International Journal of Engineering & Technology, 7 (4) (2018) 3312-3316

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International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET
doi: 10.14419/ijet.v7i4.19530
Research paper

Optimal reactive power sizing in a distributed network

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Abstract

Optimal allocation of capacitor bank for reactive power compensation in radial distribution system (RDS) with the objective of minimizing the power loss of system subjected to equality and inequality constraints is proposed in this paper. Potential buses for reactive power com-pensation have been determined using the loss sensitivity factor approach. Here, a vector based distribution load flow (VDLF) technique is used for radial distribution system load flow and for applying the loss sensitivity factor method for optimal bus selection for reactive power compensation. In this paper, the Genetic Algorithm is used to determine the reactive power size that has to be injected at the candidate buses by considering the power loss minimization as the objective function. The validity and effectiveness of proposed approach is tested on six standard (i.e., 15 node, 31 node, 33 node, 34 node, 69 node and 85 node) radial distribution systems.

Keywords: *Reactive Power Compensation; Optimal Capacitor Sizing; Distribution Load Flow; Evolutionary Algorithms; Loss Sensitivity Factors; Distribution Network.*

1. Introduction

Optimal placement and size of shunt capacitors for reactive power compensation plays a significant role in minimizing the cost of reactive power compensation and energy loss in distribution systems. In practice, a power system network is complicated as it has a number of power generating stations of different types, transmission lines, sub-transmission lines, interconnected by a system of tie lines, and distribution networks to supply different types of loads to various consumers. The distribution network is dedicated for delivering electric energy to end user/customer [1]. A comprehensive review/survey of optimum placement and sizing of shunt capacitor for reactive power management in distribution systems is presented in [2]-[5].

An integrated approach of Loss Sensitivity Factor (LSF) and Voltage Stability Index (VSI) to determine the optimal location for the installation of capacitor banks is proposed in [6]. In reference [7], a Shark Smell Optimization (SSO) algorithm is proposed to solve the optimal capacitor placement problem in the distribution system by satisfying all the operating constraints. Two algorithms for optimal capacitor placement in radial distribution system (RDS) with a view to enhance voltage stability are proposed in [8].

Optimal capacitor placement in RDSs using various evolutionary algorithms such as using clustering based optimization algorithm is proposed in [9], using teaching learning based optimization algorithm is proposed in [10], using Gravitational Search Algorithm is proposed in [11], using Flower Pollination Algorithm is proposed in [12], using fuzzy GA method is proposed in [13], using hybrid swarm intelligence algorithm is proposed in [14], using Hybrid Big Bang–Big Crunch algorithm in the fuzzy framework is proposed in [15], using efficient heuristic algorithm is proposed in [16], using genetic algorithm is proposed in [17], using Whale Optimization Algorithm is proposed in [18]-[19]. Optimal placement of shunt capacitor banks in distribution feeders for the purpose of reduction of power loss, total annual expenses and voltage deviations is proposed in [20]. An optimal allocation methodology for capacitor placement in unbalanced distribution systems to achieve loss minimization with an adequate voltage profile is presented in [21]. Reference [22] proposes a heterogeneous decomposition based distributed optimal reactive power flow method for global transmission and distribution networks.

From the above literature review, it can be observed that the distribution system losses can be reduced and voltage profile can be improved through proper dispatch of reactive power/voltage control devices. Hence, the reduction of power loss in distribution systems is economically very important. The procedure for reduction of losses in distribution systems is based on the measurement of reactive power at sending end of feeder, then supplying power consumption of line by means of equally sized and located capacitor banks. The problem of optimal capacitors consists of determining sizing and number of capacitors to be installed in distribution systems such that maximum benefits are achieved while operational constraints at different loading levels are satisfied.

The remainder of this paper is organized as follows: Section 2 describes the procedure to determine the candidate bus location for reactive power compensation using loss sensitivity factors. The reactive power sizing/capacitor sizing at potential buses using Genetic Algorithms is proposed in Section 3. Section 4 presents the simulation results and discussion. Finally, Section 5 presents the contributions with concluding remarks.

