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A Binary Particle Swarm Optimization for Optimal Placement and Sizing of Capacitor Banks in Radial Distribution Feeders with Distorted Substation Voltages

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Abstract

This paper proposes a binary particle swarm optimization (PSO) for optimal placement and sizing of fixed capaci-tor banks in radial distribution lines with nonsinusoidal substation voltages. The objective function includes the cost of power losses and capacitor banks with constraints which include limits on voltage, total harmonic distortion (THD) and sizes of installed capacitors. A binary PSO applied to a test system and solutions of the binary PSO are compared with those of heuristic numerical algorithm that is based on the method of local variations. Computer simulation shows that the harmonic components affect the optimal capacitor placement and sizing.

Keywords: *capacitor placement, binary particle swarm optimization, harmonics, power flow, capacitor sizing*.

1. Introduction

Power distribution from electric power plants to ultimate consumers is accomplished via the transmission sub transmission, and distribution lines. Studies have indicated that as much as 13% of total power generated is consumed as I^2R losses at the distribution level [1]. The I^2R losses can be separated to active and reactive component of branch current, where the losses produced by reactive current can be reduced by the installation of shunt capacitors. Capacitors are widely used in distribution systems to reduce energy and peak demand losses, release the kVA capacities of distribution apparatus and to maintain a voltage profile within permissible limits. The objective of optimal capacitor placement problem is to determine the size, type, and location of capacitor banks to be installed on radial distribution feeders to achieve positive economic response. The economic benefits obtained from the loss reduction weighted against capacitors costs while keeping the operational and power quality constraints within required limits.

Most of the capacitor placement techniques assume sinusoidal conditions and ignore the effect of harmonics [2]-[18]. Limited publications have taken into consideration the presence of harmonics when solving the capacitor placement problems [19]-[27]. Capacitor significantly influences the propagation of system harmonics, and could cause parallel resonance. Therefore, the optimal selection and placement of capacitor banks must be integrated with the estimation of harmonic levels.

A new evolutionary computation technique, called particle swarm optimization (PSO), has been proposed and presented recently [28]-[39]. This technique has been developed through the simulation of simplified social models [28], and has been found to be robust in solving continuous nonlinear optimization. Moreover Kennedy and Eberhart [39] have adapted the PSO to search in binary spaces. Therefore the method can be expanded to solve nonlinear optimization problems with both equality and inequality constraints [32]-[35].

Recently, PSO have been successfully applied to various fields of power system optimization such as reactive power and voltage control [36], power system stabilizer design [37] and reactive power dispatch [38].

In this paper a binary PSO algorithm applied to a test system shown in [19] with the same formulation, assumption and constraints for optimizing shunt capacitor sizes at a candidate buses (4, 5 and 9) on radial distribution lines with nonsinusoidal substation voltages to compare it with that obtained in [19]. Then the same binary PSO algorithm applied to the same test system to find optimal placement and sizing of shunt capacitor (apply the binary PSO algorithm to all the buses).

2. System Model at Fundamental and Harmonic Frequencies

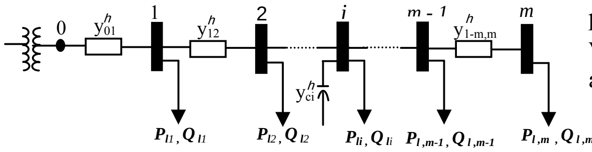

Fig. 1: One-line Diagram of radial Distribution feeder

For modeling of a distribution system Fig.1 at fundamental and harmonic frequencies the formulation and notations and assumption of [19] are used. A review of harmonic load flow found in [40] and computer modeling and analysis of power systems harmonics found in [41].

