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OPTIMAL CAPACITOR PLACEMENT AND SIZING IN TABRIZ ELECTRIC POWER DISTRIBUTION SYSTEM USING LOSS SENSITIVITY FACTORS AND PARTICLE SWARM OPTIMIZATION (PSO)

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Abstract- This paper presents a new approach in order to determine the optimal placement and size of capacitors in TABRIZ radial distribution system to minimize investment cost, energy loss reduction, improvement of voltage profile. Capacitor optimal placement & sizing are done by determination of loss sensitivity factors and PSO. Loss sensitivity factors can be introduced as an important parameter for sequencing of effective nodes in loss reduction. In this paper, combination of this method with PSO algorithm is used as a novel approach for optimal capacitor placement. This method is tested on a 10 buses distribution system and applied on the all feeders of Roshanaei and Golestan regions of Tabriz Electric Power Distribution Company (Tabriz, Iran). The findings clearly demonstrate the advantage of proposed method comparing with fuzzy-reasoning. Finally, investment return time, loss reduction percentage and capacity release of feeders have economically justified the practical usage of this method.

Keywords: Optimal Capacitor Placement, Loss Sensitivity Factors, Particle Swarm Optimization.

I. INTRODUCTION

Development and complexity of distribution system result in several problems such as loss increase and voltage drop. "Studies have indicated that approximately 13% of generated power is consumed as loss at the distribution level" [1]. In addition, with respect to existing loads in distribution systems, voltage profile drops along these systems below acceptable operating limits. So, loss reduction is an important aspect of power system. On the other hand, having widespread harmonics-producing devices used in distribution systems, THD increases. So, location and sizing of capacitors are done in order to satisfy THD constraint. Due to this fact, shunt capacitors are used for loss reduction, voltage profile improvement and power factor correction.

In the 80's, several method such as a mixed integer non-linear programming were suggested by Grainger and Baran Wu [2-5]. In the 90's, algorithms like neural network were introduced for solving capacitor placement problem [6]. In [7], using of dynamic fuzzy programming model was explained by Chin. He used this model for explaining real power loss and voltage deviation. In [8], Sundharajan used genetic algorithm for optimal capacitor placement. Particle swarm optimization algorithm (PSO) is based on metaphor of social interaction, searches a space by adjusting the trajectories of moving points in a multi dimensional space and used for the optimization of continues and discrete non linear problems [9].

The main advantages of the PSO are summarized as follows: simple concept, easy implementation robustness to control parameters and better computational efficiency when compared with other heuristic algorithms. In this paper, optimal capacitor placement & sizing is done with respect to loss sensitivity factors and PSO algorithm. PSO is applied for minimizing objective function that consists of two parameters: cost of energy loss, investment cost.

II. LOAD FLOW ALGORITHM

Comparing with transmission systems, distribution systems usually have two characteristics: radial construction and high ratio of (r/x) [10]. Above characteristics attribute the incomplete network to distribution systems. This problem causes not to use usual transmission systems load flow algorithm for distribution systems. If these algorithms are used for distribution systems, load flow will be diverged. So, it's necessary to use another load flow algorithm like forward-backward that is appropriate for this study.

A. Forward-Backward Algorithm

The forward-backward algorithm uses Kirchhoff's Laws. Figure 1 shows a distribution systems consist of n

nodes with n-1 branches and one voltage source in root node. In this tree construction, for proposed branch of L, L_1 and L_2 are named for nodes that is near and far from root node respectively. Branches in every layer are numbered with respect to getting far from root node [11].

B. Forward-Backward Algorithm Solution

With the given voltage magnitude and phase angle at the root and known system load information, voltage of all buses is considered equal to voltage of root node. The power flow algorithm needs to determine the voltages at all other buses and currents in each branch. So, these steps are done:

B.1. Calculation of Node Current

This is an injecting current of ith node to system in kth iteration that explained as (1).

$$I_i^{(k)} = \left(S_i / V_i^{(k-1)}\right)^* - Y_i V_i^{(k-1)} \quad , \quad i = 1,2,3,...,n \qquad (1)$$

In (1), $V_i^{(k-1)}$, S_i and Y_i are ith node voltage in (k-1)th iteration, injecting power to ith node and sum of shunt admittance connecting to ith node, respectively.

