Optimization of Capacitor Bank Placement in Electric Network Using Genetic Algorithm

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Abstract. Minimizing losses in electric network should be considered the placing a shunt capacitor, the voltage level on each bus, the size and number of shunt capacitors to be used, and the supply of maximum and minimum of generator power. This paper is conducted the determination of location and size of shunt capacitor to be allocated in electric power transmission networks. The simulation using Genetic Algorithms (GA) method was applied to solve the problem of reactive power compensation optimization. To find out amount of compensation for voltage drop and power losses that occur in the system, a load flow analysis was performed using the Newton-Raphson method. The result of capacitor placement and capacitor capacity were shown the highest voltage conditions on bus 4 of 1.050 Mvar and the lowest on bus 24 of 9.69 Mvar. The optimization system was revealed the total losses system of 12.793 MW with a total generation cost of 15447.44 $/h for the capacitor reduction size of 18.8 Mvar. Therefore, the system can save 6.2 Mvar's capacitors.

1. Introduction

The capacitor bank is needed to maintain stability of reactive power compensation. An installation of capacitor bank equipment can reduce the voltage drop and the power losses. The general problem of equipment placement is the determination capacitor bank to be located in the electric power transmission or distribution system [1]. Voltage limitation parameters, capacitor working range and load variations are all needed and carefully considered to determine the placement of compensation equipment to the system [2]. Therefore, the optimum cost operational of the electric power transmission network can be obtained.

The optimization method can solve the problems in various power system analyses and evaluation, which one of them is Genetic Algorithms [3]-[10]. Many researchers have implemented the GA in the different manner by formulating and solving problems such as analytical, simulation and real conditions in the field. Some researchers use GA for only voltages control or voltage phase angles or only consider capacitors. Other researchers take into account the changing of loads; location and size of capacitors were considered. Otherwise, included the minimizing cost for optimal power flow is very crucial also to consideration [11]-[14].

The power flow analysis is important to investigation before optimizing the placement location and capacity of the capacitor bank. The power flow analysis can be used the Newton-Raphson method [15]-[16], which is used to stabilize the electrical network system so that the power flow increases. Some parameters to be determined in the capacitors bank such as voltage, voltage phase angle, active power (P), reactive power (Q), active power loss (Ploss), and reactive power loss (Qloss) on each bus.
before installation of equipment. After all parameter values are known, then the location of the placement and capacity of the bank might be investigation and analysis.

In this paper the optimization of placement location and capacitor bank capacity in distribution networks uses the Genetic Algorithm (GA) method. To optimize the placement location and capacity of the capacitor bank in accordance with the declining feeder, optimization of the placement location and the capacitor bank capacity are carried out by the simulation. Furthermore, the optimal power transmission system can be obtained to get the minimum cost for power system operation.

2. Methodology

This research was performed the simulation to optimal the capacitor bank placement using GA method. The purpose of capacitor bank placement is to reduce energy losses and voltage levels no more than the allowable limit when minimizing the total cost of the system. Because energy losses affect the results of capacitor placement, load variations must be considered for the time period.

The proposed function for placement of the capacitors is:

\[
\min F = K_E T P_{loss} + K_{ef} Q_t
\]

\(P_{loss}\): Total power loss
\(K_E\): Cost per MWh
\(T\): Duration of load
\(K_{ef}\): Value of shunt capacitor
\(Q_t\): The total size of the shunt capacitor installed

The total power loss can be calculated using power flow outputs through the following equation:

\[
P_{loss} = \sum_{i=1}^{n} \sum_{j=l}^{n} V_i V_j Y_{ij} \times \cos(\theta_i - \theta_j - \delta_{ij})
\]

Where: \(V_i\) and \(Q_t\) are the magnitude and phase of the voltage on the bus i, \(Y_{ij}\) and \(\delta_{ij}\) are the magnitude and phase of the admittance line between bus i dan bus j. The voltage limits for each bus considered are:

\(V_{min} = 0.95pu\) and \(V_{max} = 1.05pu\)

The capacitor bank is used to control voltage and reactive power. Rapid control of reactive power needs to be maintained as long as the system operates. The reactive power control depends on the capacitor bank, which helps to maintain the system’s voltage profile during changes in load condition. An inductive load requires a reactive load and causes the system voltage to drop, to compensate for this voltage reduction the injection of reactive power requires the load. The capacitor bank equipment is installed to reduce and excess of the voltage and the optimum speed for supplying reactive power. The capacitor bank placement can improve the power factor that can reduce the voltage on the receiving side (VR) and VS (the sender’s voltage side).

