OPTIMIZING REACTIVE POWER COMPENSATION IN A DISTRIBUTION SYSTEM IN CASE TAKING INTO ACCOUNT ACTUAL CAPACITORS

Nguyen Huu Hieu

University of Science and Technology - The University of Danang; nhhieu@dut.udn.vn

Abstract - The reduction of losses in Distribution System (DS) is one of the main missions of power utilities. The method of economic compensation is often considered because here capacitors are used to compensate reactive power. With the growth of load and the expansion of topology, the existing capacitors in the network are not efficient, in terms of economy. Thus, the purpose of this paper is to find the optimal locations and optimize the size of capacitors with the objective: "maximal economic profit". Here, the proposed model also considers the existing capacitors on the network. The proposed algorithm is validated by two cases which are IEEE model network-16 buses and a partial feeder of Cam Le district, Da Nang city network.

Key words - power losses; economic compensation; optimization; power; cost; profit

1. Introduction

Capacitors for reactive power are widely used in DS to reduce power losses, improve voltage, enhance power factor. These benefits depend on quantity, location, type (static or dynamic) and capacity of capacitors. Therefore, installation of capacitors must guarantee the profit from the reduction of power losses more than the cost of procurement and operation of capacitors as well as accessories.

The method of finding location, the capacity of reactive power which needs to be installed was proposed by Neagle and Samson [1]. In this study, Neagle and Samson proposed installation of capacitors for reduction of power losses with strong hypotheses: load considered as constant and equal, power lines considered as equal, the losses of power line are only considered from reactive power, neglectful of costs for installation and operation of capacitor.

With the development of computers, goals and calculation models for determination of location, the capacity of reactive power in DS are getting complicated. Therefore, there are two main methods which are being studied:(i) diversifying objective functions such as minimization of power losses, of installation cost, improvement of voltage, dispatching power, enhancement of network stability [2] and (ii) studying optimization algorithms. The issue of optimizing reactive power compensation is the optimal combination. Therefore, it is necessary to introduce an advanced optimization technique to obtain an efficient solution. The optimization technique used to solve the problem can be divided into four levels: analysis, digital programming, smart method and artificial intelligence [3].

In Vietnam, the problem of optimal reactive power compensation has been studied. In general, all studies focus on using the commercial software PSS/ADEP (CAPO) [4] to determine the location and size of capacitors, it thus can maximize the profit (the profit is the subtraction of revenue and sum of installation, operation cost of capacitors) [5]. On the other hand, some authors develop an optimization algorithm to optimize the location and the size of capacitors in DS with the goal to reduce losses only [6].

However, the characteristic of Vietnam power network is the significant growth of load (over 10%/year with big cities), leading to the fact that power network is usually upgraded and expanded. When load changes and/or power network structure changes, capacitors located at old locations are no longer suitable, thus it can not bring high profits although the capacitors still operate well. The replacement of capacitors to new locations is cheaper and brings more profit in comparision with building a new one. However, all studies just consider the optimization of location and capacity of the new capacitors for the highest economic goal.

Therefore, in this paper, the authors propose an advanced method to optimize the installation of capacitors in DS, in which the reallocation of existing capacitors are the priority. Moreover, the implemented proposed model is completely new in Matlab environment.

There are 5 sections in this paper.Section 1 is the introduction; the mathematic model (objective and constraints) is introduced in section 2. Section 3 introduces the adoption of a genetic algorithm to deal with constraints. Here, the model is validated by IEEE Network – 16 buses in comparison with the commercial software PSS/ADEP. Section 4 shows the application of the proposed model in Cam Le district, Da Nang city. Finally, the conclusion will be presented in section 5

2. Mathematical modelling

The objective is to determine the size and location of capacitors which are installed in the distribution network. In such problems, different objective functions may be defined. In this paper, the main goal is to maximize the profits cost and bring the buses voltages within the allowable limits. Therefore, to simplify the problem, the proposed model uses only the fixed capacitor which can not vary the value as SVC or TCSC.

2.1. Objective function

When determining reactive power compensation in DS, there are many proposed objective functions. Some authors propose that the objective function is to minimize active power, some propose a multi-objective function which satisfies the minimization of both active power and compensation equipment on the network. Other authors propose that the objective function is to maximize the economic efficiency when installing capacitors (the amount of money saved from the reduction of losses minus the cost of installation and operation of the equipment). This objective function is more accurate when it comes to the benefits of installing capacitors. Therefore, software for calculation and installation of capacitors like PSS/ADEPT uses this objective function [4]

$$F = (Z_1 - Z_2) \rightarrow Max \quad (1)$$

Which can be modified into:

$$F = (Z_2 - Z_1) \rightarrow Min \quad (2)$$

where:

- Z1: amount of money gained from reduction of power losses when installing capacitor.
- Z2: calculating cost when installing and operating capacitor (in one year unit)

$$Z_1 = Ne\int_0^T \left(c_P.\delta P + c_Q.\delta Q\right)dt \quad (3)$$

$$Z_2 = Q_c.\left(K_c^* + N_e.c_{om}\right) \quad (4)$$

In which:

- δP : amount of active power losses reduced after installing capacitor (kW)

- δQ : amount of reactive power losses reduced after installing capacitor (KVAr)

- C_P: cost per unit for active power losses (đ/kWh) (this value can change according to time within a day)

- C_Q: cost per unit for reactive power losses (đ/kVArh)

- Q_c: compensation capacity needed (kVAr)

- K_c^* : cost per unit for installing compensation capacity (đ/kVAr)

- c_{om}: cost for operation and maintenance of capacitor (đ/kVAr/year)

- Ne: equivalent time quantity

$$Ne = \sum_{n=1}^{N}\left(\frac{1+i}{1+r}\right)^n \quad (5)$$

where:

- N: Evalution period (year).

- i: Inflation rate (pu/yr).

- r: Discount rate (pu/yr).

Currently, cost for reactive power losses considered is negligible. Therefore, Z_1 function (1) can be rewritten:

$$Z_1 = Ne\int_0^T c_P.\delta P dt = Ne.c_P.\int_0^T \delta P dt$$

$$= Ne.\int_0^T \left(c_P.\Delta P_b - c_P.\Delta P_a\right)dt = Ne.\left(Z_{1b} - \int_0^T \Delta P_a dt\right) \quad (6)$$

With:

- $\Delta P_b, \Delta P_a$: The losses before and after installing capacitor

- *Z_{1b}:* The money which is lost due to losses before installing capacitor.

As mentioned above, the purpose of this study is to calculate the compensation of reactive power, considering the replacement of existing capacitor in the topology. From the objective function developed in (1) with added value of placing capacitor. The new objective function is determined as follows:

$$F_n = (Z_{2n} - Z_1) \rightarrow Min \quad (7)$$

With Z_2 being changed:

$$Z_{2n} = Z_{2nc} + Z_{2d} + Z_{2om} \quad (8)$$

- Z_{2nc}: cost for newly installing capacitor:

$$Z_{2nc} = Q_{cn}.K_c^* \quad (9)$$

- Z_{2d}: cost for placing capacitor

$$Z_{2d} = Q_{cd}.K_d^* \quad (10)$$

K_d^* : cost per unit for placing capacitor (đ/kVAr)

- Z_{2om}: cost for operation of capacitor

$$Z_{2om} = Q_c.N_e.c_{om} \quad (11)$$

It can be seen that compensation capacity needed in the objective function (4) is determined clearly in the new function (8) into three different quantities: the compensation of capacity needed Q_{cn} compensation capacity placed Q_{cd} and compensation capacity fixed Q_{cf}.

Notice that the total existing compensation capacity in the studied network has value $Q_{cd} + Q_{cf}$.

2.2. Variable

Variable in this problem is the location and size of capacitor which needs to be newly installed as well as replaced.

2.3. Constraint

In solving the optimal capacitor placement problem, the magnitude of the voltage at each bus should be kept within its limits as follows:

$$U_{min} \le U_i \le U_{max} \quad (12)$$

Where:

- U_i: voltage magnitude at bus i,
- U_{min}: minimum voltage limit,
- U_{max}: maximum voltage limit.

2.4. Calculation of voltage and power losses

To determine the value of the objective function as well as constraints, the value of bus voltage as well as power losses need to be determined. In the previous study of DS, there are series and loop network; therefore, the proposed model uses the Newton-Raphson method to calculate the load flow.

The losses on the network equal total losses on power lines:

$$\Delta P = \sum_{i \neq j} \Delta P_{ij} \quad (13)$$

The losses on power lines ij is determined

$$\Delta P_{ij} = \left| real\left[U_i.\left(I_i\right)^* - U_j.\left(I_j\right)^*\right]\right| \quad (14)$$

Where U_i, I_i, U_j and I_j are voltages and currents at the from bus i and to bus j.

3. Algorithm and program

3.1. Algorithm

In this study, the evolution algorithm ES is applied. The evolution algorithm ES is an optimization algorithm which stems from the theory of evolution in biology. This algorithm was developed by Schwefel et Rechenberg [7].

This paper only briefly introduces mutation process because this is an advantage of the algorithm and there are many studies on mutation process which are applied in the field of optimal design of the network.