B.2. Backward Sweep

Starting from branches in the last layer, branches current is calculated according to injecting current to nodes and other current branches foreside it. Supposing $J_L^{(k)}$ as Lth branch current in kth iteration, equation (2) can be written exactly as a simple KCL [12].

$$J_L^{(k)} = -I_{L2}^{(k)} + \text{(current of branches connected to } L_2\text{)} \qquad (2)$$

where $I_{L2}^{(k)}$ is the injected current to L_2 at kth iteration.

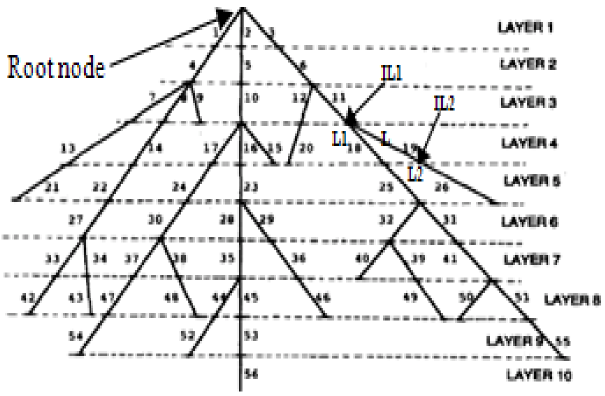

Figure 1. Layering and numbering of tree construction [10]

B.3. Forward Sweep

Starting from branches near to root node and using (2), voltage nodes is modified in kth iteration until reach to last nodes and branches. L_2 node's voltage for per branch of L is calculated by using corrected voltage of $V_{L1}^{(k)}$ and current's branch of L [11]:

$$V_{L2}^{(k)} = V_{L1}^{(k)} - Z_L J_L^{(k)} \quad , \quad L=1,2,3,.... \qquad (3)$$

B.4. Convergence Criteria

This algorithm uses the maximum difference of voltage magnitude between kth and (k-1)th steps as convergence criteria. If the difference is less than 10^{-15}, load flow is converged [11].

III. SENSITIVITY ANALYSIS AND LOSS SENSITIVITY FACTORS

The methodology is used to determine the candidate nodes for the placement of capacitors using Loss Sensitivity Factors. The estimation of these candidate nodes basically helps in reduction of the search space for the optimization procedure. Consider a distribution line connected between 'p' and 'q' buses as in Figure 2.

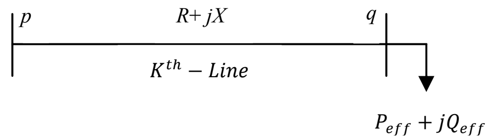

Figure 2. Connected line between bus p and bus q

Active power loss in the kth line is given by $[I_k]^2 \times R[k]$, which can be expressed as (4).

$$P_{line\_loss}[q] = \frac{(P_{eff}^2[q] + Q_{eff}^2[q])R[k]}{V^2[q]} \qquad (4)$$

$P_{eff}[q]$ is the total effective active power supplied beyond the node 'q'. $Q_{eff}[q]$ is the total effective reactive power supplied beyond the node 'q'. So, the Loss Sensitivity Factors can be obtained as shown in (5).

$$\frac{\partial P_{line\_loss}}{\partial Q_{eff}} = \frac{2 \times Q_{eff}[q] \times R[k]}{V^2[q]} \qquad (5)$$

IV. NODE SELECTION USING LOSS SENSITIVITY FACTORS

The loss sensitivity factors $(\partial P_{line\_loss} / \partial Q_{eff})$ are calculated using the base case load flows and Equation (5). The values are arranged in descending order for all the lines of the given system. A vector bus position is used to store the respective 'end' buses of the lines arranged in descending order of the values.

The descending order of elements vector will decide the sequence in which the buses are to be considered for compensation. At these buses, normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given by ($norm[i]$ = $V[i]$/0.95). Now for the buses whose $norm[i]$ value is less than 1.01 are considered as the candidate buses requiring the Capacitor Placement. These candidate buses are stored in 'rank bus' vector. It is worth note that the 'Loss Sensitivity factors' decide the sequence in which buses are to be considered for compensation placement and the '$norm[i]$' decides whether the buses needs Q-Compensation or not.

