Reduction in Transmission System Loss by Improving the Reliability of Capacitor Banks Based on Economic Optimization

Rattapol Promsith[1], Pichit Sukchareonpong[2]

Engineering Management Program, Kasetsart University
50 Ngam Wong Wan Rd, Lat Yao Chatuchak Bangkok Thailand 10900
[1]g5515550737@ku.ac.th
[2]fengpcs@ku.ac.th

Abstract- **The electrical power transferred from a power plant to the customer is transmitted through the transmission line. There will be power loss caused by power transmission through an electrical circuit with resistance. The power loss can be reduced by installation of a capacitor bank. The power bank composed of capacitor units. The capacitor banks in an electrical transfer system have a failure rates. The failure of each capacitor bank causes a higher electrical power loss. The electrical power loss can be reduced by improving the capacitor bank reliability through the proper replacement of the capacity units. The aim of this research is to find the method which provides an investment guideline by determining the appropriate location and amount of capacitor units to be replaced in order to minimize the total cost, the investment cost of the capacitor units and the cost of power loss. The proposed method is applied to IEEE 30 buses test system. The results show that the proposed method can significantly reduce the total cost of the transmission system.**

***Keywords*— Capacitor bank, Capacitor unit, Reliability, Power loss, Transmission system, Optimization**

I. Introduction

An electric power system composes of three subsystems: generation system, transmission system and distribution system. The electrical energy is transmitted from the generation system to the distribution system or end users via the transmission system through high-voltage transmission lines. However, the high-voltage transmission lines have resistance which cause energy loss. In the recent years, there is a continuing growth in the business, industry and tourism sectors. These growths cause an increasing in electricity demand. As a result, the energy loss due to the transmission of electric energy through the high-voltage transmission system increases accordingly, causing a higher electricity costs. As a result, the competitiveness of the country is decreased.

Several methods can be used to reduce the power loss in the high-voltage transmission lines. One of the most popular methods is the installation of a capacitor bank at the transmission system on the appropriate location and with the appropriate size to minimize the energy loss. However, the capacitor bank has failure rate. Whenever the capacitor bank failed, it causes a power system loss. In the recent years, the failure rate of the capacitor bank in Thailand's transmission system has been significantly increased, as shown in Table 1.

TABLE I
FAILURE RATE OF THE 69 KV CAPACITOR BANK IN THAILAND

Year	Failure rate of the capacitor bank (times/ total capacitor banks/ year)
2011	0.621
2012	0.636
2013	0.682

The capacitor unit is a device which when damaged cannot be repaired. The damage of the capacity unit causes the capacitor bank failed. The average lifespan of a capacitor unit depends on the design of the individual manufacturers and the condition of use [1]. Thus increasing the reliability of the capacitor banks can be achieved by replacing the capacitor units before the capacitor units failed.

However, improving the reliability of the capacitor bank by replacing the capacity units to the highest level require a lot of investment. In general, higher reliability requires higher investment in capacitor units' replacement but power loss can be reduced. Thus the trade off between the costs of investment and the costs power loss need to be considered. The optimal procedure to replace the capacitor units at the appropriate location with the appropriate size is to minimize the total costs of investment and the power loss costs.

The Newton-Raphson load flow analysis method can be used to evaluate the power loss under certain capacitor banks' reliability. It has been proven that the stated method is an effective, reliable, fast converges and the number of iterations for calculation do not depend on the size of the power system itself [2]. In addition, the Monte Carlo simulation technique can be used to evaluate the reliability of the complex system more efficient than the analytical methods [3].

This research presents the optimal guidelines to replace the capacitor units at the appropriate place, with the appropriate amounts. So thus the total cost of the investment and the cost of electrical power loss due to the failure of the capacitor banks are minimized.

II. Problem Formulation

A. Capacitor Banks and Reliability

A capacitor banks is composed of current limiting reactors, transformers, power circuit breakers, disconnecting switches and capacitor units, as shown in Fig. 1.