During mutation process, each individual is characterized by its object variables x(i) and an associated standard deviation $\sigma(i)$. Children ($x_c(i)$,$\sigma_c(i)$) are created from their parents ($x_p(i)$,$\sigma_p(i)$) using the following rule.

$$\begin{cases} \sigma_c(i) = \sigma_p(i)\exp(\tau' N(0,1) + \tau N_i(0,1)) \\ x_c(i) = x_p(i) + \sigma_c(i) N_i(0,1) \end{cases} \quad (15)$$

Where $N(0,1)$ denotes a normally distributed random number with mean 0 and standard deviation 1.

$N_i(0,1)$ indicates that the random number is generated anew for each value of i. The factors τ and τ' are commonly set to $(2n^{1/2})^{-1/2}$ and $(2n)^{-1/2}$, n denoting the number of design variables. The application of this rule leads to an automatic adaptation of the strategy control parameters (i.e. standard deviations) during the search.

3.2. Management of constraints

In fact, the ES can not optimally calculate inequality constraints. Therefore, this study proposes changing objective functions for management of constraints. To conduct this, studies propose using penalty function, after reviewing many different methods. The idea of the method is as follows [8]:

- If only one option satisfies constraints, the option which is satisfying constraints will be better than options which are not satisfying constraints.
- If both satisfy or can not satisfy constraints, the option with better fitness is better.

Therefore, to manage constraints which are defined at item (12), the objective function (7) is modified as follows:

$$F_{mod} = \begin{cases} F_n & \text{if bus voltage satisfies condition (12)} \\ F_{nmax} + \sum_{k=1}^{m}\left[\min(0, U_i - U_{min})\right]^2 + \sum_{k=1}^{m}\left[\max(0, U_i - U_{max})\right]^2 & \text{Otherwise} \end{cases} \quad (13)$$

With F_{nmax}: the maximal value which objective function F_n can reach.

3.3. Program

The program for optimal calculation of reactive power compensation is written in Matlab environment with the integration of Matpower [9] to calculate current as well as voltages at buses, branches.

3.4. Verification of the proposed model

To verify the proposed model, the algorithm and program for optimization of operation are run by IEEE power network -16 buses [10]. This network includes 3 source buses, 13 load buses, rated voltage 11kV and total load power 28.7 MW (Figure 1) is used. Power line parameter, as well as, load demand can be found at [10].

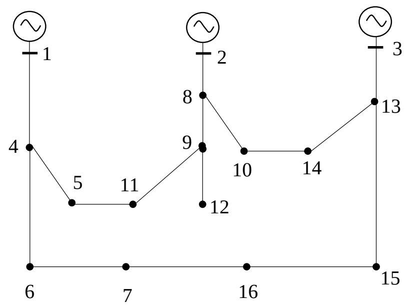

Figure 1. *IEEE model network-16 buses*

The optimal operation of the IEEE-16 buses model is studied numerously such as [10], [11]. However, it just considers the reduction of power losses when installing capacitors. Therefore, the commercial software PSS/ADEPT is used to compare with the proposed model. To compatible with software PSS/ADEPT, the cost of placement of capacitors is put extremely high so that the software does not take the placement of capacitor, but new installation into account. It is hypothesized that the network is used all time to maximize power, the voltage at source bus is 1.0 pu.

The value of economic goal is as follows:

C_P= 1958 VND/kW C_Q= 0 VND/ kVAr

K_c^* = 211 130 VND/kVAr i = 0.05

K_d^* = 10^{20}VND/kVAr r = 0.12

c_{om} =6334 VND/kVAr /year N= 8 years

The capacity of each set of capacitor: 300kVAr

Constraint: $0.95 \le U_i \le 1.05$ (pu)

Table 1. *Comparision of the results between the proposed method with software PSS/ADEPT of IEEE model network-16 buses without condensator move*

	PSS/ ADEPT	**The proposed method**
Qb (MVAr)	13.5	13.2
ΔP_b (kW)	542	542
ΔP_a (kW)	412	412
Z_1(billion dong)	13.488	13.486
Z_2 (or Z_{2n}) (billion dong)	3.143	3.073
The profit gained (billion dong)	**10.345**	**10.413**

Table 2. *Compensation capacity (MVAr) at buses of IEE model network-16 buses without condensator move.*

Bus	**1,2,3**	**4**	**5**	**6**	**7**	**8**	**9**
PSS/ADEPT	0	0	1.5	0.9	0.3	1.8	3.3
The proposed method	0	0.3	1.5	0.9	0.3	1.8	3.0
Bus	**10**	**11**	**12**	**13**	**14**	**15**	**16**
PSS/ADEPT	0.9	0.3	2.1	0	0.6	0.9	0.9
The proposed method	0.9	0.0	2.1	0	0.6	0.9	0.9