The modeling steps are as follows:

- Calculate the magnitudes and the phase angles of the bus voltages at fundamental frequency by using Newton-Raphson power flow method and calculate the power losses at the power frequency Eqn. (1).
- Calculate the h-th harmonic frequency load admittances, shunt capacitor admittances and feeder admittances Eqns. (2)-(4) respectively.
- Calculate the harmonic voltages [19], the rms voltage and the total harmonic distortion from Eqns. (5)-(7) respectively.

$$P^1_{loss(i,i+1)} = R_{i,i+1}[|V^1_{i+1} - V^1_i||y^1_{i,i+1}|]^2 \qquad (1)$$

$$y^h_{li} = \frac{P_{li}}{|V^1_i|} - j\frac{Q_{li}}{h|V^1_i|^2} \qquad (2)$$

$$y^h_{ci} = hy^1_{ci} \qquad (3)$$

$$y^h_{i,i+1} = \left(R_{i,i+1} + jhX_{i,i+1}\right)^{-1} \qquad (4)$$

$$\begin{bmatrix} Y^h_{11} & Y^h_{11} & 0 & & 0 & \\ Y^h_{11} & Y^h_{11} & . & & & \\ 0 & . & . & & & \\ . & & . & . & 0 & \\ . & & & . & Y^h_{m-1,m-1} & Y^h_{m-1,m} \\ 0 & & & 0 & Y^h_{m,m-1} & Y^h_{m,m} \end{bmatrix} \begin{bmatrix} V^h_1 \\ V^h_2 \\ . \\ . \\ V^h_{m-1} \\ V^h_m \end{bmatrix} = \begin{bmatrix} y^h_{01}V^h_0 \\ 0 \\ . \\ . \\ 0 \\ 0 \end{bmatrix} \qquad (5)$$

$$|V_i| = \sqrt{\sum_{h=1}^{H} |V^h_i|^2} \qquad (6)$$

$$THD_i(\%) = \frac{100}{|V^1_i|}\sqrt{\sum_{h \neq 1}^{H} |V^h_i|^2} \qquad (7)$$

Where:

V^1_i	the fundamental voltage at bus i.
P_{li}, Q_{li}	load active and reactive powers at bus i,
$R_{i,i+1}$, $X_{i,i+1}$	resistance and inductive reactance of feeder section between buses i and i+1.
H	the upper limit of considered harmonic order

3. Problem Formulation

The objective function Eqn. (10) is to minimize the total annual cost due to capacitor placement and power losses with constraints that include limits on voltage Eqn. (12), total harmonic distortion Eqn. (11) and size of installed capacitors Eqn. (9).

$$P_{loss} = \sum_{h=1}^{H}\left(\sum_{i=0}^{m-1} P^h_{loss(i,i+1)}\right) \qquad (8)$$

$$Q^c_{\max} = LQ^c_0 \qquad (9)$$

$$F = K^p P_{loss} + \sum_{j=1}^{J} K^c_j Q^c_j \qquad (10)$$

$$THD_i \le THD_{\max} \qquad (11)$$

$$V_{\min} \le |V_i| \le V_{\max} \qquad (12)$$

Where:

P_{loss}	the total power losses.
L	an integer.
Q^c_0	smallest capacitor size.
F	the total annual cost function.
K_p	annual cost per unit of power losses.
K^c_j	the capacitor annual cost/kvar.
Q^c_j	the shunt capacitor size placed at bus j.
J, m	shunt capacitor buses and number of buses.
$V_{\min}$	minimum permissible rms voltage.
$V_{\max}$	maximum permissible rms voltage.
$THD_{\max}$	maximum permissible total harmonic distortion.

4. Particle Swarm Optimization

Particle Swarm Optimization is an algorithm developed by Kennedy and Eberhart [28] that simulates the social behaviors of bird flocking or fish schooling and the methods by which they find roosting places, foods sources or other suitable habitat.