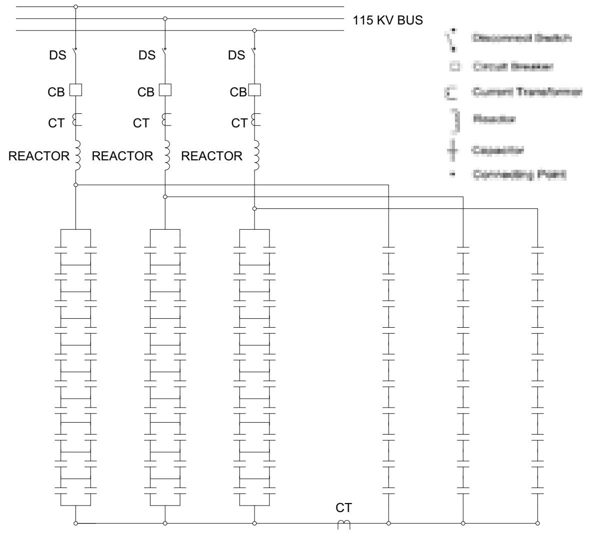

Fig. 1 Schematic diagram of a capacitor bank

When capacitor unit failed, the capacitor bank will be disconnected from the power system to prevent widespread disruption of the entire electric power system. Therefore, the transmission power losses will be increased. In general the reliability of a capacitor bank can be calculated by multiplying the reliability of each capacitor unit [4]. The calculation of the capacitor bank reliability is presented in equation (1).

$$R_s = \prod_{i=1}^{n} R_i \qquad (1)$$

Where R_s is the reliability of the capacitor bank, R_i is the reliability of each capacitor unit, and n is the number of capacitor units.

B. Power losses

The electric power transmitted through the transmission system via high-voltage transmission line. However, the high-voltage transmission lines have resistance and causes energy loss. One of the most popular power loss evaluation methods is the Newton-Raphson's load flow analysis technique. The stated technique calculates the real power, the reactive power and the power loss flowing through each transmission line as shown in equation (2):

$$P_i - jQ_i = V_i^* \sum_{n=1}^{N} Y_{in} V_n \qquad (2)$$

Where P_i is the real power flowing into bus i, Q_i is the reactive power flowing into bus i, V_i and V_n is voltage at bus i and bus n, respectively, V_i^* is the complex conjugate of the voltage at bus i, Y_{in} is a member in position i,n of the bus admittance matrix, and N is the number of buses in power systems.

In the Newton-Raphson load flow analysis technique, equation (2) will be transformed from a nonlinear equation to a linear equation using the Taylor series expansion. The computation is performed iteratively until the tolerances of the power at every point in the system are satisfied [2].

C. Objective Function

Determining the minimum total cost of the capacitor units replacement in an appropriate size and location to reduce power losses in the power transmission system can be expressed as shown in equation (3) and (4) [5].

$$TC_P = C_{CAPITAL} + \sum_{t=1}^{T} C_{LOSS,t} \qquad (3)$$

$$TC_A = \frac{TC_P \cdot i(1+i)^n}{(1+i)^n - 1} \qquad (4)$$

Where TC_P is the total cost in present value, TC_A is the total annual cost, $C_{CAPITAL}$ is the investment cost to replace the capacitor unit, C_M is the repair cost when capacitor banks failed, C_{LOSS} is the cost of power loss in the transmission system, and i is interest rate.

The power loss in the transmission system can be converted to the power loss cost as shown in equation (5):

$$C_{LOSS} = k_L P_{LOSS} \qquad (5)$$

Where k_L is the power loss cost per unit in Baht/kWh, and P_{LOSS} is power loss in the transmission system in kW.

III. Methods

A. Simulation Model for the Reliability of a Capacitor Unit

In general, the operation of a device in the power system can be represented by a two-state Markov model, up and down, as shown in Fig. 2 and Fig. 3, respectively.

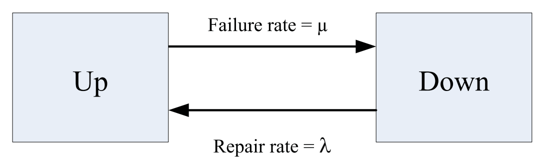

Fig. 2 A two-state Markov model

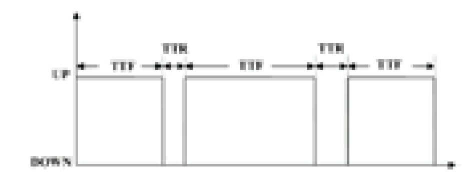

Fig. 3 An operation cycle model of a capacitor bank

The time spent in the up state before the device failed is the Time-To-Failure (TTF). The TTF can be represented by a Weibull probability distribution. The Weibull probability distribution reflects the real nature of the devices' failures rather than the exponential probability distribution [6]. The time spent in the down state is the required time to repair the device, Time-To-Repair (TTR), can generally be represented by the exponential probability distribution.

B. Monte Carlo Simulation

The Monte Carlo method can be used to simulate the devices' behaviour in the system that responds to random events. The simulation can be repeatedly performed to assess the required performances. The uniform random variable from 0 to 1 or U (0,1) has been generated to solve the problem. This research employed the Monte Carlo simulation method to each state of the capacitor units, using the developed Markov reliability model.

