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The Impact of Shunt Capacitor Size and Location on Power Losses in Radial Distribution System

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Abstract: High power losses is produced in the distribution side as compared to another subsystem of the power system (transmission and generation). Installation of a shunt capacitor in the distribution is one of the alternative solution for power losses reduction. However, the non-optimal location and size of shunt capacitor may lead to the increment of losses. In order to reduce the power losses, the location and size of shunt capacitor are optimised simultaneously using Particle Swarm Optimization (PSO) algorithm. Different cases are carried out to observe the impact of the shunt capacitor placement. The result shows that the location of shunt capacitor influences the system power losses reduction. The shunt capacitor must be located near to the load. The optimal location and size of shunt capacitor is achieved efficiently using PSO algorithm. The study is tested on the 33-bus test system and is simulated by using MATLAB software.

Keywords: Particle swarm optimisation; Power losses; Shunt capacitor.

1. INTRODUCTION

The percentage of power losses in the distribution side is significantly higher than losses in the transmission and generation sides [1]. This is due to the transition power from generation side to the distribution side [2], where inductive loads such as generator, transformers and AC induction motor [3] are the most assertive loads in this side. During the heavy load condition, the load current drawn from generator is increasing and leads to the increment of system loss. In addition, the high R/X ratio of the radial distribution system contributes to the system power.

This scenario has become a great concern, especially for distribution utilities to keep the power supply within the user's requirements. Therefore, a number of methods have been implemented to solve this issue without having a major construction to the existing system such as network reconfiguration [4], installation of distributed generation (DG) [5] and shunt capacitors [1]. Shunt capacitor is used extensively all over the world as reactive power compensation. By installing the shunt capacitor, a part of the reactive power demand is compensated, hence reduces the power. In addition, the installation of shunt capacitor not only reduce loss but able to improve the voltage.

However, shunt capacitor has its own limitation where it leans on the location, size, number of shunt capacitor and the control setting. In other word, the location and size of the capacitor are very crucial aspect in reducing power losses. The non-optimal location and size of shunt capacitor may affect the power system stability besides causing the increment of power losses. To solve this problem, the location and size of capacitor must be properly optimised.

Therefore, many studies have been carried out in optimising shunt capacitor sizes and locations in distribution networks with different aims and targets. Improving voltage stability was the main objective in [6] and many research focused on network losses [7-10]. However, these studies optimised the size and location of shunt capacitor separately where it leads to a non-optimal solution. The capacitor location and size optimization problem is a large-scale optimisation problem, which involved both continuous and discrete variables. In addition, both size and location of shunt capacitor depends on each other, making the problem becomes complex. Therefore, a meta-heuristic optimisation technique is the best method, and thus is often applied to solve the problem [11-12].

This paper determines the optimal size and location of shunt capacitor simultaneously using the particle swarm optimisation (PSO) algorithm. PSO algorithm is one of the meta-heuristic technique and it is widely applied in the optimisation problem. This is due to the advantage of PSO that is simple to be implemented and requires less computational time. Moreover, the PSO algorithm generates a high-quality solution in shorter time and stable convergence characteristics compared to other stochastic methods. Furthermore, this paper study the impact of the shunt capacitor installation in the distribution network during heavy load condition towards the power losses.

2. PROBLEM FORMULATION

The shunt capacitor is formulated as a nonlinear expression with two variables that represent the shunt capacitor's location and size. In order to have an appropriate size of the capacitor, the selection of the values is based on available size in the market [12] which are 300 kVAr, 600 kVAr, 900 kVAr, 1200 kVAr, and 1500 kVAr. The main objective of this project is to reduce the power losses in the radial distribution system by optimising the shunt capacitor location and size while satisfying all the constraints. The system is assumed in balanced condition and the linear loads are invariant with time. The objective function is formulated as in Equation (1).

$$\min f\,(x_1, x_2) = \sum_{i-1}^{n} P_{realloss,i} \tag{1}$$

where x_1 is the location of shunt capacitor in the system, x_2 is the size of shunt capacitor, n is the total number of lines and $P_{realloss,i}$ is the active power loss at each line i.

$$P = I^2 R \tag{2}$$

where P is a real power (kW), I is a current, (A) and R is a resistance (Ω).