An ideal power system, the voltage and frequency at each distribution point are expected to be constant, free from harmonics and the power factor approaches the value of one. But the parameters are strongly influenced by the size and characteristics of the consumer’s load. In an ideal system, each load performance can be designed to be optimum through the distribution of the given voltage. The system voltage and frequency are not being expected become interfered by variations in consumer load.

Maintaining the voltage level at the specified limit is very complicated because the power distribution at a very large load is obtained from many generating units. Varied load requirements require varying reactive power transmission. Because reactive power cannot be transmitted at long
distances, voltage control is carried out using a special device installed on the system. Proper selection and coordination of equipment to control reactive power and stress is a major challenge in power system techniques.

Voltage control level is carried out by controlling the production, absorption and reactive power flow at all levels in the system. The generating unit provides a voltage control device and AVR field excitation control to maintain the voltage level specified at the generator terminal. Additional tools are usually used to control voltage in the electrical system. The equipment used for this purpose is classified as follows:

1. Reactive resources, such as parallel capacitors, parallel reactors, synchronous condensers and Static Var Compensator (SVCs).
2. Wire reactance compensator, such as a series capacitor.
3. Setting the transformer such as changing the transformer tap and pushing (booster).

In this paper, a load flow analysis is performed using the Newton-Raphson method, which the power flow equation is formulated in polar form. The current enters to the bus \( i \) can be written with the following equation (in polar form) [17]:

\[
I_{ki} = \sum_{j=1}^{p} |V_{ij}| |V_{j}| \angle \theta_{ij} + \delta_{j}
\]

The complex power on bus \( i \) is:

\[
R_{ki} - jQ_{ki} = V_{ki}^* I_{ki}
\]

Based equation (4) and (5) are obtained equation as follows:

\[
R_{k} - jQ_{k} = |V_{k}| - \delta_{k} \sum_{j=1}^{p} |V_{ij}| |V_{j}| \angle \theta_{ij} + \delta_{j}
\]

Or if the real and imaginary parts are separated:

\[
R_{k} = \sum_{j=1}^{p} |V_{ij}| |V_{j}| \cos (\theta_{ij} - \delta_{i} - \delta_{j})
\]

and

\[
0 = \sum_{j=1}^{p} |V_{ij}| |V_{j}| |V_{j}| \sin (\theta_{ij} - \delta_{i} - \delta_{j})
\]

In the simulation carried out there are several assumptions that are considered, as follows:

1. The capacitor is fixed.
2. Loads work on a balanced system.

In this paper, method for the simulation presents the ability of the Genetic Algorithm in the process of optimizing the replacement of capacitors on the 26 bus system. The optimization process aims to minimize the total size of the shunt capacitor used and the total power losses in the system net. For optimum operation of generating units, Economic Dispatch is applied in the calculation process. Furthermore, in this simulation GA is performed to optimize the total size of the shunt capacitor used. Through Economic Dispatch, the total power losses can be minimized as little as possible.

3. Result and Discussion

In an ideal electric power system, the voltage and frequency at each distribution point are expected to be constant, free of harmonics and the power factor. However, these parameters are greatly influenced by the size and characteristics of the consumer’s burden. In an ideal system, each load performance can be designed to be optimum through the distribution of the applied voltage. System voltage and frequency are expected not to be interfered with by variations in consumer loads. Maintaining the voltage level within the specified limits is very complicated because power distribution at very large loads from many generating units. The varied load requires variation of reactive power transmissions.
Because reactive power cannot be transmitted over long distances, voltage control is carried out using special tools installed on the system. In term of optimize the channel system, the replacement of capacitors on the 26 bus system was carry out in this paper. The channel model adopted in this study was the data from the 26 IEEE bus systems. The data consists of a 6-bus generator and 20 load buses. Bus 1 is assumed to be a bus slack. The single line diagram for the 26 buses system can be seen in Figure 1.

![Figure 1. Diagram of one line of the 26 buses IEEE system](image)

The system test results such as the data of generator, line data and the data of bus, which was adopted from [17]. It can be seen in Table 1, data on the bus for voltage settings and generator reactive power capacity. In Table 1, the Bus 1 was performed as the slack bus with its voltage adjusted to 1.025 \( \pm 0 \) pu. Table 2 is depicted the data of transformer such as transformer design and tap setting per unit. The data of shunt capacitors can be seen in Table 3. The operation limitation of the generator active power of MW minimum and MW maximum is shown in Table 4.