The relationship between the random number and the time of each state can be represented as shown in equation (6) and (7).

$$TTF = \alpha[-ln\,(1 - U_F)]^{\frac{1}{\beta}} \tag{6}$$

$$TTR = -\frac{1}{\lambda} ln(1 - U_R) \tag{7}$$

Where TTF and TTR are time-to-failure and time-to-repair generated from a random number between 0 and 1, U_F and U_R, α is the scale parameter and β is the shape parameter for the Weibull distribution, λ is the repair rate for the exponential distribution.

The power losses in the power system are calculated by the Newton-Raphson power flow analysis technique. The expected value of the electrical power loss in the power system in each capacitor bank condition is then determined.

C. Particle swarm optimization (PSO)

There are several methods that can be used to find the optimum numbers and position of the capacitor units to be replaced by the new capacitor units with higher reliability before it is failed in order to minimize the total cost. One of the effective and efficient methods is the particle swarm optimization (PSO) technique. The PSO method has been proven for it's flexibility and reliability for finding the global optimum solution [7].

The swarm is typically modelled by particles in multidimensional search space that have a position and a velocity where each particle represents a candidate solution to the optimization problem. All particles have fitness values which are evaluated by the fitness function to be optimized.

For any calculation iteration, each particle keeps the best position compared to the other particles, pbest, and the best position of particles relative to the total particle population, gbest. Each individual particle try to reposition itself- from its' present position, velocity and distance- compare with the pbest and gbest to obtain the best solution [8].

D. Procedure

The procedure of this research is shown in Fig. 4.

1) *Data Consolidates:* The average load for each customer, the parameters of the power system, the capacitor banks parameters consisting of capacitor units installed, the capacitor banks failure records, and the statistic on the time-to-repair a failed capacitor banks are collected.

2) *Analysis of the data by statistical methods:* Analysis of the time-to-failure probability distribution from the failure records and the time-to-repair probability distribution with statistical analysis is then performed.

3) *Mathematical reliability modelling of each capacitor bank:* The two-state Markov model is then developed using the time-to-failure and the time-to-repair probability distribution parameters obtained from step 2)

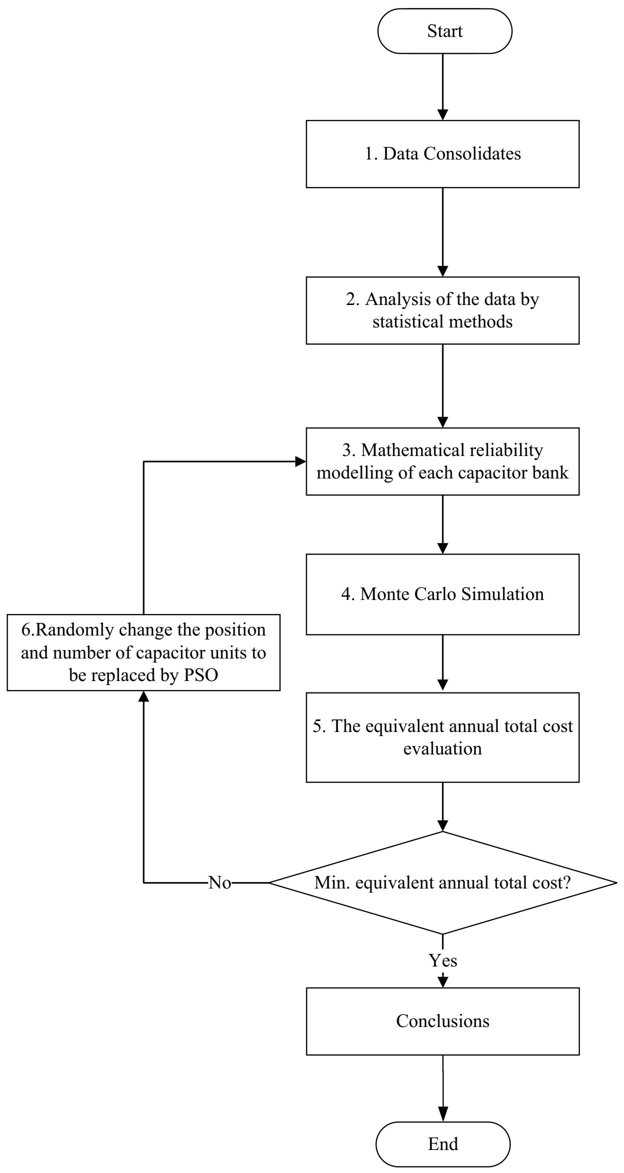

Fig. 4 Procedure of the research

4) *Monte Carlo Simulation:* The computer program used to simulate the failure events of the capacitor banks by Monte Carlo simulation has been developed to determine the state of a capacitor bank in each period.

