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Optimal Capacitor Placement using Particle Swarm Optimisation (PSO): A Case Study in 33kV Distribution System

Deependra Neupane [a], Bishop Poudel [b], Nawaraj Khatri [c],
Dharmendra Yadav [d], Dhiraj Khadka [e]

[a, b, c, d, e] *Department of Electrical Engineering, Purwanchal Campus, Institute of Engineering, Tribhuvan University, Nepal*
Corresponding Email: [a] deependra@ioepc.edu.np, [b] bishop@ioepc.edu.np, [c] nawaraj@ioepc.edu.np,
[d] dharmendra@ioepc.edu.np, [e] dhiraj@ioepc.edu.np

Abstract

The use of capacitors in power systems has many well-known benefits that include improvement of the system power factor, improvement of the system voltage profile, increasing the maximum flow through cables and transformers, and reduction of losses due to the compensation of the reactive component of power flow. By decreasing the flow through cables, the systems' loads can be increased without adding any new cables or overloading the existing cables. These benefits depend greatly on how capacitors are placed in the system. The proposed methodology used Loss Sensitivity Factors to identify the buses requiring compensation and then a Particle Swarm Optimization (PSO) Algorithm is used to determine the sizes of the capacitors to be installed. The load flow and the PSO Algorithm was coded in MATLAB program. The program uses Gauss-Seidel technique.

This project identifies sensitive buses and compute the optimal size of the capacitors that are to be installed in the 33-kV primary distribution system considering Duhabi Grid as a reference bus. After the optimal placement of capacitor, the percentage reduction of power loss is obtained to be 14.25% and 7.893% at 7am and 7pm of 2076/01/30 respectively.

Keywords

Loss Sensitivity Factor – Particle Swarm Optimization (PSO) – Capacitor Placement

1. Introduction

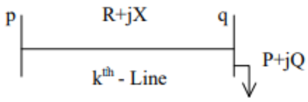
S Distribution Systems are growing large and being stretched too far, leading to higher system losses and poor voltage regulation, the need for an efficient and effective distribution system has therefore become more urgent and important. In this regard, Capacitor banks are added on Radial Distribution system for Power Factor Correction, Loss Reduction and Voltage profile improvement [1].

With these various Objectives in mind, Optimal Capacitor Placement aims to determine Capacitor location and its size.

In this paper, Capacitor Placement and Sizing is done by Loss Sensitivity Factors and Particle Swarm Optimization (PSO) respectively. PSO is used for estimation of required level of shunt capacitive compensation to improve the voltage profile of the system.[2] The proposed method is tested on 15 bus radial distribution systems and finally applied on Duhabi feeder data and the results are very promising.

2. Sensitivity Analysis and Loss Sensitivity Factors

A new 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. Let us consider a distribution line connected between 'p' and



'q' buses.[1]

The active power loss,

$$P_{loss} = I_{pq}^2 R_{pq} = \frac{s_{pq}^2}{V_p^2} R_{pq} = \frac{P_{pq}^2 + Q_{pq}^2}{V_p^2}$$

Now, loss sensivity factro is given by,

$$\frac{\partial P_{loss,k}}{\partial Q_{pq}} = \frac{2Q_{pq}}{V_q^2} R_{pq}$$

The loss sensitivity factors are calculated from the base case load flow (that is, without compensation) and the values are arranged in descending order for all the transmission lines of the given system. A vector that holds the respective "end buses" of the lines arranged in descending order of the values of the loss sensitivity factors is stored. The bus with inflowing power is the one considered for capacitor placement. The descending order of the loss sensitivity factors will decide the sequence in which the buses are to be considered for compensation.[3]

3. Particle Swarm Optimisation

The Particle Swarm Optimization algorithm (abbreviated as PSO) is a novel populationbased stochastic search algorithm and an alternative solution to the complex non-linear optimization problem. The PSO algorithm was first introduced by Dr. Kennedy and Dr. Eberhart in 1995, and its basic idea was originally inspired by simulation of the social behavior of animals such as bird flocking, fish schooling and so on. It is based on the natural process of group communication to share individual knowledge when a group of birds or insects search food or migrate and so forth in a searching space, although all birds or insects do not know where the best position is. But, from the nature of the social behavior, if any member can find out a desirable path to go, the rest of the members will follow quickly.[4]