In the basic PSO technique, suppose that the search space is d-dimensional,

- Each member is called *particle*, and each particle (i-th particle) is represented by d-dimensional vector and described as $X_i = [x_{i1}, x_{i2}, \ldots, x_{id}]$.
- The set of n particle in the swarm are called *population* and described as *pop* = $[X_1, X_2, \ldots, X_n]$.
- The best previous position for each particle (the position giving the best fitness value) is called *particle best* and described as $PB_i = [pb_{i1}, pb_{i2}, \ldots, pb_{id}]$.
- The best position among all of the particle best position achieved so far is called *global best* and described as $GB = [gb_1, gb_2, \ldots, gb_d]$.
- The rate of position change for each particle is called *the particle velocity* and described as

$V_i = [\, v_{i1}, v_{i2}, \ldots, v_{id} \,]$.

At iteration k the velocity for d-dimension of i-particle is updated by:

$$v_{id}^{k+1} = w v_{id}^{k} + c_1 r_1 (pb_{id}^{k} - x_{id}^{k}) + c_2 r_2 (gb_{d}^{k} - x_{id}^{k}) \quad (13)$$

Where i= 1,2,..,n and n is the size of population, w is the inertia weight, c_1 and c_2 are the acceleration constants, and r_1 and r_2 are two random values in range [0,1]. The optimal selection of the previous parameters found in [29]-[30].

- The i-particle position is updated by

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \quad (14)$$

For binary discrete search space, Kennedy and Eberhart [39] have adapted the PSO to search in binary spaces, by applying a sigmoid transformation to the velocity component Eqn. (15) to squash the velocities into a range [0,1], and force the component values of the locations of particles to be 0's or 1's. The equation for updating positions Eqn. (14) is then replaced by Eqn. (16).

$$sigmoid(v_{id}^{k}) = \frac{1}{1 + e^{-v_{id}^{k}}} \quad (15)$$

$$x_{id}^{k} = \begin{cases} 1, \text{ if } rand < sigmoid(v_{id}^{k}) \\ 0, \quad otherwise \end{cases} \quad (16)$$

The PSO technique can be expressed as follow:

Step 1) *(Initialization):* Set the iteration number k=0. Generate randomly n particles, $\{X^{0}_{i}$, i = 1, 2, …., n}, where $X^{0}_{i} = [x^{0}_{i1}, x^{0}_{i2}, \ldots, x^{0}_{id}]$, and their initial velocities $V^{0}_{i} = [v^{0}_{i1}, v^{0}_{i2}, \ldots, v^{0}_{id}]$. Evaluate the objective function for each particle $f(X^{0}_{i})$. If the constraints are satisfied, then set the *particle best* $PB^{0}_{i} = X^{0}_{i}$, and set the *particle best* which give the best objective function among all the particle bests to *global best* GB^0. Else, repeat the initialization.

Step 2) *Update iteration counter* k=k+1

Step 3) *Update velocity* using Eqn. (13).

Step 4) *Update position* using the sigmoid function Eqn. (15) and Eqn. (16).

Step 5) *Update particle best:*

If $f_i(X_i^k) < f_i(PB_i^{k-1})$ then $PB_i^k = X_i^k$

else

$PB_i^k = PB_i^{k-1}$

Step 6) *Update global best:* $f(GB^k) = \min\{f_i(PB_i^k)\}$

If $f(GB^k) < f(GB^{k-1})$ then $GB^k = GB^k$

else

$GB^k = GB^{k-1}$

Step 7) Stopping criterion: If the number of iteration exceeds the maximum number iteration, then stop, otherwise go to step 2.

5. Formulation of Capacitor Placement Using Binary PSO

The system shown in Fig.1 is m-bus radial distribution system. Table 1 shows a sample of the yearly cost of fixed capacitor sizes. To select the capacitor size Q^{c}_{j} to be placed at bus j, a combination of capacitor sizes (R-size) is chosen from Table 1, as an example,

$$Q^{c}_{j} = (b_1\, sz_1 + b_2\, sz_2 + \ldots + b_r\, sz_r + \ldots + b_R\, sz_R) \quad (17)$$

Where:

$j \in J$, J is a set of candidate buses to capacitors placement

$b_r = \{0,1\}$.

sz_r : capacitor size from Table I.