2. Optimal location using loss sensitivity factors approach

In this paper, the optimal allocation of capacitor bank in radial distribution system (RDS) with the objective of minimizing power loss of the system subjected to equality and inequality constraints is proposed. For voltage profile improvement at various buses of distribution network, we need to plan reactive power compensation at potential buses. Loss sensitivity factor offers the important information about the sequence of potential nodes/buses for reactive power compensation in the system. These factors are determined using the single run of base case load flow study. A new methodology is used to determine the candidate nodes for reactive power compensation using loss sensitivity factors. The estimation of these candidate nodes basically helps in reduction of search space for the optimization procedure [23]. Figure 1 depicts a distribution line connected between bus i and bus j.

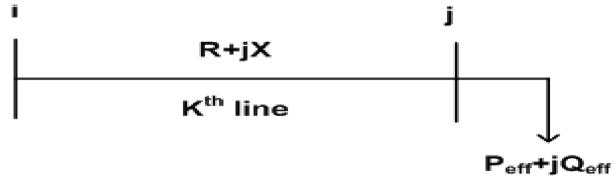

Fig. 1: Distribution Line Connected between Bus I and Bus J.

Active power loss in k^th line is expressed using,

$$P_{loss}(j) = \frac{[P_{eff}^2(j)+Q_{eff}^2(j)]R(k)}{V(j)^2} \quad (1)$$

Reactive power loss in k^th line is expressed using,

$$Q_{loss}(j) = \frac{[P_{eff}^2(j)+Q_{eff}^2(j)]X(k)}{V(j)^2} \quad (2)$$

where $P_{eff}^2(j)$ and $Q_{eff}^2(j)$ are total effective active and reactive powers supplied beyond node ‘j’. The loss sensitivity factors for real and reactive power losses are expressed using [24],

$$\frac{\partial P_{loss}}{\partial Q_{eff}} = \frac{2Q_{eff}(j)R(k)}{V(j)^2} \quad (3)$$

$$\frac{\partial Q_{loss}}{\partial Q_{eff}} = \frac{2Q_{eff}(j)X(k)}{V(j)^2} \quad (4)$$

2.1. Candidate bus selection by loss sensitivity factors approach

The loss sensitivity factors ($\partial P_{loss}/\partial Q_{eff}$) are calculated from the base case load flows and the values are arranged in descending order for all the lines of given distribution system. A bus position vector ($B_{pos}(i)$) is used to store the respective ‘end’ buses of the lines arranged in descending order of ($\partial P_{loss}/\partial Q_{eff}$) values. The descending order of ($\partial P_{loss}/\partial Q_{eff}$) elements of bus position vector will decide the sequence in which the buses are to be considered for compensation. This sequence is purely governed by the ($\partial P_{loss}/\partial Q_{eff}$). At these buses of $B_{pos}(i)$ vector, the normalized voltages ($V_{norm}(i)$) are calculated by considering the base case voltage magnitudes and they are expressed using [25],

$$V_{norm}(i) = \frac{V(i)}{0.95} \quad (5)$$

Now, the buses whose $V_{norm}(i)$ values that are less than 1.01 are considered as the candidate buses requiring the compensation. These candidate buses are stored in the $rank_{bus}(i)$ vector. Here, the loss sensitivity factors are used to decide the sequence in which buses are to be considered for compensation placement, and whether a bus requires reactive power compensation or not is decided by using the $V_{norm}(i)$ vector. If the voltage at a bus in the sequence is healthy (i.e., $V_{norm}(i)>1.01$) such bus needs no compensation and that will not be listed in the $rank_{bus}(i)$ vector. The $rank_{bus}(i)$ vector provides the information about possible potential or candidate buses for reactive power compensation.