| No Bus | Magnitude of Voltage | Capacities Mvar min | Capacities Mvar max |
|--------|----------------------|---------------------|---------------------|
| 2      | 1.020                | 40                  | 250                 |
| 3      | 1.025                | 40                  | 150                 |
| 4      | 1.050                | 40                  | 80                  |
| 5      | 1.045                | 40                  | 160                 |
| 26     | 1.015                | 15                  | 50                  |
Table 2. Data of transformers

| Design of Transformer | Tap setting Per unit |
|-----------------------|----------------------|
| 2 to 3                | 0.960                |
| 2 to 13               | 0.960                |
| 3 to 13               | 1.017                |
| 4 to 8                | 1.050                |
| 4 to 12               | 1.050                |
| 6 to 19               | 0.950                |
| 7 to 9                | 0.950                |

Table 3. Data of shunt capacitors.

| No Bus | Mvar |
|--------|------|
| 1      | 4.0  |
| 4      | 2.0  |
| 5      | 5.0  |
| 6      | 2.0  |
| 9      | 3.0  |
| 11     | 1.5  |
| 12     | 2.0  |
| 15     | 0.5  |
| 19     | 5.0  |

Table 4. Limitation of operating the active power of the generator.

| Generator | MW minimum | MW maximum |
|-----------|------------|------------|
| 1         | 100        | 500        |
| 2         | 50         | 200        |
| 3         | 80         | 300        |
| 4         | 50         | 150        |
| 5         | 50         | 200        |
| 26        | 50         | 120        |

The cost of operating the generator of $/h, with $P_i$ in the MW that is following:

\[
H_1 = 240 + 7.00 P_1 + 0.0070 P_1^2 \,$/h
\]

\[
H_2 = 200 + 10.0 P_2 + 0.0095 P_2^2 \,$/h
\]

\[
H_3 = 220 + 8.50 P_3 + 0.0090 P_3^2 \,$/h
\]

\[
H_4 = 200 + 11.0 P_4 + 0.0090 P_4^2 \,$/h
\]

\[
H_5 = 220 + 10.5 P_5 + 0.0080 P_5^2 \,$/h
\]

\[
H_{26} = 190 + 12.0 P_{26} + 0.0075 P_{26}^2 \,$/h
\]

The simulation results were obtained as presenting on Table 5, Table 6 and Table 7. In the Table 5 and Table 6 were presented the results of the calculation of power flow in the initial conditions before the optimization process and after the optimization process, respectively. The location and size of the capacitors might be applied, it can be seen at row 8th of the both tables (Table 5 and 6). From the results of calculations before and after optimization, the max stresses were found in range from 0.95 to 1.050, with the highest voltage on bus 4 of 1.050 and the lowest voltage on bus 24 of 0.969 and still
within the normal stress range. While, the phase angle did not occurred a significant change, it was found after the optimization of the increase in the angle of view of 0.011 on bus 15.

Table 5. Results of prior optimization of the power flow calculations.

| Bus No. | Voltage Mag. | Angle Degree | Load MW | Load Mvar | Generator MW | Generator Mvar | Injection Mvar |
|---------|--------------|--------------|---------|-----------|--------------|----------------|----------------|
| 1       | 1.025        | 0.000        | 51.000  | 41.000    | 447.611      | 250.582        | 4.000          |
| 2       | 1.020        | -0.200       | 22.000  | 15.000    | 173.087      | 57.303         | 0.000          |
| 3       | 1.045        | -0.639       | 64.000  | 50.000    | 263.363      | 78.280         | 0.000          |
| 4       | 1.050        | -2.101       | 25.000  | 10.000    | 138.716      | 33.449         | 2.000          |
| 5       | 1.045        | -1.453       | 50.000  | 30.000    | 166.099      | 142.890        | 5.000          |
| 6       | 1.001        | -2.874       | 76.000  | 29.000    | 0.000        | 0.000          | 2.000          |
| 7       | 0.995        | -2.406       | 0.000   | 0.000     | 0.000        | 0.000          | 0.000          |
| 8       | 0.998        | -2.278       | 0.000   | 0.000     | 0.000        | 0.000          | 0.000          |
| 9       | 1.010        | -4.387       | 89.000  | 50.000    | 0.000        | 0.000          | 3.000          |
| 10      | 0.991        | -4.311       | 0.000   | 0.000     | 0.000        | 0.000          | 0.000          |
| 11      | 0.998        | -2.824       | 25.000  | 15.000    | 0.000        | 0.000          | 1.500          |
| 12      | 0.994        | -3.282       | 89.000  | 48.000    | 0.000        | 0.000          | 2.000          |
| 13      | 1.022        | -1.261       | 31.000  | 15.000    | 0.000        | 0.000          | 0.000          |
| 14      | 1.008        | -2.445       | 24.000  | 12.000    | 0.000        | 0.000          | 0.000          |
| 15      | 0.999        | -3.229       | 70.000  | 31.000    | 0.000        | 0.000          | 0.500          |
| 16      | 0.990        | -3.990       | 55.000  | 27.000    | 0.000        | 0.000          | 0.000          |
| 17      | 0.983        | -4.366       | 78.000  | 38.000    | 0.000        | 0.000          | 0.000          |
| 18      | 1.007        | -1.884       | 153.000 | 67.000    | 0.000        | 0.000          | 0.000          |
| 19      | 1.005        | -6.074       | 75.000  | 15.000    | 0.000        | 0.000          | 5.000          |
| 20      | 0.983        | -4.759       | 48.000  | 27.000    | 0.000        | 0.000          | 0.000          |
| 21      | 0.977        | -5.411       | 46.000  | 23.000    | 0.000        | 0.000          | 0.000          |
| 22      | 0.980        | -5.325       | 45.000  | 22.000    | 0.000        | 0.000          | 0.000          |
| 23      | 0.978        | -6.388       | 25.000  | 12.000    | 0.000        | 0.000          | 0.000          |
| 24      | 0.969        | -6.672       | 54.000  | 27.000    | 0.000        | 0.000          | 0.000          |
| 25      | 0.975        | -6.256       | 28.000  | 13.000    | 0.000        | 0.000          | 0.000          |
| 26      | 1.015        | -0.284       | 40.000  | 20.000    | 86.939       | 27.892         | 0.000          |

