as per IEEE limits for power quality.

Table 9 shows the BFO Algorithm provides efficient system performance. Summarizing the obtained results,

1. The Total Harmonic distortion in current and voltage reduced significantly in all buses compared to the results without compensation.
2. The voltage magnitudes remained in the specified limits in all buses.
3. The source power factor improved in all buses.

3.2. Results and Discussion

Conventional passive filter design and control is simple. But it will not be an optimal solution in terms of cost, power factor and losses. Bacterial foraging optimization algorithm gives optimal filter at Bus 4 with values C = 6.97uF, L=11.1mH, R = 4.56Ω. This filter improves performance of the system by improving power factor, voltage magnitude and other system parameters as shown in the table 9. The proposed auto tuned passive filters are effective in reducing % THD in the source current and voltage in the system to meet the IEEE standards limits compared to the conventional passive filters thereby reducing the limitations of passive filters.

4. CONCLUSION

This paper implements Bacterial Foraging optimization algorithm based shunt passive filter configuration in reconfigured IEEE standard 5 bus system with non linear loads. The simulation results show that it achieves current harmonic reduction, voltage harmonic reduction, power factor improvement and damps out the resonance in the network. Compared to conventional shunt passive filter it achieves good performance for the selected system. However, conventional shunt filters may perform better compared to the optimized solution for non linear loads with low amount of distortions.

Acknowledgement

Authors would like to thank Amrita Vishwa Vidyapeetham and Department of Science and Technology, New Delhi for providing support for the entire work.

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