Particle swarm optimization algorithm is based on interaction of swarm of particles. Every particle includes two values of position and velocity that are updated during the iteration runs by considering each particle's best experience (best position) and the best achieved experience (global position) of all particles.[5]

Each particle movement is updated by relation given below:

$p_i^{k+1} = p_i^k + v_i^{k+1}$ Where, P_i^{k+1} and p_i^k are the positions of particle 'i' in the iteration k+1 and k respectively;, v_i^{k+1} is the velocity of the paritcle in k + 1 iteration. A particle's velocity is defined as follows:

$$v_i^{k+1} = w * v_i^k + c_1 * rand_1(p_{best_i} - P_i^k) +$$
$$c_2 * rand_2 * (gbest - P_i^k)$$

where, pbesti is the best so far position of particle i as the best experience, while gbest is the best positon among the whole swarm with all teh paritcles in movement as global experience. c_2 and c_2 are the weighting factors, while $rand_1$ and $rand_2$ are two random numbers between 0 and 1. The parameters w is the inertia factor varying between$[w_{min} and w_{max}]$ which is a linear decreasing inertia weight.

$$w = w_{max} * \frac{w_{max} - w_{min}}{iter_{max}}$$

where, k and $iter_{max}$ are the current iteration and the maximum number os iterations during simulations respectively. The general steps of PSO on solving the problem are as follows:

1. Set initial parameters w_{min}, w_{max}, c_1 and c_2

c_1	c_2	W_{max}	W_{min}	V_{max}(pu)	V_{min}(pu)	K_p($/kW)	Iter.max
2	2	0.9	0.4	1.1	0.9	168	100

2. Generate inital populations having initial positions p and velocities v.
3. Set iteration k = 1.
4. Calculate fitness of particles $F_i^k = f(p_i^k)$, and find the index of the best particle b.
5. Select $pbest_i^k = p_i^k$, and set $gbest^k = p_b^k$.
6. Update intertia factor $w = w_{max} * \frac{w_{max} - w_{min}}{iter_{max}} * k$
7. Update the velocity and postion of particles.
$$v_i^{k+1} = w * v_i^k + c_1 * rand_1(p_{best_i} - P_i^k) +$$
$$c_2 * rand_2 * (gbest - P_i^k)$$
$$p_i^{k+1} = p_i^k + v_i^{k+1}$$
.
8. Calculate fitness, $F_i^{k+1} = f(P_i^{k+1})$, and obtain the index of the best particle b_1.
9. Update pbest for all particles
if $F_i^{k+1} < F_i^k$, then $pbest_i^{k+1} = p_i^{k+1}$ else $pbest_i^{k+1} = pbest_i^k$
10. Update gbest of the population
if $F_{b1}^{k+1} < F_b^k$, then $gbest_i^{k+1} = pbest_{b1}^{k+1}$ and $b = b_1$ else $gbest^{k+1} = pbest^k$
11. If $k < iter_{max}$ then k = k + 1 and go to step 6 else got to step 12.
12. Print $gbest^k$ as optimum solution.

4. Methodology For Capacitor Sizing and Placement

4.1 Load and Line Parameter Calculations

The load data has been taken from the log book of different substations that are involved under study. Data parameters are Mva loadings, power factor and bus voltages at two different time of the day. viz. 7 a.m and 7 p.m. Similarly, line resistance is calculated by taking the line length form different substations and determing the standard resistance from conductor table and normalizing it at 35^0 C. Line inductance is calculated accordingly observing the line configuration, bundling and conductor type. The load data for two different time of the day and line parameter data is shown below:

From Bus – To Bus	Resistance of Line (R, Ω)	Line Reactance (X ,Ω)
1 – 2	0.59572	0.70455
1 – 3	1.4893	1.83397
1 – 4	5.9572	7.04553
1 – 6	5.9572	7.04553
1 – 7	1.93609	2.289795
1 – 8	0.79429	0.9394
1 - 9	8.9358	5.359309
3 – 4	2.9786	3.52276
4 – 5	6.85078	8.10496
9 – 10	4.17004	4.93187
9 – 11	3.87218	4.57959
11 – 12	4.76576	5.6364
12 - 13	2.68074	3.17049
13 - 14	13.4037	15.85243
13 – 15	5.65934	6.169325
15 – 16	2.38288	2.8182
15 - 17	4.17004	4.93187