The installation of a shunt capacitor compensates the lagging reactive power that usually is consumed in the distribution side. Compensation of load lagging reactive power reduces the current drawn from the supply, hence reduces the power losses. Losses account for approximately one-third of one percent of the reactive power rating [8]. There are two types of constraints considered, which are operational and capacitor constraints.

2.1 Operational Constraints

The voltage each bus, V_i must be within the permissible limits.

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{3}$$

2.2 Capacitor Constraints

The number of capacitors, N_C must be less than or equal to the maximum number of possible locations, N_C^{max} as:

$$N_C \leq N_C^{max} \tag{4}$$

The leading reactive power injection must be within feasible minimum and maximum limits.

$$Q_{Cj}^{min} \leq Q_{cj} \leq Q_{Cj}^{max} \tag{5}$$

where Q_{cj} is the reactive power injection at location j. The total leading reactive power injection, Q_C^{total} must be less than or equal to the total load reactive power, Q_L^{total} as:

$$Q_C^{total} \leq Q_L^{total} \tag{6}$$

3. PARTICLE SWARM OPTIMIZATION (PSO) ALGORITHM

PSO is one of the popular meta-heuristic methods that is applied to solve different types of optimisation problems. The PSO algorithm is based on the movement of the organism such as a schooling of fish and a flocking bird [13]. The birds or fish move to the food in certain speed or position. The particle will fly over to the search space with adjusted velocities [14]. Their motion will rely on their own best experience, and the best experience from other friends in the group. The new velocity, v_j^{k+1} and the new position, $x_j^{k+1}$are attained using Equations (7) and (8), respectively.

$$v_j^{k+1} = \omega * v_j^k + c_1 rand_1 \left(p_{best\,j}^k - x_j^k\right) + c_2 rand_2 \left(g_{best\,j}^k - x_j^k\right) \tag{7}$$

$$x_j^{k+1} = x_j^k + v_j^{k+1} \tag{8}$$

where v_j^k is the velocity of particle j in iteration k, x_j^k is the position of particle j in iteration k, $rand_1$ and $rand_2$ are the random numbers between 0 and 1. $p_{best\,j}^k$ is the best value of the fitness function that has been achieved by particle j before iteration k. While $g_{best\,j}^k$ is the best value of the fitness function that has been achieved so far in the entire group of particles. Constraints c_1 and c_2 are the accelerations constants.

The PSO algorithm involves the generation of random particles to achieve the best fitness value by emphasising their position and velocity as their solutions approach. The fitness function aimed to obtain the latest and better solutions to replace unsatisfied solutions in the group of particles. The flow chart for the PSO technique is shown in Figure 1.

