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sParticle Swarm Optimization Algorithm for Optimal Capacitor Placement on Electric Power Distribution Networks

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Abstract— Optimal capacitor allocation in distribution systems has been studied for a long times. It is an optimization problem which has an objective to define the optimal sizes and locations ofcapacitors to be installed.This paper presents a new methodology using particle swarm optimization (PSO) Algorithm for the placement of capacitors on the distribution systems to reduce the power losses and to improve the voltage profile.The optimization algorithm described here has been applied successfully in a real system. Results obtained by simulation of real system, is presented to validate the proposed solution method. The simulation results show that the proposed method has good performance.

Index Terms— capacitor, PSO, optimization, power loss, voltage profile, power system, cost

1 Introduction

THE complex social behaviors of insects have been intensively studied in science and in research of computer technology. The attempt is to develop algorithms inspired by insect behavior to solve optimization problems. These behavior patterns can offer models for solving difficult combinatorial (distributed) optimization problems. One of search algorithms with such concept is PSO [1]. PSO has been widely applied to solving various combinatorial optimizations problems such as clustering, neural network training, nonlinear problems solving, etc [2, 3].

Since 1970s, researchers are working towards the goal of producing computational methods in order to optimize power systems. In the late 80s and early 90s, work oriented to distribution systems became more common, after the emergence of efficient computational methods, such as, the power summation load flow method [4] used for simulating electricity distribution radial systems. At that time, also began to emerge general purpose heuristics, called metaheuristics, applied successfully in many optimization problems. For capacitor placement optimization, it is emphasized the Tabu Search [5, 6], Genetic Algorithms [7, 8] and Ant Colony [9, 10, 11], due to the frequency with which they are addressed in technical literature and survey.

Distribution networks in a power system connect the distribution substation to the customers. They are designed as a set of radial feeders rooted at the substations, which are subdivided in primary networks, at the upper level, and secondary networks, at the lower level [4]. Difficult combinatorial optimization problems pervade the planning and operation of these networks. They include the definition of the best design and mix of facilities to meet demands [4, 5], finding optimal network configurations [6- 8], obtaining the best strategy for service restoration after a fault [9] and optimal capacitor allocation.

shunt capacitor in distribution feeders has always been an important research area [10]. It is because a portion of power loss in distribution systems could be reduced by adding shunt capacitors to supply a part of the reactive power demands [11]. For this reason, the source of the system does not necessarily to supply all reactive power demands and losses. Consequently, there is a possibility to decrease the losses associated with the reactive power flow through the branches in the distribution systems. It has been realized that the benefits of capacitor placement in distribution systems are power factor correction, bus voltage regulation, power and energy loss reduction, feeder and system capacity release as well as power quality improvement.

The optimal capacitor allocation problem searches for the best compromise between cost of capacitors and their benefits to a network; it must unveil the ideal number, best places and optimal sizes for shunt capacitor banks on radial power distribution feeders.

Techniques to search the best alternatives for capacitor allocation on radial distribution feeders have been developed for more than 50 years [12, 13]—most of these are concerned with capacitor placement for loss reduction and voltage regulation. The early studies proposed approximated models that enabled the application of analytical methods [12- 15].

In [13] author relied on dynamic programming to address the problem under a formal optimization framework, though with restricting assumption which inhibited application of his ideas. For instance, the optimization procedure was designed for single-ended feeders (in other feeders without lateral

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branches). Extrapolation of the procedure to consider multi-ended feeders seemed to require additional state dimensions, in such a way that would preclude its application to real scale capacitor allocation problems; some papers even put in words that a dynamic programming approach for the problem would meet the ‘‘curse of dimensionality’’ e.g., [17].

During the years that followed the publication of [16], no new studies reported ideas that could allow the improvement of his contribution. Today heuristic methods prevail in the literature about capacitor allocation on distribution feeders: [18, 19] proposed a two stages heuristic method, where a master problem uses a greedy approach to determine the locations of capacitors and a slave problem approximate the optimal size of capacitors with a non-linear programming approach; [20, 21] developed constructive heuristics; In [22] author adopted the tabu search heuristic; [23] proposed microgenetic algorithms; In [24] author designed a hybrid genetic algorithm. Other recent papers also rely on genetic algorithm approaches [25, 26]. A new two stages approximation with a contemporary perspective was proposed by [27]: an interior point conic programming method is used in the first stage to obtain the best continuous values for injection of reactive power; the second stage obtains discrete values for capacitors by solving a mixed integer programming problem that seeks to minimize L1-norm deviations from the reactive injections obtained in the first stage.

The study of the optimal placement and sizing of fixed capacitor banks placed on distorted interconnected distribution systems using PSO is presented in this paper.