Figure 1: Line Data

Bus No.	7 AM (2076/01/30)		7 PM (2076/01/30)	
	P(MW)	Q(MVAr)	P(MW)	Q(MVAr)
1	14.796	6.137	15.199	5.1455
2	2.667	1.512	4.115	2.658
3	8.695	6.726	9.668	9.665
4	6.530	5.643	7.441	8.697
5	2.679	2.231	3.959	3.428
6	3.048	1.438	5.659	2.667
7	6.295	2.449	8.677	3.852
8	16.476	5.378	17.185	12.889
9	10.196	2.973	11.450	5.544
10	0.392	0.243	0.145	0.109
11	0.294	0.096	0.408	0.306
12	1.582	0.766	2.708	1.387
13	0	0	0	0
14	0.349	0.082	0.378	0.085
15	0.1732	0.084	0.294	0.182
16	0	0	0.504	0.312
17	0.606	0.375	1.169	0.725

Figure 2: Load Data

4.2 33 kV Existing System

The rated line voltage of the existing system is 33 kV. We have considered Duhabi Grid as a reference bus (slack bus). The total number of buses are 17 including one switching station i.e. Hile Switching Station (Bus-13). There are 3 generating stations viz. Duhabi Multifuel Diesel Power Plant (Bus-2), Chatara Power Station (Bus-10) and Piluwa Substation (Bus-17). The tower configuration is taken triangular except the line between Duhabi Grid (Bus-1) and Dharan Substation (Bus-9). The conductor used in all distribution lines is DOG. In our project, we have considered two different point of time i.e. of 7 AM (off-peak load case) and 7 PM (peak load case) of 2076/01/30. During this period only Piluwa Substation (Bus-17) was in operation.

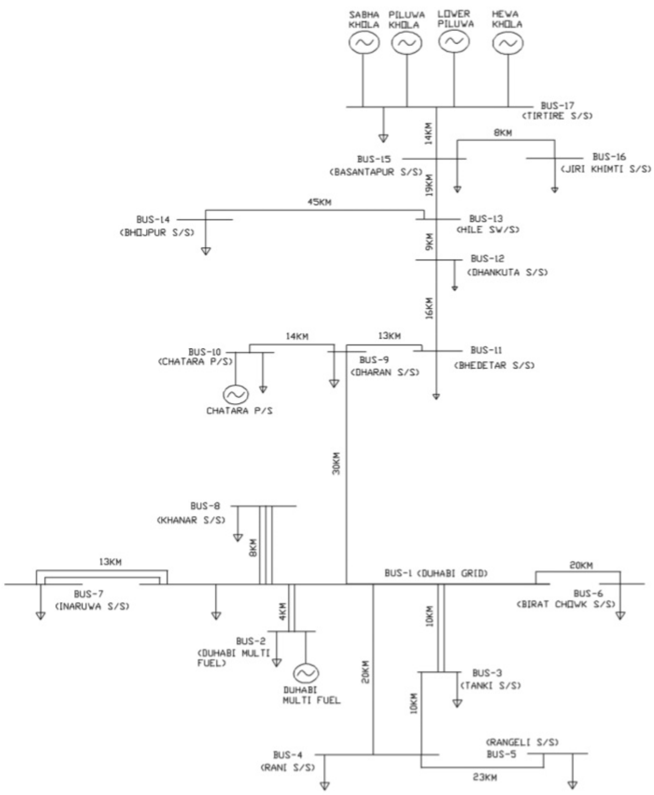


Figure 3: Single line diagram of 33 kV primary distribution system considering Duhabi Grid as a reference bus

4.3 Problem Formulation

The optimal capacitor placement and sizing problem is formulated as a constrained nonlinear integer optimization problem with both locations and sizes of shunt capacitors being discrete. The objective function encompasses the total cost of the total real power loss and that of shunt capacitors.[6]