Total system losses = 12.807 MW
Total generator costs = 15447.72 $/h

Table 6. Power flow after optimization calculation results.

| Bus No. | Voltage Mag. | Angle Degree | Load MW | Load Mvar | Generator MW | Generator Mvar | Injection Mvar |
|---------|--------------|--------------|---------|-----------|--------------|----------------|----------------|
| 1       | 1.025        | 0.000        | 51.000  | 41.000    | 447.602      | 253.660        | 0.600          |
| 2       | 1.020        | -0.200       | 22.000  | 15.000    | 173.087      | 57.303         | 0.000          |
| 3       | 1.045        | -0.641       | 64.000  | 50.000    | 263.406      | 76.283         | 0.000          |
| 4       | 1.050        | -2.101       | 25.000  | 10.000    | 138.693      | 34.559         | 0.600          |
| 5       | 1.045        | -1.452       | 50.000  | 30.000    | 166.065      | 147.564        | 0.100          |
| 6       | 1.001        | -2.874       | 76.000  | 29.000    | 0.000        | 0.000          | 3.200          |
| 7       | 0.995        | -2.407       | 0.000   | 0.000     | 0.000        | 0.000          | 0.000          |
| 8       | 0.998        | -2.278       | 0.000   | 0.000     | 0.000        | 0.000          | 0.000          |
| 9       | 1.011        | -4.387       | 89.000  | 50.000    | 0.000        | 0.000          | 4.600          |
| 10      | 0.991        | -4.312       | 0.000   | 0.000     | 0.000        | 0.000          | 0.000          |
| 11      | 0.998        | -2.827       | 25.000  | 15.000    | 0.000        | 0.000          | 2.500          |
12  0.994  -3.282  89.000  48.000  0.000  0.000  0.000  0.000
13  1.023  -1.265  31.000  15.000  0.000  0.000  0.000  0.000
14  1.008  -2.451  24.000  12.000  0.000  0.000  0.000  0.000
15  1.000  -3.240  70.000  31.000  0.000  0.000  0.000  4.700
16  0.990  -3.995  55.000  27.000  0.000  0.000  0.000  0.000
17  0.983  -4.364  78.000  38.000  0.000  0.000  0.000  0.000
18  1.008  -1.883  153.000  67.000  0.000  0.000  0.000  0.000
19  1.004  -6.067  75.000  15.000  0.000  0.000  0.000  2.500
20  0.983  -4.760  48.000  27.000  0.000  0.000  0.000  0.000
21  0.977  -5.410  46.000  23.000  0.000  0.000  0.000  0.000
22  0.980  -5.325  45.000  22.000  0.000  0.000  0.000  0.000
23  0.978  -6.385  25.000  12.000  0.000  0.000  0.000  0.000
24  0.969  -6.669  54.000  27.000  0.000  0.000  0.000  0.000
25  0.975  -6.255  28.000  13.000  0.000  0.000  0.000  0.000
26  1.015  -0.285  40.000  20.000  86.939  27.555  0.000  0.000

Total  1263.000  637.000  1275.792  596.492  18.800

Total system losses = 12.7928 MW
Total cost of generator = 15447.44 $/h

In Table 7 was depicted a comparison of simulation results before and after optimization. Based on these results, it can be seen that power losses, stress profiles, total active power generation and plant operating costs after optimization, which can be reduced to comparison to the initial conditions. But there was a significant savings from the size of the capacitor used after the optimization process. The total size of Mvar capacitor 25 in the initial conditions can be reduced to 18.8 Mvar. Furthermore, the system can save 6.2 Mvar capacitors.