The rest of paper is organized as follows. Section 2 explains the problem. Section 3 presents the optimization algorithm. Section 4 describes the proposed method. Section 5, shows simulation results and finally Section 6 concludes the paper.

2 Problem formulation

2.1 Assumptions

The optimal capacitor placement problem has many variables including the capacitor size, location, capacitor cost, voltage and harmonic constraints on the system. In this section we described the problem.

2.2 Capacitor size and cost

Only the smallest standard size of capacitors and multiples of this standard size are allowed to be placed at the buses to have more realistic optimal solution. The capacitor sizes are treated as discrete variable and the cost of the capacitor is not linearity proportional to the capacitor size, this makes the formulated problem a combinatorial one.

2.3. Objective Function

The objective of the capacitor placement problem is to reduce the total energy losses of the system while striving to minimize the cost of capacitors installed in the system. The objective function consists of two terms. The first is the cost of the capacitor placement and the second is the cost of the total energy losses.

The cost associated with capacitor placement is composed of a fixed installation cost, a purchase cost and operational cost (maintenance and depreciation). The cost function described in this way is a step-like function rather than a continuously differentiable function since capacitors in practice are grouped in banks of standard discrete capacities with cost not linear proportional to the capacitor bank size.

It should be pointed that since the objective function is non differentiable, all nonlinear optimization techniques become awkward to apply.

The second term in the objective function represents the total cost of energy losses. This term is obtained by summing up the annual real power losses for the system.

2.4 Operational Constraints

Voltages along the feeder are required to remain within upper and lower limits after the addition of capacitors on the feeder. Voltage constraints can be taken into account by specifying the upper and lower bounds of the magnitude of the voltages. The distortion of voltage is considering by specifying for maximum total harmonic distortion (THD) of voltages and the maximum number of banks to be installed in one location is taken into account.

2.5 Mathematical representation

The capacitor placement problem is expressed mathematically as shown below:

$$Min\ \ \mathrm{F}=\mathrm{K_p}\ \mathrm{P_{loss}}+\sum_{j=1}^{J} K_j^c\ \mathrm{Q_j^c} \qquad (1)$$

$$V_{\min} \le \left|V_j\right| \le V_{\max} \qquad (2)$$

$$\mathrm{THD_j} \le THD_{max} \qquad (3)$$

$$\mathrm{Q_j^c} \le \mathrm{Q_{max}^c} \qquad (4)$$

$$\mathrm{Q_{max}^c} = L\mathrm{Q_0^c} \qquad (5)$$

Bounds for (2), (3) are specified by the IEEE-519 standard [28].

3 PSO

The basic operational principle of the particle swarm is reminiscent of the behavior of a group, for example, a flock of birds or school of fish, or the social behavior of a group of people. Each individual flies in the search space with a velocity

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F	The total annual cost function.
K_p	Annual cost per unit of power losses.
P_{loss}	The total power losses. (Result from ETAP PowerStation Harmonic Load Flow Program).
J	Number of buses.
K_j^c	The capacitor annual cost/kvar
Q_j^c	The shunt capacitor size placed at bus j.
V_j	The rms voltage at bus j. (Result from ETAP PowerStation Harmonic Load Flow Program).
V_{min}	Minimum permissible rms voltage.
V_{max}	Maximum permissible rms voltage.
THD_j	The total harmonic distortion at bus j. (Result from ETAP PowerStation Harmonic Load Flow Program).
THD_{max}	Maximum permissible total harmonic distortion.
Q_{max}^c	Maximum permissible capacitor size.
L	An integer.
Q_0^c	Smallest capacitor size.

which is dynamically adjusted according to its own flying experience and its companions' flying experience, instead of using evolutionary operators to manipulate the individuals like in other evolutionary computational algorithms. Each individual is considered as a volume-less particle (a point) in the N-dimensional search space. At time step t,theith particle is represented as: $X_i(t) = (x_{i1}(t), x_{i2}(t), ..., x_{iN}(t))$.The set of positions of m particles in a multidimensional space is identified as $X = \{X_1, ..., X_j, ..., X_l, ..., X_m\}$.The best previous position (the position giving the best fitness value) of the ith particle is recorded and represented as $P_i(t) = (p_{i1}, p_{i2}, ..., p_{iN})$. The index of the best particle among all the particles in the population (global model) is represented by the symbol g. The index of the best particle among all the particles in a defined topological neighborhood (local model) is represented by the index subscript l. The rate of movement of the position (velocity) for particle i at the time step t is represented as $V_i(t) = (v_{i1}(t), v_{i2}(t), ..., v_{iN}(t))$.The particle variables are manipulated according to the following equation:

$$\begin{aligned} v_{in}(t) &= w_i * v_{in}(t-1) + c_1 * rand1(.) * \\ &(p_{in} - x_{in}(t-1)) + c_2 * rand2(.) * (p_{gn} - x_{in}(t-1)) \\ x_{in}(t) &= x_{in}(t-1) + v_{in}(t) \end{aligned} \quad (6)$$

where n is the dimension . $(1 \le n \le N)$,c_1 and c2 are positive constants, rand1(.) and rand2(.) are two random functions in the range [0,1], and w is the inertia weight. For the neighborhood $(lbest)$ model, the only change is to substitute p_{ln} for p_{gn} in the equation for velocity. This equation in the global model is used to calculate a particle's new velocity according to its previous velocity and the distance of its current position from its own best experience $(pbest)$ and the group's best experience $(gbest)$. The local model calculation is identical, except that the neighborhood's best experience is used instead of the group's best experience. Particle swarm optimization has been used for approaches that can be used across a wide range of applications, as well as for specific applications focused on a specific requirement. Its attractiveness over many other optimization algorithms relies in its relative simplicity because only a few parameters need to be adjusted [1, 29].

4 Application of PSO to the Capacitor Placement Problem (PSO-CPP)

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 [30]. To select the capacitor size Q_j^c to be placed at bus *j*, a combination of capacitor sizes (R-size) is chosen from Table 1, as an example:

$$Q_j^c = (b_1\ sz_1 + b_2\ sz_2 + ... + b_r\ sz_r + ... + b_R\ sz_R) \quad (7)$$

Where:

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

$b_r = \{0,1\}$

sz_r :Capacitor size from Table I.

$Q_j^c \le Q_{max}^c$, Q_{max}^c :The maximum allowable capacitor size to be placed at any bus.

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

1.The capacitor Q_j^c which will be placed at candidate bus *j* consists of small capacitor sizes (*R*-size) Eqn.(7), where The candidate buses are *J*-bus.

2. A population of *n* particles at iteration *k* is represented by:

$$pop^k = [X_1^k, X_2^k, ..., X_i^k, ..., X_n^k]$$

3.Each particle *i* represented in *J*-dimensional (*J* represents the candidate buses) by:

$$X_i^k = [x_{i1}^k, x_{i2}^k, ..., x_{ij}^k, ..., x_{iJ}^k]$$

Each dimension *j* represented in *R*-dimensional (*R* represents the number of capacitor sizes to choose from) by:

$$x_{ij}^k = [x_{i1}^k, x_{i2}^k, ..., x_{ij}^k, ..., x_{iJ}^k]$$

Therefore, each particle *i* represented in (*J*,*R*) dimensions by:

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

4. The capacitor size at bus *j* at iteration *k* in particle *i* represented by:

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

The dimension x_{ijr}^k indicates if the capacitor size sz_r is placed at bus *j* at iteration *k* in particle *i* or not. In other words, x_{ijr}^k is a binary value such that $x_{ijr}^k = 1$ if the capacitor size sz_r is placed at bus *j* at iteration *k* in particle *i*, $x_{ijr}^k = 0$ if it is not placed.

5.The particle best, global best and the particle velocity are represented also in (*J*, *R*) dimensions.

TABLE 1

YEARLY COST OF FIXED CAPACITORS

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

5. SIMULATION RESULTS

The proposed PSO were applied to the test system described in [30] and the results were compared to that's obtained in [30] 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: "The optimal placement and sizing ofcapacitors"

5.1 Before capacitor placement

Table 1 represents the defined indices before capacitor placement in test system. Voltage magnitude profile of all buses, before capacitor placement, is shown in Figure 1. Also voltage THD of all nodes, before capacitor placement, is shown in Figures 2.

TABLE 2

THREE PHASE LOAD DATA

Bus No.	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 (Ω)	X # i, i+1 (Ω)
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

TABLE 4

OBTAINED RESULT BEFORE CAPACITOR PLACEMENT

total capacitor [kvar]	-
min. voltage[pu]	0.83
max. voltage[pu]	0.99
Max. THD [%]	4.91
power losses [kW]	7.8519e+005 Watt