Objective Function: The goal is to minimize the cost of the total real power loss and that of the shunt capacitor installation. The cost function is given by:

$$F = K_p P_{loss} + \sum_{i=1}^{nc} K_{ci} Q_{ci}$$

Where, K_{ci} = annual cost per unit of the reactive power injected(dollar/kVAr/year)
K_p = annual cost per unit of real power loss (dollar/kW/year)
Q_{ci} = reactive power injection at bus' i'(kVAr)
N_c = total number of shunt capacitors to be installed
P_{loss} = total real power loss(kW)
Constraints: The objective function is subjectd to the following constraints:[1]

1. $V_{min} \le V_i \le V_{max}$ where, V_{min} is the lower boud of bus voltage limit(0.9 pu)// V_{max} is the upper bound of bus voltage limit(1.1 pu)// V_i is the voltage at the bus i

2. The total reactive power injection is not to exceed the total reactive power demand ; i.e

$$\sum_{i=1}^{nc} Q_{ci} \le Q_T$$

Where, Q_T is the total reactive power demand. The possible choice of capacitor sizes and costs are tabulated below;

Capacitor Size (Qc,kVAr)	$/kVAr	Capacitor Size (Qc,kVAr)	$/kVAr
150	0.5	2250	0.197
300	0.35	2400	0.17
450	0.253	2550	0.189
600	0.22	2700	0.187
750	0.276	2850	0.183
900	0.183	3000	0.18
1050	0.228	3150	0.195
1200	0.17	3300	0.174
1350	0.207	3450	0.188
1500	0.201	3600	0.17
1650	0.193	3750	0.183
1800	0.187	3900	0.182
1950	0.211	4050	0.179
2100	0.176		

Figure 4: Yearly cost of fixed capacitors

4.4 Loss Sensitivity Factor Calculation

The loss sensitivity factor calculation is tabulated below:

From above table, bus with norm[i] less than 1.01 are 5,9 and 10. So, sensitive buses are 5, 9 From above table, bus with norm[i] less than 1.01 are 5,9,10,11,12 and 14. So, sensitive buses are 5, 9, 10, 11, 12 and 14.

4.5 Load Flow Calculations

The load flow calculations has been done using Gauss Seidal method[7] in MATLAB for different time of day, specifically, 7 am and 7 pm. The same system is

From	To	Qi	Ri	Vq	L.S.F	L.S.F in des	End bus	Base voltage	Norm i
1	2	1.519	0.59572	0.998	0.00166856	0.05442291	4	0.939	1.04333333
1	3	10.482	1.4893	0.963	0.03091547	0.04100718	9	0.902	1.00222222
1	4	4.386	5.9572	0.939	0.05442291	0.03606525	5	0.901	1.00111111
1	6	1.425	5.9572	0.973	0.01646772	0.03091547	3	0.963	1.07
1	7	2.435	1.93609	0.983	0.00896024	0.0244975	15	0.974	1.08222222
1	8	5.33	0.79429	0.983	0.0080464	0.02289336	4	0.939	1.04333333
1	9	2.033	8.9358	0.902	0.04100718	0.01825781	17	1	1.11111111
3	4	3.69	2.9786	0.939	0.02289336	0.01646772	6	0.973	1.08111111
4	5	2.327	6.85078	0.901	0.03606525	0.01300666	12	0.927	1.03
9	10	0.211	4.17004	0.899	0.00199943	0.01159027	13	0.942	1.04666667
9	11	1.161	3.87218	0.913	0.00990486	0.00990486	11	0.913	1.01444444
11	12	1.277	4.76576	0.927	0.01300666	0.00896024	7	0.983	1.09222222
12	13	2.089	2.68074	0.942	0.01159027	0.0080464	8	0.983	1.09222222
13	14	0.082	30.4067	0.936	0.00522677	0.00522677	14	0.936	1.04
13	15	2.236	5.65934	0.974	0.0244975	0.00199943	10	0.899	0.99888889
15	16	0.028	2.38288	0.974	0.00012916	0.00166856	2	0.998	1.10888889
15	17	2.384	4.17004	1	0.01825781	0.00012916	16	0.974	1.08222222

Figure 5: Loss sensitivity factor arranged in descending order in 17-bus system (7 AM)