$Q^{c}_{j} \leq Q^{c}_{max}$, Q^{c}_{max}: the maximum allowable capacitor size to be placed at any bus.

For optimal capacitor placement a binary PSO will be used as follows:

- The capacitor Q^{c}_{j} which will be placed at candidate bus j consists of small capacitor sizes (R-size) Eqn.(17), where The candidate buses are J-bus,
- A population of n particles at iteration k is represented by: $pop^k = [X^k_1, X^k_2, \ldots, X^k_i, \ldots, X^k_n]$,
- Each particle i represented in J-dimensional (J represents the candidate buses) by: $X^k_i = [x^k_{i1}, x^k_{i2}, \ldots, x^k_{ij}, \ldots, x^k_{iJ}]$,
  Each dimension j represented in R-dimensional (R represents the number of capacitor sizes to choose from) by: $x^k_{ij} = [x^k_{ij1}, x^k_{ij2}, \ldots x^k_{ijr}, \ldots x^k_{ijR}]$ therefore, each particle i represented in (J,R) dimensions by:

$$X_i^k = \begin{bmatrix} x_{i11}^k & x_{i12}^k & \cdots & x_{i1r}^k & \cdots & x_{i1R}^k \\ x_{i21}^k & x_{i22}^k & \cdots & x_{i2r}^k & \cdots & x_{i2R}^k \\ . & . & \cdots & & \cdots & . \\ x_{ij1}^k & x_{ij2}^k & \cdots & x_{ijr}^k & \cdots & x_{ijR}^k \\ . & . & \cdots & & \cdots & . \\ x_{iJ1}^k & x_{iJ2}^k & \cdots & x_{iJr}^k & \cdots & x_{iJR}^k \end{bmatrix}$$

- The capacitor size at bus j at iteration k in particle i represented by :

$$Q_{ij}^{c(k)} = x^k_{ij1}\, sz_1 + x^k_{ij2}\, sz_2 + \ldots + x^k_{ijr}\, sz_r + \ldots + x^k_{ijR}\, sz_R$$

- The dimension x^k_{ijr} indicates if the capacitor size sz_r is placed at bus j at iteration k in particle i or not. In other words, x^k_{ijr} is a binary value such that $x^k_{ijr} = 1$ if the capacitor size sz_r is placed at bus j at iteration k in particle i, $x^k_{ijr} = 0$ if it is not placed.
- The particle best, global best and the particle velocity are represented also in (J, R) dimensions.

TABLE 1
YEARLY COST OF FIXED CAPACITORS [19]

	1	2	3	4	5	6	7
Capacitor size (kvar)	150	300	450	600	750	900	1050
Capacitor cost ($/kvar)	0.5	0.35	0.253	0.22	0.276	0.183	0.228
	8	9	10	11	12	13	14
Capacitor size (kvar)	1200	1350	1500	1650	1800	1950	2100
Capacitor cost ($/kvar)	0.17	0.207	0.201	0.193	0.187	0.211	0.176
	15	16	17	18	19	20	21
Capacitor size (kvar)	2250	2400	2550	2700	2850	3000	3150
Capacitor cost ($/kvar)	0.197	0.17	0.189	0.187	0.183	0.18	0.195
	22	23	24	25	26	27	
Capacitor size (kvar)	3300	3450	3600	3750	3900	4050	
Capacitor cost ($/kvar)	0.174	0.188	0.17	0.183	0.182	0.179	

TABLE 2
3-PHASE LOAD DATA

Bus #	P (kW)	Q (kvar)
1	1840	460
2	980	340
3	1790	446
4	1598	1840
5	1610	600
6	780	110
7	1150	60
8	980	130
9	1640	200