3. Reactive power sizing using genetic algorithm

Genetic Algorithm (GA) were modeled and developed by John Holland at University of Michigan in 1975. It is one kind of direct random search algorithm modeled after mechanics of biological evolution [26]. In nature, individuals in a population compete with each other for various kinds of sources such as food, shelter, and water. Those individuals, who have stronger existing abilities can survive (survival of fittest) and have relatively larger number of offspring. Conversely, poorly performing ones have less chance to survive and they will produce less or even no offspring at all. This means that highly adapted genes will spread to an increasing number of individuals of the later generation. The combination of good characteristics from different ancestors will probably produce offspring whose fitness is better than that of either ancestor. Finally, the species will evolve to be more and more suitable to the environment. For the detailed description of GA, the reader may refer references [26]-[27].

Once the $rank_{bus}(i)$ vector is identified using the loss sensitivity factors approach, where capacitive shunt compensation is to be placed. GA is used to determine the optimum capacitor size at each potential/candidate bus, indicated by $rank_{bus}(i)$. After placing the estimated shunt capacitive value at the most preferred bus, again GA is performed for fixing the optimum capacitor size at next preferred potential bus. This procedure is repeated till no additional compensation is required and any further compensation increases the losses in the distribution network. The procedure is terminated at that stage. Here, the vector based distribution load flow (VDLF) is used for solving the radial distribution system load flow and then the loss sensitivity factor method for optimal bus selection for reactive power compensation. As mentioned earlier, the amount of reactive power size has to be injected at the candidate buses is determined using the GA by considering the power loss minimization as the objective function to be optimized. The power loss minimization function is expressed as,

minimize,

$$P_{loss}(j) = \frac{[P_{eff}^2(j)+Q_{eff}^2(j)]R(k)}{V(j)^2} \quad (6)$$

3.1. Algorithm for reactive power sizing by genetic algorithm

The algorithm for optimal sizing of reactive power compensation using GA is presented next:

Step 1: Read the system data.

Step 2: Run the base case distribution system load flow (by using VDLF approach) and determine the active power loss (P_{loss}).

Step 3: Identify the candidate buses for reactive power compensation using loss sensitivity factor approach.

Step 4: Candidate bus loop: For i = 1 to n (where ‘n’ is the number of candidate buses (obtained from loss sensitivity factor approach).

Step 5: Read the data related to the Genetic Algorithm: read string length (S_{len}), population size (P_{size}), cross over probability (P_c), mutation probability (P_m), elitism probability (P_e), maximum number of generations (G_{max}), minimum and maximum limits of reactive powers (Q_{min} and Q_{max}).

Step 6: Randomly generate the initial population. Population = randint(P_{size}, S_{len}).

Step 7: Generation loop: For generation = 1 to G_{max}

Step 8: Population loop: For i = 1 to P_{size}

Sum = 0

For j = 1 to S_{len} (Decode the population)

Sum = Sum+ Population (i, j)*2^{-j}

End of j th loop

Step 9: Calculate the reactive power compensation required (Q_{comp}) using,

$$Q_{comp}(i) = Q_{min} + (Q_{max} - Q_{min}) * Sum \quad (7)$$

Step 10: Place the shunt capacitor of value Q_{comp} at the selected candidate/potential bus obtained from Step 9.

Step 11: Run the load flow and then calculate the active power loss (P_{loss}). Here, the power loss minimization is considered as

the objective function. Evaluate the fitness value using: fitness (i) = 1 / (1+P_{loss}).
Step 12: Restore the actual reactive power load at the candidate bus.
Step 13: Sort the chromosomes in the descending order of their fitness values, and check for convergence.
Step 14: Find error. Error = fitness(first chromosome) – fitness(last chromosome).
If error < ε (epsilon), then the problem is converged. Store the corresponding Q_{comp} value and go to Step 15 else go to Step 16.
Step 15: Place the compensation Q_{comp} at the candidate bus and go to Step 18.
Step 16: Perform elitism, cross over, and mutation operations on old population and generate new population.
Step 17: Increase the generation count. If generation count = G_{max}, then go to Step 20 else go to Step 9.
Step 18: If the saving in active power loss > 1.5KW then increment the candidate bus loop else go to Step 20.
Step 19: Problem is not converged in $\boldsymbol{G_{max}}$ generations.
Step 20: Display the results and stop the algorithm.