From	To	Qi	Ri	Vq	L.S.F	L.S.F in des	End bus	Base voltage	Norm i
1	2	2.658	0.59572	0.996	0.00293144	0.108602597	9	0.856	0.95111
1	3	15.651	1.4893	0.951	0.04733315	0.086926931	4	0.915	1.01667
1	4	6.652	5.9572	0.915	0.08692693	0.058862055	5	0.856	0.95111
1	6	2.674	5.9572	0.949	0.03248428	0.047333145	3	0.951	1.05667
1	7	3.852	1.93609	0.976	0.01437852	0.037576427	4	0.915	1.01667
1	8	12.889	0.79429	0.976	0.01973789	0.034472894	15	0.917	1.01889
1	9	4.849	8.9358	0.856	0.1086026	0.032484282	6	0.949	1.05444
3	4	5.751	2.9786	0.915	0.03757643	0.0285973	17	0.95	1.05556
4	5	3.428	6.85078	0.856	0.05886206	0.019737893	8	0.976	1.08444
9	10	0.117	4.17004	0.855	0.00122573	0.016327269	13	0.881	0.97889
9	11	0.917	3.87218	0.859	0.00883773	0.014378524	7	0.976	1.08444
11	12	1.126	4.76576	0.865	0.01317166	0.013171658	12	0.865	0.96111
12	13	2.574	2.68074	0.881	0.01632727	0.008837729	11	0.859	0.95444
13	14	0.085	30.4067	0.875	0.00619975	0.006199751	14	0.875	0.97222
13	15	2.789	5.65934	0.917	0.03447289	0.002931437	2	0.996	1.10667
15	16	0.368	2.38288	0.915	0.00192358	0.001923579	16	0.915	1.01667
15	17	3.37	4.17004	0.95	0.0285973	0.001225733	10	0.855	0.95

Figure 6: Loss sensitivity factor arranged in descending order in 17-bus system (7 PM)

taken for capacitor placement by determining the optimal loaction and optimal sizes by using particle swarm algorithm.
The figure 7 shows the comparison of base case and PSO method for 7 AM. The voltage profile

Bus no.	Existing System		Proposed PSO System	
	Size (MVAr)	V (pu)	Size (MVAr)	V (pu)
5	0	0.901	4.05	0.947
9	0	0.902	4.05	0.922
10	0	0.899	0.15	0.920
Total MVAr	0	×	8.25	×
Active power loss	2.469 MW		2.117 MW	

Figure 7: Comparison of base case and PSO method (7 AM)

improvement at each bus before and after capacitor placement is shown in figure 8: The figure 9 shows the comparison of base case and PSO method for 7 PM. The voltage profile improvement at each bus before and after capacitor placement is shown in figure 10:

In each cases, the voltage profile is improved after the implementation of capacitor of appropriate sizes in sensitive buses. The algorithm determines the optimal sizes of capacitor that needs to be placed in the

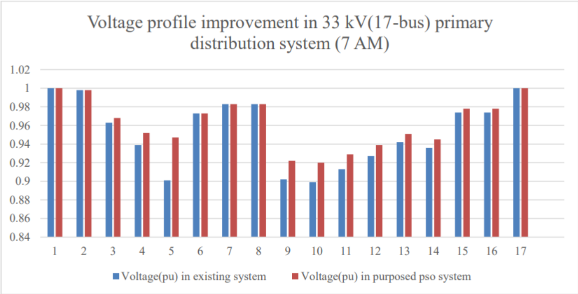


Figure 8: Voltage profile improvement in 33 kV(17-bus) primary distribution system (7 AM)

Bus no.	Existing System		Proposed PSO System	
	Size (MVAr)	V (pu)	Size (MVAr)	V (pu)
5	0	0.856	5.5	0.921
9	0	0.856	5.5	0.908
10	0	0.855	5.5	0.933
11	0	0.859	0.15	0.907
12	0	0.865	0.15	0.909
14	0	0.875	0.15	0.918
Total MVAr	0	×	16.95	×
Active power loss	4.662 MW		4.294 MW	

Figure 9: Comparison of base case and PSO method (7 PM)

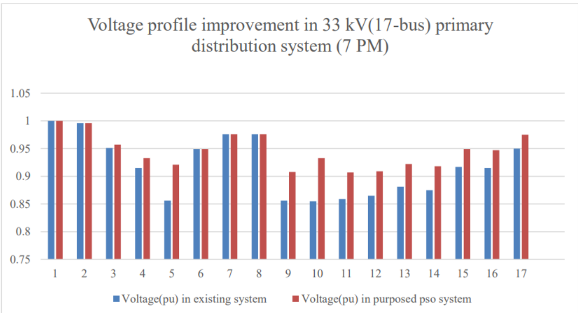


Figure 10: Voltage profile improvement in 33 kV(17-bus) primary distribution system (7 PM)

sensitive buses to improve voltage level of every buses with minimum total cost of capacitors.