TABLE 3
FEEDER DATA AT 60 HZ

Bus# i	Bus# i+1	$R_{i,i+1}(\Omega)$	$X_{i,i+1}(\Omega)$
0	1	0.1233	0.4127
1	2	0.014	0.6051
2	3	0.7463	1.205
3	4	0.6984	0.6084
4	5	1.9831	1.7276
5	6	0.9053	0.7886
6	7	2.0552	1.164
7	8	4.7953	2.716
8	9	5.3434	3.0264

6. Numerical Example

The proposed binary PSO were applied to the test system described in [19] and the results were compared to that's obtained in [19] using a simple heuristic numerical algorithm that is based on the method of local variations. The load and the feeder data are listed in Table 2 and Table 3 respectively. It is desired to find:

(1) The optimal values of capacitor sizes to be placed at buses 4, 5, and 9.

(2) The optimal placement and sizing of capacitors (apply binary PSO to all the 9 buses).

Kp was selected to be 168 $/kW, and the voltage limits on the rms voltages were selected as Vmin= 0.9 pu, and Vmax=1.1 pu. It was assumed that the substation voltage contains 4% and 3% of 5-th and 7-th harmonic, respec-tively, resulting in a total harmonic distortion of 5%.

Commercially-available capacitor sizes with real costs/kvar were used in the analysis. It was decided that the largest capacitor size Q^c_{max} should not exceed the total reactive load, i.e., 4186 kvar. The yearly costs of capacitor sizes [19] are shown in Table 1.

Optimum shunt capacitor sizes have been evaluated for the following cases: (a) the harmonic frequencies are ignored, (b) the harmonic frequencies are taken into account, but no limit is imposed on the total harmonic distortion, (c) the higher frequency components are taken into account, but limits are imposed on the total harmonic distortion. Two limits were selected: (i) THDmax= 8%, and (ii)THDmax=5%.

The parameters used through the simulation are as follows:

n=20 particles, w=0.8, $c_1=c_2=2$,

R=7 sizes, $sz_1=150$, $sz_2=300$,……, $sz_7=1050$.

J=3 for buses {4, 5, 9}, and J= 9 for all the buses.

Test results and discussion

The simulation results showed in Table 4 clear that:

- Before shunt capacitor placement, the annual costs function equal to $131675 due to the total power losses of 783.3 kW. The minimum rms voltage was 0.383 Pu, and the maximum THD was 4.9%.
- Case (a) when the THD are ignored, applying the heuristic optimization (H.O.) at a candidate buses [4, 5 and 9] shows a yearly benefits of $12167 and max.THD of 11.2%, applying a binary PSO at the same candidate buses [4, 5 and 9] shows an increasing in yearly benefits to $12979 and max.THD of 12%, applying a binary PSO to optimal capacitor placement and sizing shows the best benefits $15907 and max.THD of 12.75%.
- Case (b) when the THD are taken into account but without limits, the benefits and the max.THD of H.O., a binary PSO at a candidate buses and a binary PSO at all buses are ($12939, 10.8%), ($14588,11.9%), and ($16506, 13.4%), respectively. Note that the benefits in case (b) are better than that in case (a) this is due to the effect of the harmonic frequencies which increase the rms voltages. Thus, less kvars are needed to bring the voltage levels up to the minimum permissible level.
- Case (c) when the THD are taken into account with limits of (i) max.THD = 8% (ii) max.THD = 5%, the benefits and the THD of H.O., a binary PSO at a candidate buses and a binary PSO at all buses in (i) and (ii) are (i) ($5511, 7.96%), ($6713, 7.95%) and ($6735, 7.99%), respectively (ii) ($-7410, 5%), ($-5856, 4.95%) and ($-5856, 4.95%), respectively. In case (chi) the benefits are negative to control the max.THD and the rms voltages to acceptable levels.
- In all cases optimization of the system by a binary PSO algorithm at a candidate buses indicates yearly benefit better than that indicates by heuristic algorithm at the same candidate buses, and the optimal placement and sizing (apply the algorithm to all the 9 buses) using binary PSO indicate the best benefits.