4. Conclusion
In this paper the Genetic Algorithm was employed for the proposed method to solve the placement problems, replacing and determining the size of the capacitor bank on the electric power system nets. Power losses were used as an objective functions. The maximum and minimum voltages for each bus, the number and size of the capacitor were used as the constraints consideration. Based simulation was showed the satisfactory results. Based on the results achieved, the location and size of the shunt
capacitor were not trapped at optimum local prices and the results achieved that was close to optimum global.

References
[1] Reddy M D, Veera Reddy V C 2005 Optimal capacitor placement using fuzzy and real coded genetic algorithm for maximum saving J. of Theor and Appl Inform. Tech. 4(3) 219-224
[2] Charette A, Xu J, Ba-Razzouk A, Pillay P and Rajagopalan V 2000 The use of the genetic algorithm for in-situ efficiency measurement of an induction motor, IEEE Power Engineering Society Winter Meeting, 1(1) 392-397
[3] Furong L, Pilgrim J, Dabeedin C, Cheboo A and Aggarwal R 2005 Genetic algorithms for optimal reactive power compensation on the national grid system, IEEE Transactions on Power Systems, 20(1), 493-500
[4] Swarnkar A, Gupta N and Niazi K R 2010 Optimal placement of fixed and switched shunt capacitors for large-scale distribution systems using genetic algorithms Innovative Smart Grid Technologies Conference 1-8.
[5] Saonerkar A K and Bagde B Y 2014 Optimized DG placement in radial distribution system with reconfiguration and capacitor placement using genetic algorithm IEEE International Conference on Advanced Communications, Control and Computing Technologies, 1077-1083
[6] Ellithy K, Al-Hinai A and Moosa A 2008 Optimal shunt capacitors allocation in distribution networks using genetic algorithm practical case study International Journal of Innovations in Energy Systems and Power 3(1) 13-45
[7] Masoum M A S, Ladjevaedi M, Jafarian A and Fuchs E F 2004 Optimal placement, replacement and sizing of capacitor banks in distorted distribution networks by genetic algorithms IEEE Transaction on Power Delivery 19(4)
[8] Xu Y, Dong Z Y, Wong K P, Liu E and Yue, B 2013 Optimal capacitor placement to distribution transformers for power loss reduction in radial distribution systems 28(4) 4072 - 4079
[9] Sharma D and Mahor A 2013 Optimal placement of capacitor in radial distribution system using real coded genetic algorithmm International Journal of Electrical, Electronics and Computer Engineering 2(2) 3-29
[10] Carpinelli G, Proto D, Noce C, Russo A and Varilone P 2009 Optimal allocation of capacitors in unbalanced multi-converter distribution systems: a comparison of some fast techniques based on genetic algorithm Electric Power Systems Research 80(6) 642-650
[11] Bouktir T, Slimai L and Belkacemi M 2004 A Genetic algorithm for solving the optimal power flow problem Leonardo Journal of Sciences 3(4) 44-58
[12] Guvenc U, Altun E, Bekir and Serhat D 2012 Optimal power flow using genetic algorithm based on similarity Energy Education Science and Technology Part A: Energy Science and Research 29 1-10
[13] Khamees A K, El-Rafei A, Badra N M and Abdelaziz A Y 2017 Solution of optimal power flow using evolutionary-based algorithms International Journal of Engineering, Science and Technology 9(1) 55-68
[14] Swarup K S 2005 Genetic algorithm for optimal capacitor allocation in radial distribution systems Proceedings of the 6th WSEAS Int. Conf. on Evolutionary Computing Lisbon Portugal June 16-18, 152-159
[15] Eltamaly A M, Sayed Y, El-sayed A H M and Elghaffar A N A 2018 Optimum power flow analysis by Newton raphson method, a case study International Journal of Engineering Tome XVI 51-58
[16] Rajaei N, Ahmed M H and Salama M M A 2016 A novel newton-raphson algorithm for power flow analysis in the presence of constant current sources *IEEE/PES Transmission and Distribution Conference and Exposition (T&D) Dallas TX* 1-5

[17] Saadat H 1999 Power System Analysis *Series in Electrical and Computer Engineering* Grainger McGraw-Hill