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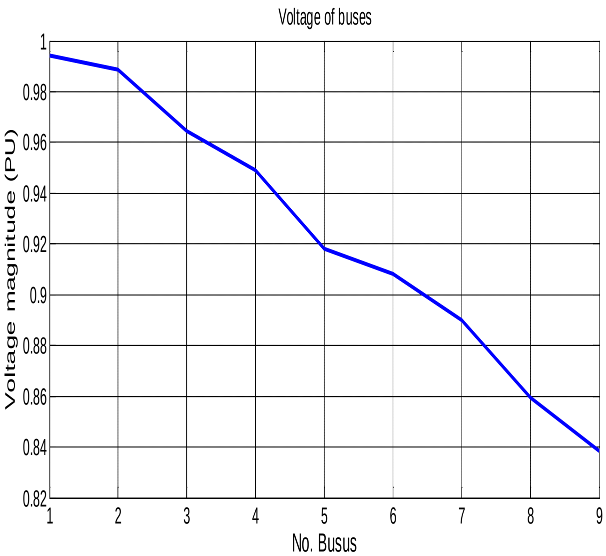

Fig 1. Voltage magnitude profile of test system before capacitor installation

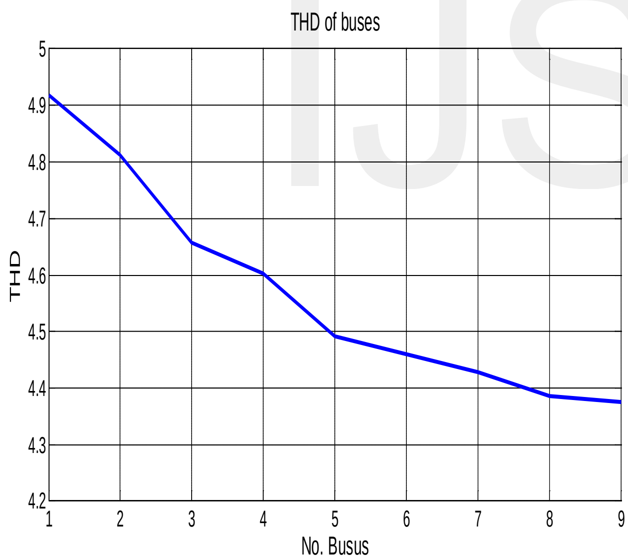

Fig 2. Voltage *THD* of test system before capacitorinstallation

5.2 With optimization

In this subsection the proposed algorithm is applied to test system. Table 5 shows the PSO parameters. Table 6 represents the defined indices after capacitor placement in test system. Voltage magnitude profile of all buses in, after capacitor placement, is shown in Figure 3. Also voltage THD of all nodes, after capacitor placement, is shown in Figures 4.

TABLE 5

PARAMETERS USED IN THE PSO

Number of particles, n	20
C1	1.5
C2	2.5
Number of parameters	240
Number of iterations, R	70

TABLE 6

OBTAINED RESULT AFTER CAPACITOR PLACEMENT

total capacitor [kvar]	411.6
min. voltage[pu]	0.8489
max. voltage[pu]	1
Max. THD [%]	6.5567
power losses [kW]	7.69+005Watt

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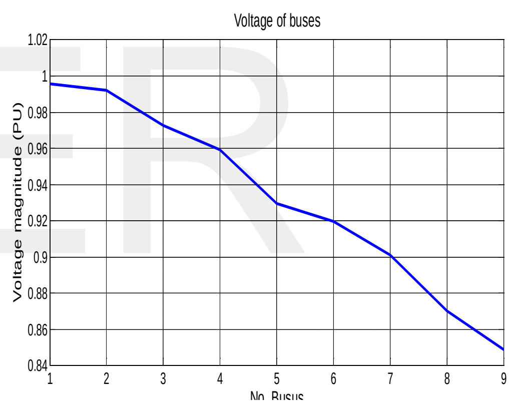

Fig 3. Voltage magnitude profile of all buses, afterca-pacitor placement

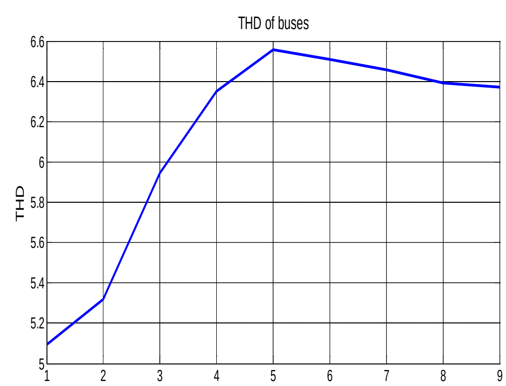

Fig 4. Voltage *THD* of all nodes, after capacitorPlace-ment

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6 Conclusion

The capacitor placement problem is a quite complex optimization problem due to its combinatorial nature. This paper considered the capacitor placement problem using PSO known as PSO-CPP. The present paper demonstrated the quality of the suggested algorithm through the test system. The PSO shows good characteristics in terms of accuracy and simulation running time.

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