If the voltage at a bus in the sequence list is healthy such bus needs no compensation and that bus will not be listed in the 'rank bus' vector. The 'rank bus' vector offers the information about the possible potential or candidate buses for capacitor placement. Now sizing of Capacitors at buses listed in the 'rank bus' vector is done by using PSO based algorithm. Table 1 shows loss sensitivity factors placed in descending order along with its bus identification and normalized voltage magnitudes of 10 buses radial.

Table 1. Loss sensitivity coefficients' placed in descending order of a 10-bus radial distribution system

$(\partial P_{line\_loss} / \partial Q_{eff})$ (descending)	Bus No	$\frac{V[i]}{0.95}$	Base Voltage
6.7099	6	0.9653	0.917
6.5899	4	1.0137	0.963
5.2298	9	0.9042	0.859
5.2257	5	0.9979	0.948
3.3824	10	0.8821	0.838
2.6279	8	0.9358	0.889
1.4457	7	0.9547	0.907
1.3061	2	1.0453	0.993
0.1324	3	1.0398	0.987

Information of branches and loads of given network is available in [12]. The candidate buses for capacitor placement of 10 bus distribution system are {6, 9, 5, 10, 7 and 8}.

V. SIMULATION RESULTS

The objective function is consisting of the cost of the total annual energy loss and that of shunt capacitors. The objective function is limited by inequality and equality constraints. The goal is to minimize the cost of the annual energy loss and that of the shunt capacitor installation. The cost function is given by (6).

$$F = P_{loss} \times K_p \times d + (\sum_{j=1}^{Nc} QjK_e) + K_{fc} \times N_q \qquad (6)$$

Subject to

$Q_{\min} < Q_j < Q_{\max}$

$V_{\min} < V_i < V_{\max}$

$THD_i\,(\%) \le THD_{\max}$

where

P_{loss} total real power loss (kW);
Q_j reactive power injection at bus j (kVAR);
K_p annual cost of energy loss (Rial/ kW /hour);
Kc annual variable cost of reactive power injection (Rial/kVAR/year);
K_{fc} annual fixed cost of capacitors installation (Rial/year);
d time (hour);
Nc number of candidate buses;
Nq number of capacitors to be installed;
Q_{min} lower bound of reactive power injection (kVAR);
Q_{max} upper bound of reactive power injection (kVAR);
V_{min} lower bound of bus voltage limits;
V_{max} upper bound of bus voltage limits;
THD_{max} Maximum allowable harmonic distortion level.

VI. PARTICLE SWARM OPTIMIZATION

PSO is a heuristic optimization technique introduced in 1995 by Kennedy and Eberhart [13-14]. "Fundamental idea of PSO algorithm is a population called a swarm is randomly generated. The swarm consists of individuals called particles. Each particle in the swarm represents a potential solution of the optimization problem. Each particle moves through a D-dimensional search space at a random velocity. Each particle updates its velocity and position according to the following equations:

$$\upsilon_{id}^{t+1} = w\upsilon_{id}^{t} + c_1 \,\text{rand}_1 (pbest_{id}^{t} - x_{id}^{t}) + c_2 \,\text{rand}_2 (gbest_{d}^{t} - x_{id}^{t}) \qquad (7)$$

$$x_{id}^{t+1} = x_{id}^{t} + \upsilon_{id}^{t+1} \qquad (8)$$

where

c_1, c_2 acceleration constants;
w inertia weight;
$\text{rand}_1, \text{rand}_2$ two random numbers in [0, 1];
$pbest_i^t$ best position ever visited by the particle at the ith iteration;
$gbest^t$ global best position in the entire swarm;

VII. TEST RESULT

In the simulation, parameters are selected as Table 2. Table 3 shows the results of capacitor placement for 10 buses system. These results have been compared with that of [12] that uses fuzzy-reasoning algorithm for capacitor placement. In PSO algorithm, c_1, c_2 and W are considered as 2.5, 2.5 and 1.2, respectively. Load flow results indicate that [12] placed 4950 kvar resulting in 10.06% loss reduction where as the proposed method placed 3300 kvar with 11.17% loss reduction.