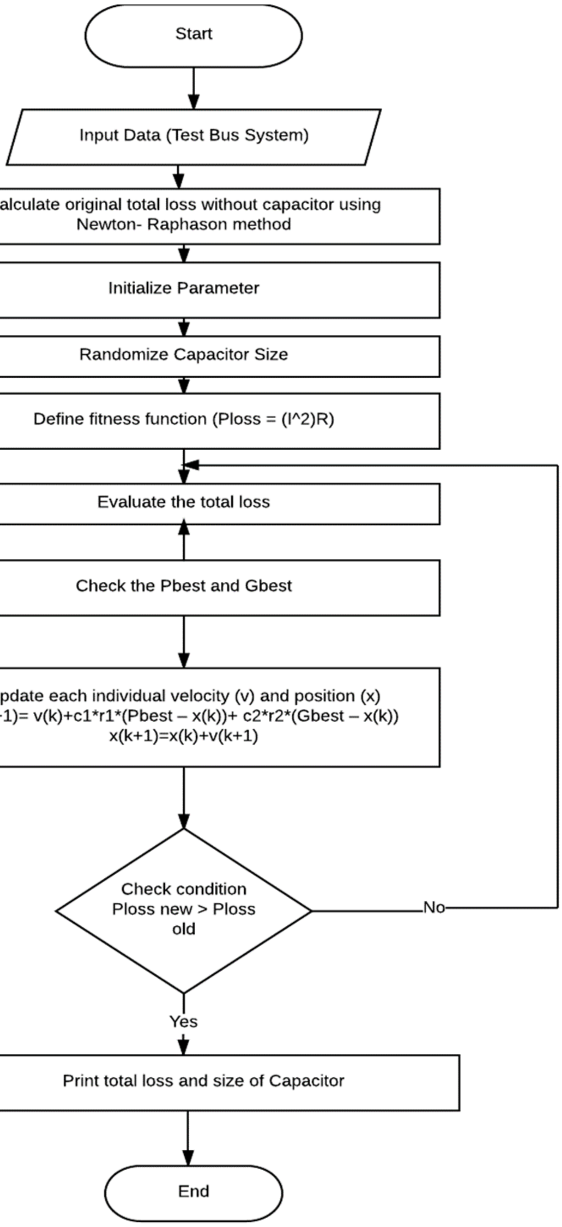

Figure 1. Flowchart of PSO

The optimisation process of PSO algorithm that is applied to determine the optimal size and location of shunt capacitor in radial distribution system is as follows:

1. Read the system input data, which are bus and line data of the test system.
2. Initialise the PSO parameters such as N size of particles population, ω by using Equation (9), c_1 and c_2, and maximum iteration.
$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{k_{max}}(k) \tag{9}$$
where k_{max} is the maximum number of iteration and k is the present iteration number, ω_{max} and ω_{min} are maximum and minimum of the inertia weights, respectively.
3. Generate initial particles, x^1 and x^2 randomly that consist of the location and size of shunt capacitor with the size of N number of particles population.
4. Compute fitness value based on the initial particles.
5. Determine the best fitness value, g_{best} and the best particle, p_{best} based on the g_{best}.
6. Generate the new particles after calculating the new velocity and new position using Equations (7) and (8), respectively.
7. Calculate the new fitness value based on the new particles.
8. Compare the new and old fitness value to identify the g_{best} and update the p_{best} based on current g_{best}.
9. Keep the best results.
10. Repeat the procedure from step 6 to step 9 until the maximum iteration is reached.

4. RESULT AND DISCUSSION

The 33 bus test system is tested in this paper as shown in Figure 2. The system consists of 33 buses and 32 lines with the total load of 3.715 MW and 2.3 MVAr [15]. Both systems are connected to the main substation of 132/13.8 kV. These two test systems are rated at 100 MVA as base power with the secondary side as base voltage at 13.8kV. The parameters used in PSO are number of particles population, N is 20, initial weight, ω where ω_{max} and ω_{min} are equal to 0.9 and 0.4 respectively, coefficient of acceleration, c_1 and c_2, both are equal to 2 [10,16] and maximum iteration is 100.

The location and the size of shunt capacitor are optimised simultaneously using PSO. Three cases are carried out in order to analyse the effect of allocation and sizing of shunt capacitor in reducing the power loss. In addition, the effect of non-optimal location and size of the capacitor in the radial distribution network is also analysed. The first case study is about analysing the power loss in the system during normal load and during heavy load. Second case study is carried out to determine the optimal location and size of single shunt capacitor with optimisation process. The third case study is to analyse the effect of non-optimal placement of shunt capacitor in distribution network.

4.1 Location and Size of Capacitor during Normal Load and Heavy Load Conditions

The total power losses in normal load and heavy load are shown in Table 1. The result shows that during normal load the total power losses is 281.5877 kW. Then, after the load is increased, the power losses increased to 996.9835 kW. The difference in power losses between normal load and heavy load is 254.06%. The location and size of capacitor are then optimised to reduce the power losses.

Table 1. Power losses at system during normal load and heavy load

Normal Load (KW)	Heavy Load (KW)	Percentage Losses (%)
281.5877	996.9835	254.06

4.2 Effects of Shunt Capacitor Placement on Distribution System

In order to analyse the effect of shunt capacitor placement, the single capacitor size is fixed to 900 kVAR and is located at buses 2, 3, 4, 16, 17 and 18 in separated optimisation for the heavy load condition. The total power losses in this condition is 996.9835 kW. Generally, the power losses are reduced when the shunt capacitor is located in the system as shown in Table 2. The power loss is reduced to 744.0622 kW when the shunt capacitor is located at bus 16 which is lower compared to the shunt capacitor placement at buses 16 and 18. This is because bus 16 is nearer to bus 33, which has high load. Therefore, when the shunt capacitor is located at bus 16, the shunt capacitor compensates the lagging reactive power, hence reduces current flowing from the generation side. The allocation of capacitor at bus 16 caused 26% of losses reduction. The power losses of 983.6763 kW is obtained when the shunt capacitor is located at bus 2, which is almost equal to the losses without shunt capacitor. This is due to bus 2 is nearest to the generation side. This result shows that the capacitor location has effects on the power loss value and shunt capacitor is not suitable to be placed near to the generation side.