An extension of this work will be in another paper under writing now. In this paper we applied the PSO to two test systems; the first is 9-bus with varying load levels, predetermined voltage regulator and the harmonics in the loads. The second is 34-bus radial distribution test system with a main feeder and four laterals (subfeeders).

TABLE 4
OPTIMAL SOLUTIONS FOR DIFFERENT CASES USING HEURISTIC ALGORITHM [19] AND BINARY PSO ALGORITHM

case number		before* capacitor placement	case (a)			case (b)			case (ci)			case (cii)		
optimization method			H.O.**	PSO1***	PSO2****	H.O.	PSO1	PSO2	H.O.	PSO1	PSO2	H.O.	PSO1	PSO2
Capacitor Bank placement	Q^c_1	---	---	---	1800	---	---	150	---	---	0	---	---	0
	Q^c_2	---	---	---	1650	---	---	2700	---	---	0	---	---	0
	Q^c_3	---	---	---	1200	---	---	1500	---	---	0	---	---	450
	Q^c_4	---	2700	4050	1800	1950	3750	2100	3000	1800	1350	2100	600	300
	Q^c_5	---	2850	1950	1200	2850	1500	450	0	900	1050	0	300	300
	Q^c_6	---	---	---	450	---	---	600	---	---	0	---	---	0
	Q^c_7	---	---	---	0	---	---	0	---	---	0	---	---	0
	Q^c_8	---	---	---	450	---	---	450	---	---	450	---	----	0
	Q^c_9	---	900	900	450	900	900	450	2100	1950	1650	2850	2700	2700
total capacitor [kvar]		---	**6450**	**6900**	**9000**	**5700**	**6150**	**8400**	**5100**	**4650**	**4500**	**4950**	**3600**	**3750**
min. voltage[pu]		**0.838**	**0.906**	**0.907**	**0.901**	**0.901**	**0.9**	**0.9**	**0.902**	**0.9**	**0.9**	**0.91**	**0.9**	**0.9**
max. voltage[pu]		**0.994**	**1**	**1**	**1**	**0.999**	**0.999**	**1**	**0.998**	**0.997**	**0.997**	**0.998**	**0.996**	**0.997**
Max. THD [%]		**4.9**	**11.2**	**12**	**12.75**	**10.8**	**11.9**	**13.4**	**7.96**	**7.95**	**7.99**	**5**	**4.95**	**4.995**
power losses [kW]		**783.8**	**704.26**	**698.78**	**678.73**	**700.2**	**690.1**	**675.26**	**745.6**	**738.4**	**738**	**822.6**	**814.2**	**813.6**
capacitor cost [$/year]		---	**1191.15**	**1301.1**	**1741.2**	**1130.7**	**1152.45**	**1724.55**	**909.6**	**912.75**	**951.15**	**891.5**	**741.9**	**828.75**
total cost [$/year]		**131675**	**119508**	**118696**	**115768**	**118736**	**117087**	**115169**	**126164**	**124962**	**124939**	**139085**	**137531**	**137512**
benefits [$/year]		---	***12167***	***12979***	***15907***	***12939***	***14588***	***16506***	***5511***	***6713***	***6735***	***-7410***	***-5856***	***-5873***

* simulation results befor shunt capacitor placement

** simulation results after heuristic optimization algorithm that is based on the method of local variations, at a candidate buses [4, 5and 9]

*** simulation results after PSO, at a candidate buses [4, 5and 9]

**** simulation results after PSO, PSO applied at all the buses to find optimal placement and sizing of fixed capacitor banks

7. Conclusion

In this paper, we have proposed a binary PSO on radial distribution feeders with distorted voltage supply to determine (1) the optimal shunt capacitor sizing at a candidate buses (2) the optimal capacitor placement and sizing.

The effectiveness of the binary PSO to solve the discrete optimization problems of capacitor placement and sizing has been demonstrated through the numerical example. It was found that the optimal placement and sizing at fundamental frequency of voltage without taken into account the effect of harmonics can result unacceptable THD levels.

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