4. Simulation results and discussion

In this paper, the capacitor sizing at potential buses by using Genetic Algorithm (GA) has been tested on various distribution test systems, i.e., 15 node, 31 node, 33 node, 34 node, 69 node and 85 node radial distribution systems (RDSs). The GA parameters selected for this optimal capacitor sizing problem are: string length is 16, population size is 40, elitism probability (P_e) is 0.15, cross over probability (P_c) is 0.85, mutation probability (P_e) is 0.001.
The VDLF method is developed using the MATLAB software and it is applied on the 15 node, 31 node, 33 node, 34 node, 69 node and 85 node radial distribution systems (RDSs). These base case results are used for evaluating the loss sensitivity factors of various buses and these factors are arranged in descending order. $B_{pos}(i)$ vector of size n×1 clearly indicates the sequence of buses to be compensated for reactive power. $V_{norm}(i)$ vector is useful in identifying the $rank_{bus}(i)$ vector in the table gets terminated prematurely when $V_{norm}(i)$ is greater than 1.01. It may be noted that loss sensitivity factors, $B_{pos}(i)$ and $rank_{bus}(i)$ vectors are calculated from base case load flow results.

4.1. Simulation results on 15 node RDS

Table 1 presents the simulation results for the 15 node RDS system. As mentioned earlier, the loss sensitivity factors approach is used to determine the potential/candidate buses for the reactive power compensation. From this loss sensitivity approach, it is found that buses 6, 3 and 11 are suitable for the placement of shunt capacitors for the reactive power compensation. The size of shunt capacitors required at buses 6, 3 and 11 are 458.52KVAR, 499.15KVAR and 285.28KVAR, respectively. The active power losses before and after placing the shunt capacitors are 62.85KW and 30.89KW, respectively. Therefore, the reduction in active power loss with respect to base case load flows is 50.85%.

Table 1: Simulation Results for 15-Node Radial Distribution System

Candidate buses for compensation	Loss sensitivity factor	Size of reactive power
6	0.0311	458.52 KVAR
3	0.0174	499.15 KVAR
11	0.0168	285.28 KVAR
Total KVAR	---	1242.95 KVAR
Base case active power loss (KW)	---	62.85
Active power loss after compensation (KW)	---	30.89

4.2. Simulation results on 31 node RDS

Table 2 presents the simulation results for the 31 node RDS system. From the loss sensitivity factor approach, it is found that buses 7 and 9 are suitable for the placement of shunt capacitors for reactive power compensation. The size of shunt capacitors required at buses 7 and 9 are 1466.12 KVAR and 1484.52 KVAR, respectively. The active power losses before and after placing the shunt capacitors are 1098.67 KW and 961.31 KW, respectively. Therefore, the reduction in active power loss with respect to base case load flows is 12.5%.

Table 2: Simulation Results for 31 Node Radial Distribution System

Candidate buses for compensation	Loss sensitivity factor	Size of reactive power
7	0.0132	1466.12 KVAR
9	0.0097	1484.52 KVAR
Total KVAR	---	2950.64 KVAR
Base case active power loss (KW)	---	1098.67
Active power loss after compensation (KW)	---	961.31

4.3. Simulation results on 33 node RDS

Table 3 presents the simulation results for the 33 node RDS system. From the loss sensitivity factor approach, it is found that buses 6, 28 and 29 are suitable for the placement of shunt capacitors for reactive power compensation. The size of shunt capacitors required at buses 6, 28 and 29 are 562.21 KVAR, 593.94 KVAR and 583.12 KVAR, respectively. The active power losses before and after placing the shunt capacitors are 204.57 KW and 136.91 KW, respectively. Therefore, the reduction in active power loss with respect to base case load flows is 33.7%.