5) *The equivalent total annual cost evaluation:* The equivalent total annual cost of the capacitor banks' state specified in step 4 is then calculated.

6) *Randomly change the position and number of capacitor units to be replaced:* The particle swarm optimization algorithm is then used to change the position and number of the capacitor units to be replaced.

7) *Repeat step 3-6:* Step 2 to step 6 are then repeated until the equivalent total annual cost is minimized. The optimum numbers and location of the replaced capacitors is obtained.

IV. Results

The purposed method is applied to the IEEE 30-bus test system, a portion of the American Electric Power System in the Midwestern, as shown in Fig. 5. The result is conformed to the study done in [2] with additional statistical information of capacitor banks as shown in Table 2 and Table 3. The cost of replacing a capacitor unit is 25,000 Bahts/unit with 10% interest rate per year and covers a study period of 25 years.

Fig. 5 The IEEE 30-bus test system

TABLE II
Capacitor Bank Data

Bus No.	Rated (Mvar)	Failure rate (λ)	Number of capacitor units	Manufacturer/ Type
10	19	8.7	50	A
24	4.3	18.5	10	B

TABLE III
Capacitor Unit Data

Manufacturer/ Type	Scale parameter (β)	Shape parameter (α)
A	1.06	916.5
B	1.20	2345.2

TABLE IV
Results

Results	Number of replaced capacitor units (Units)	Power loss in the system (MW)	Equivalent annual total cost (Bahts/year)
Before	-	17.5457	503,515,052
After	Bus no 24 = 6	17.5386	503,333,930

The results showed that the optimal guideline is to replace the capacitor units at bus No. 24 by 6 units. The transmission loss is then reduced by 7.1 kW and the equivalent total annual transmission cost is saved by 181,122 Bahts per year.

V. Conclusions

This research presents a guideline to determine the optimal location and amount of the capacitor units that should be replaced in order to minimize the total costs, the capacitor unit investment cost and the cost of energy loss due to the failure of the capacitor banks. The particle swarm optimization (PSO) technique has been employed. The required statistical data including the capacitor failure rate and the capacitor banks characteristics. The cost of power loss is determined by the Monte Carlo simulation using the Newton–Raphson load flow analysis technique.

The proposed method is applied to the IEEE 30-bus test system with additional statistical information of the capacitor banks. The results show that the proposed method provides an optimal guideline for determining the appropriate location and amounts of the capacitor units to be replaced in the electric power transmission system. The total annual cost of the electric power transmission system under studied is reduced by 181,122 Bahts/year.

References

[1] A. S. Farag, C. Wang, T. C. Cheng, G. Zheng, Y. Du, L. Hu, B. Palk, and M. Moon, III, "Failure analysis of composite dielectric of power capacitors used in distribution systems," in Coil Winding, Insulation and Electrical Manufacturing - International Conference and Exhibition, 1997, pp. 557-564.
[2] H. Saadat, Power Systems Analysis: McGraw-Hill Primis Custom, 2002.
[3] L. Goel, "Monte Carlo simulation-based reliability studies of a distribution test system," Electric Power Systems Research, vol. 54, pp. 55-65, 2000.
[4] M. P. Stephens, Productivity and Reliability-Based Maintenance Management: Pearson/Prentice Hall, 2004.
[5] I. Ziari, G. Ledwich, A. Ghosh, D. Cornforth, and M. Wishart, "Optimal allocation and sizing of capacitors to minimize the transmission line loss and to improve the voltage profile," Computers & Mathematics with Applications, vol. 60, pp. 1003-1013, 2010.
[6] J. F. L. van Casteren, M. H. J. Bollen, and M. E. Schmieg, "Reliability assessment in electrical power systems: the Weibull-Markov stochastic model," IEEE Transactions on Industry Applications, vol. 36, pp. 911-915, 2000.
[7] R. Ashok Bakkiyaraj and N. Kumarappan, "Optimal reliability planning for a composite electric power system based on Monte Carlo simulation using particle swarm optimization," International Journal of Electrical Power & Energy Systems, vol. 47, pp. 109-116, 2013.
[8] J. Kennedy and R. Eberhart, "Particle swarm optimization," in Neural Networks, 1995. Proceedings., IEEE International Conference on, 1995, pp. 1942-1948 vol.4.