Table 2. Value of parameters of cost function and constraints

Parameters	Value	Parameters	Value
Q_{min}	200	Q_{max}	1,200
V_{min}	0.95	V_{max}	1.05
K_{fc}	1,000,000	K_c	140,000
K_p	773	THD_{max} (%)	5

Table 3. Comparison of PSO with fuzzy-reasoning for of 10 buses radial distribution system - Base case active power loss = 783.77 KW

Proposed PSO based		Fuzzy-reasoning based	
Bus No	Size (kvar)	Bus No	Size (kvar)
6	1200	4	1050
5	1200	5	1050
9	300	6	1950
10	600	10	900
Total kVAR placed	3300	Total kVAR placed	4950
Active power loss (kW)	696.2	Active power loss (kW)	704.9

VIII. CASE STUDY

Using loss sensitivity factors and PSO, optimal capacitor placement and sizing was done for all of the feeders in Roshanaei and Golestan regions of Tabriz Electric Power Distribution Company (Tabriz, Iran). Results are reported for one of these feeders called F4. Q_j constraints are discrete values between 50 and 450 kVAR with step of 50 kVAR. Single line diagram and required information such as line's impedance, substation, and loads are available in Appendix1. According to similar load curves of all of the low voltage distribution substations along F4, load levels of peak, mean and low were seen as Figure 3. Each level has the time period of 8 hours.

Objective function of case study with constrains are in according with (6) that P_{Loss} is denoted on sum of active power loss in three levels. Table 4 shows the results of capacitors placement in F4. Capacitors are installed in low voltage (0.4 kv) side of distribution transformer. With installation the proposed capacitors in Table 4 and running load flow for F4, the results are obtained after capacitor placement and shown in Table 5.

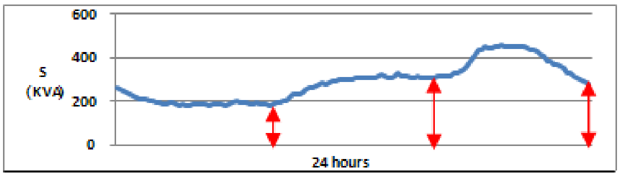

Figure 3. Sample of load curve of feeder

Table 4. Optimal capacitor placement and sizing in F4
Base case active power loss = 206.29 KW

Bus No	Size (kvar)
9	100
14	100
16	100
18	150
22	100
26	200
28	200
30	100
Total kVAR placed	1050
Total active power loss (kW)	178.82

Table 5. Total results of capacitor placement in F4

Peak load		Mean load		Low load		Load level
Acp	Bcp	Acp	Bcp	Acp	Bcp	Index
188.6	199.3	147.5	158.9	77.17	88.86	Input current (A)
0.966	0.916	0.964	0.898	0.991	0.883	Input power Factor
19.35	18.93	19.52	19.11	19.90	19.50	Minimum voltage (kV)
6315	6338	4933	4943	2650	2655	Input real power (kW)
6215	6215	4871	4871	2633	2633	Output real power (kW)
100.3	113.1	61.35	71.81	17.17	21.38	Real power loss (kW)
1.588	1.788	1.243	1.452	0.647	0.805	Percentage of real power loss
1681	2766	1342	2421	347.6	1408	Input reactive power (kW)

Bcp: Before capacitor placement   Acp: After capacitor placement

In Table 5, percentage of real power loss in each load level is calculated by (9).

$$ploss(\%) = \frac{\text{Real Power Loss (kW)}}{\text{Input real Power in each load Level (kW)}} \times 100 \quad (9)$$

Results show that installed capacitors decrease the loss reduction as 13.32%.

A. Economical Calculation

Due to objective function in (6), investment cost for buying and installation of capacitors is calculated by (10):

$$Cost_{capacitor} = (\sum_{j=1}^{Nc} Q_j Kc) + K_{fc} \times N_q \quad (10)$$

Investment cost of F4 ($cost_{capacitor}$) is equal to 155,000,000 Rials.

B. Energy Saving Economy

In order to calculation energy loss, all of load levels must be considered. The cost of energy loss before and after capacitor placement follows (11) and (12), respectively.

$$Cost_1 = K_p \sum_{i=1}^{n1} Ploss_i \times d \quad (11)$$

$$Cost_2 = K_p \sum_{i=1}^{n1} Ploss_i^{'} \times d \quad (12)$$

$Cost_1$, $Cost_2$, $Ploss_i$ and $Ploss_i^{'}$ are the cost of energy loss and real power loss before and after capacitor placement, respectively. d is time period of each load level equal to 2920 hours. Profit of loss reduction is calculated by (13). Table 6 shows the results of economical calculation of F4.

$$\Delta Cost = Cost_1 - Cost_2 \quad (13)$$

Table 6. Profit Calculation of loss reduction in F4

(Rials/year)	465,629,536
(Rials/year)	403,625,351
(Rials/year)	62,004,185.2

Investment return is calculated by (14). This time is equal to 2.49 years for F4.