5. Technical and Financial Analysis

5.1 Technical Analysis

By observing the results above, For 7 AM, percentage reduction in reactive power for bus 1 and 17 is calculated as $\% - 21.32$ and $\% - 31.25$ and for 7 PM, it is calculated as $\% - 21.32$ and $\% - 31.25$ respectively. The active and reactive power loss at 7 AM and 7 PM are calculated as -14.25% and -7.89% and -15.28% and -7.32% respectively.

Bus no.(type)	MVAr supplied at (7 AM)		MVAr supplied at (7 PM)	
	Existing System	Proposed PSO System	Existing System	Proposed PSO System
1(Slack Bus)	35.842	28.2	57.909	41.00
17(PV Bus)	2.778	1.910	4.133	3.6

Figure 11: Comparsion of Reactive Power

5.2 Financial Analysis

The financial analysis is based on cost function which is given by:

$$F = K_p P_{loss} + \sum_{i=1}^{nc} K_{ci} Q_{ci}$$

For 7 AM
Power loss in existing system (P_{loss}) = 2.469 mW
Cost per unit active power loss per annum (Kp)= $\$168/kW$
Power loss cost in existing system $=K_p P_{loss}$= $\$168 * 2,469 = \$414,792$
Total capacitor cost = 0.179*4.05*1000+0.179*4.05*1000+0.5*0.15*1000 = $\$1,524.9/annum$

Total loss in proposed PSO system = $\$168 * 2,117 + \$1,524.9 = \$357,180.9$
Total saving per annum = $\$414,79 - \$357,180.9$ = $\$57,611.1/annum$

For 7 AM
Power loss in existing system (P_{loss}) = 4.662 mW
Cost per unit active power loss per annum (Kp)= $\$168/kW$
Power loss cost in existing system $=K_p P_{loss}$= $\$168 * 4,662 = \$783,216$
Total capacitor cost = 3*0.36*5.5*1000+3*0.5*0.15*1000 = $\$6,165/annum$

Total loss in proposed PSO system = $\$168 * 4,294 +$ $\$6,165 = \$7,27,557$
Total saving per annum = $\$783,216 - \$7,27,557$ = $\$55,659/annum$

6. Conclusion

The Particle Swarm Optimization (PSO) Algorithm is used in the 17-bus distribution system considering Duhabi Grid as a reference bus. The various constants used in the proposed algorithm are capmin = 0.15

MVAr, capmax = 5.5 MVAr, K = 0.7259, c1 = c2 = 2 and wmax = 0.9 and wmin = 0.4. The sensitive buses at 7 AM are Bus-5, Bus-9 and Bus-10 and the size of capacitor required to compensate the voltage at the specified range are 4.05 MVAr, 4.05 MVAr and 0.15 MVAr respectively. Similarly, sensitive buses at 7 PM are Bus-5, Bus-9, Bus-10, Bus-11, Bus-12 and Bus-14; and required capacitor sizes are 5.5 MVAr, 5.5 MVAr, 5.5 MVAr, 0.15 MVAr, 0.15 MVAr and 0.15 MVAr respectively. After compensation, the voltage level at each bus is improved above 0.9 p.u. After optimal capacitor placement, active power loss at 7 AM and 7 PM decreases by 14.25 % and 7.894% respectively, and reactive power loss at 7 AM and 7 PM decreases by 15.28 % and 7.323 % respectively. After optimal capacitor placement, MVAr to be supplied by Duhabi Grid at 7 AM and 7 PM decreases by 21.32% and 29.2% respectively. Similarly, the MVAr to be supplied by Piluwa Substation at 7 AM and 7 PM respectively decreases by 31.25% and 12.9% respectively.

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