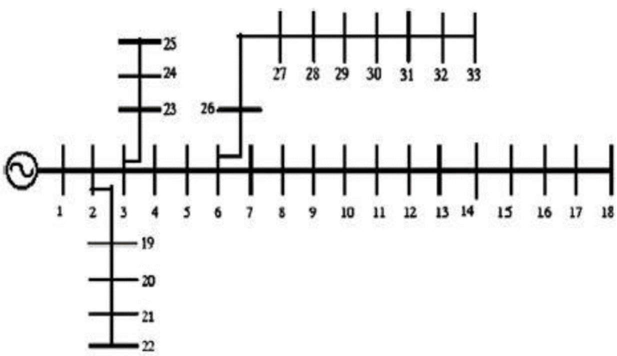

Figure 2. Schematic diagram of IEEE 33-bus system

Table 2. Effect of shunt capacitor placement in distribution system

Capacitor location (bus number)	Size of Capacitor (kVAr)	Power Losses (With Shunt Capacitor), kW	Percentage Reduction (%)
2	900	983.6763	1.33
3	900	916.5923	8.06
4	900	875.2943	12.21
16	900	744.0622	25.37
17	900	758.8871	23.88
18	900	767.6680	23.00

4.3 Optimisation of Location and Size of Shunt Capacitor using PSO Algorithm

In order to analyse the impact of shunt capacitor on power losses, the number of shunt capacitor is fixed to a single unit. Table 3 shows the result of the optimisation. The result shows that the power loss is reduced to 466.2388 kW (53.24% reduction) when 865 kVAr size of shunt capacitor is located at bus 31. This result indicates that the placement of shunt capacitor able to reduce the power losses.

The location and size of shunt capacitor are optimised using PSO. Since PSO is randomised based optimisation technique, the shunt capacitor location and size are optimised for 70 trials. Figure 7 shows the convergence graph for reaching the optimal value. The minimum fitness value which is power losses is reached at iteration 2. The result indicates that PSO able to provide fast convergence towards optimal solution. Hence, PSO is capable of yielding optimal result very quickly.

Table 3. Result of shunt capacitor placement and sizing with optimization (PSO)

Location	Size of Capacitor (kVar)	Power Losses (With Shunt Capacitor), kW	Percentage Reduction (%)
31	865	466.2388	53.24

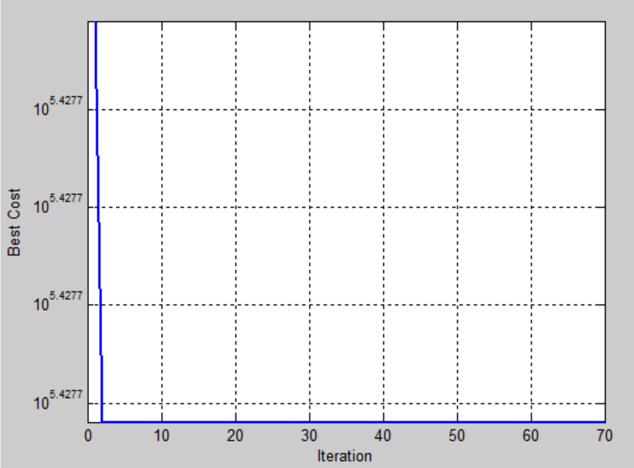

Figure 7. Convergence characteristic

5. CONCLUSION

The leading reactive power compensation by shunt capacitor causes the decreasing of current flow to the load. Hence, the power losses are reduced. However, the location of shunt capacitor plays an important role in order to ensure the minimum power losses can be produced. From the analysis, the best shunt capacitor placement is near to the highest load. In order to obtain minimum power losses, the shunt capacitor size and location are optimised using PSO algorithm. PSO algorithm is capable of providing optimal result very quickly, where it provides fast convergence towards optimal solution.

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