Table 3: Simulation Results for 33 Node Radial Distribution System

Candidate buses for compensation	Loss sensitivity factor	Size of reactive power
6	0.0173	562.21 KVAR
28	0.0141	593.94 KVAR
29	0.0137	583.12 KVAR
Total KVAR	---	1739.27 KVAR
Base case active power loss (KW)	---	204.57
Active power loss after compensation (KW)	---	136.91

4.4. Simulation results on 34 node RDS

Table 4 presents the simulation results for the 34 node RDS system. From the loss sensitivity factor approach, it is found that buses 19, 18 and 22 are suitable for the placement of shunt capacitors for reactive power compensation. The size of shunt capacitors required at buses 19, 18 and 22 are 680.05 KVAR, 681.09 KVAR and 693.41 KVAR, respectively. The active power losses before and after placing the shunt capacitors are 220.24 KW and 169.58 KW, respectively. Therefore, the reduction in active power loss with respect to base case load flows is 23%.

Table 4: Simulation Results for 34-Node Radial Distribution System

Candidate buses for compensation	Loss sensitivity factor	Size of reactive power
19	0.0086	680.05 KVAR
18	0.0075	681.09 KVAR
22	0.009	693.41 KVAR
Total KVAR	---	2054.55 KVAR

Base case active power loss (KW)	---	220.24
Active power loss after compensation (KW)	---	169.58

4.5. Simulation results on 69 node RDS

Table 5 presents the simulation results for the 69 node RDS system. From the loss sensitivity factor approach, it is found that buses 46, 47 and 50 are suitable for the placement of shunt capacitors for reactive power compensation. The size of shunt capacitors required at buses 46, 47 and 50 are 491.25 KVAR, 484.37 KVAR and 491.41 KVAR, respectively. The active power losses before and after placing the shunt capacitors are 220.24 KW and 169.58 KW, respectively. Therefore, the reduction in active power loss with respect to base case load flows is 32.9%.

Table 5: Simulation Results for 69-Node Radial Distribution System

Candidate buses for compensation	Loss sensitivity factor	Size of reactive power
46	0.0274	491.25 KVAR
47	0.0141	484.37 KVAR
50	0.0111	491.41 KVAR
Total KVAR	---	1467.03 KVAR
Base case active power loss (KW)	---	240.18
Active power loss after compensation (KW)	---	161.07

4.6. Simulation results on 85 node RDS

Table 6 presents the simulation results for the 85 node RDS system. From the loss sensitivity factor approach, it is found that buses 8, 58, 7 and 27 are suitable for the placement of shunt capacitors for reactive power compensation. The size of shunt capacitors required at buses 8, 58, 7 and 27 are 639.07 KVAR, 641.04 KVAR, 649.18 KVAR and 632.05 KVAR, respectively. The active power losses before and after placing the shunt capacitors are 311.64 KW and 169.67 KW, respectively. Therefore, the reduction in active power loss with respect to base case load flows is 45.5%.

Table 6: Simulation Results for 85 Node Radial Distribution System

Candidate buses for compensation	Loss sensitivity factor	Size of reactive power
8	0.0491	639.07 KVAR
58	0.0181	641.04 KVAR
7	0.0117	649.18 KVAR
27	0.0115	632.05 KVAR
Total KVAR	---	2561.34 KVAR
Base case active power loss (KW)	---	311.64
Active power loss after compensation (KW)	---	169.67

From the above simulation results, it can be observed that by placing the shunt capacitors (for reactive power compensation in RDS) at suitable locations, the active power losses in the system has been reduced significantly.

5. Conclusions

In this paper, the optimal capacitor placement in distribution networks is performed using Genetic Algorithm. MATLAB platform based software package is developed for vector based distribution load flow (VDLF) technique has been implemented in this paper. The converged VDLF results are used for evaluating the loss sensitivity factors of various lines and this shows the sequence of potential buses for reactive power compensation. Optimal capacitor sizes at these potential buses are determined by using the Genetic Algorithm. The performance of proposed approach is tested on standard 15 node, 31 node, 33 node, 34 node, 69 node and 85 node radial distribution systems. The simulation results shows that there is a significant reduction in active power losses in the system after placing the shunt capacitors at potential buses in the system. Determining the optimal placement and sizing of distributed generation and shunt capacitors for power loss minimization in radial distribution networks is a scope for future research work.

Acknowledgment

This research work is based on the support of “Woosong University's Academic Research Funding - 2018”.

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