Investment return time (year) = $Cost_{capacitor} / \Delta Cost$ (14)

IX. CONCLUSIONS

In this paper, the combination of PSO algorithm with loss sensitivity factors was tested on a 10-buses radial distribution system to find the optimal locations and sizes of shunt capacitors. This algorithm was applied on the all feeders of Roshanaei and Golestan regions of Tabriz Electric Power Distribution Company (Tabriz, Iran). Results are presented for one of the feeders called 'F4'. The objective was to minimize the total cost of the system energy loss and installation of shunt capacitors taking voltage profile, size of capacitor and THD, as constraints into account. The main advantage of proposed algorithm comparing with other methods is that location and sizing of capacitors are determined so that reduction in active power loss is lead to voltage profile improvement. The method places capacitors at fewer numbers of locations with optimum sizes and offers more saving in initial investment.

Table 7. Load information of F4

Node No	Low Load (kVA)	Mean Load (kVA)	Peak Load (kVA)
4	61	110	137
7	197	358	447
9	235	428	534
12	113	205	257
14	280	496	616
16	293	532	665
18	331	603	753
20	235	428	534
22	238	433	541
24	89	162	203
26	350	620	770
28	306	557	696
30	245	441	555

$\cos\varphi = 0.89$ (low) $\cos\varphi = 0.91$ (mean) $\cos\varphi = 0.93$ (peak)

Table 8. Line data of F4

Branch No	Sending end	Receiving end	R(Ω)	X(Ω)
1	1	2	0.0428	0.0244
2	2	3	0.0321	0.0183
3	3	4	6.875	29.2
4	3	5	0.1007	0.057
5	5	6	0.005	0.003
6	6	7	6.875	29.2
7	6	8	0.0263	0.015
8	8	9	9.371	36.927
9	7	10	0.0188	0.0107
10	10	11	0.0142	0.00813
11	11	12	5.4	23.384
12	10	13	0.1089	0.0621
13	13	14	6.875	29.2
14	10	15	0.0964	0.0549
15	15	16	5.4	23.384
16	15	17	0.1041	0.0594
17	17	18	5.4	23.384
18	17	19	0.0962	0.0548
19	19	20	6.875	29.2
20	19	21	0.1241	0.0707
21	21	22	6.875	29.2
22	21	23	0.1944	0.110
23	23	24	9.371	36.927
24	23	25	0.0244	0.0138
25	25	26	5.4	23.384
26	25	27	0.0438	0.0249
27	27	28	6.875	29.2
28	27	29	0.08928	0.050
29	29	30	6.875	29.2

APPENDIX

F4 Feeder Information

F4 is a radial distribution system. It has 13 medium voltage substations (20/0.4 kv). Its Length is 5.661km. Single line diagram is shown in Figure 4.

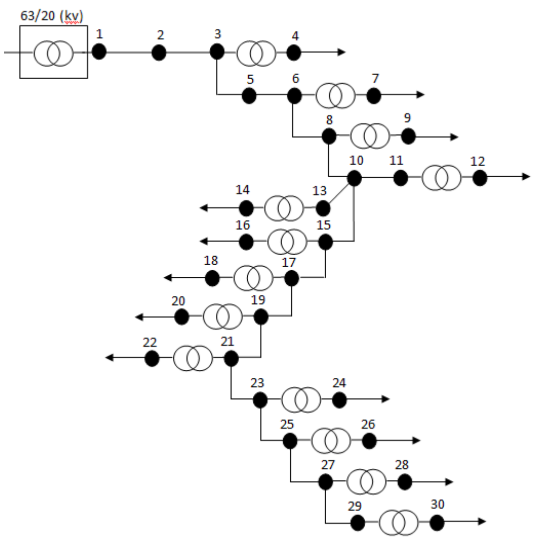

Figure 4. F4 single line diagram

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