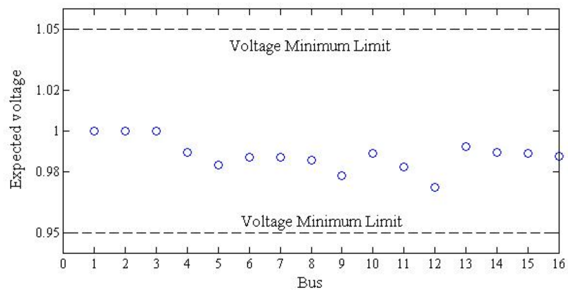

Figure 2. *Voltage at buses*

Voltage at buses when calculating with the proposed method with requirements

The results obtained from Table 1 and 2 show that: software PSS/ADEPT enables installation of more compensation capacity than the proposed method (0.3 MVAr) but the losses are equal. Therefore, the profit of the proposed method is higher than the one from PSS/ADEPT which is 0.068 billionVND (10.413 billion VND for the proposed model and 10.345 billion VND for PSS/ADEPT). However, in general, the money gained by the installation of capacitors of the two methods is almost the same, with the difference of 0.6%. Therefore, the proposed method, as well as, the proposed program is acceptable.

ApplicationThe proposed method is calculated to determine the optimal reactive power compensation of partial feeder 473-E12 of Cam Le district, Da Nang city. The diagram and data of buses are given in Figure 3 and Table 3.

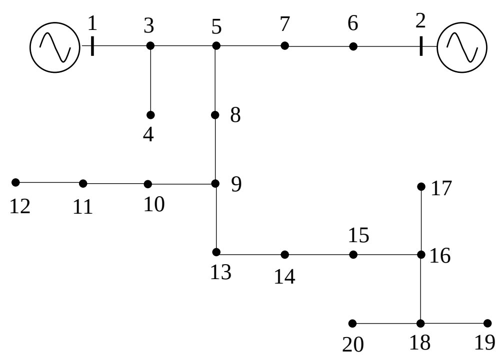

Figure 3. *Power network of partial feeder 473-E12*

Table 3. *Network parameter of partial feeder 473-E12*

Power line from bus to bus	**Resis-tance (pu)**	**Reac-tance (pu)**	**Active power at terminal bus of power line (MW)**	**Reactive power at terminal bus of power line (MVAr)**
1-3	0.02727	0.062	0	0
3-4	0.1033	0.073	0.04	0.00564
3-5	0.02727	0.062	0	0
2-6	0.02727	0.062	0	0
6-7	0.02727	0.062	0.2744	0.0546
7-5	0.02727	0.062	0	0
5-8	0.02727	0.062	0	0
8-9	0.02727	0.062	0	0
9-10	0.05785	0.07	0	0
10-11	0.05787	0.07	0.2033	0.087
11-12	0.08	0.0717	3.289	1.122
9-13	0.05578	0.0665	0.172	0.0537
13-14	0.05578	0.0665	0	0
14-15	0.05578	0.0665	0	0
15-16	0.05578	0.0665	0.205	0.0408
16-17	0.07	0.068	0.986	0.4089
16-18	0.05578	0.0665	0	0
18-19	0.05785	0.07	2.0448	0.7516
18-20	0.05785	0.07	2.0448	0.7516

In the feeder, there are capacitors with capacity: 1.2MVAr located at buses 6, 8, 15 and 16. In this part, the authors study the replacement of the existing capacitors as well as the additional installation of other capacitors to maximize the economy. Hypothetically, loads on this feeder are used all time to maximize power, meanwhile, the source voltage is 1.05 pu. The value of economic goal is as section 3.4 and cost for placement of a capacitor is K_d^* =50 000 VND/kVAr. Time to maximize losses is 2500h. Comparing the current software and the proposed method, capacitors in feeder are removed in case of the current software.

After calculating, the results obtained are as follows:

Table 4. *Comparision of the results between the proposed method with current software.of partial feeder 473-E12*

	Current software	**Current software with location modification**	**The proposed method**
Qb (MVAr)	1,5	1,5	1,8
Qblm (MVAr)	0.0	0.3	0.6
Qbdc (MVAr)	1.5	1.2	1,2
ΔP_b (kW)	266	266	266
ΔP_a (kW)	240	240	230
Z_1 (million dong)	756	756	1042
Z_{2n} (billion dong)	374	181	302
The money for new installation (million dong) Z_{2nc}	316	63	127
The money for placement (million dong) Z_{2d}	NA	60	60
Cost for operatioin and maintenance (million dong) Z_{2om}	95	95	115
The profit gained (million dong)	**382**	**575**	**740**

Table 5. *Compensation capacity (MVAr) at buses ofpartial feeder 473-E12finding byproposed method*

Bus	1,2,3,4,5,6, 7,8, 9,10,11	12	13,14,15,16, 17,18,19	20
Compensation capacity (MVAr)	0	0.9	0	0.9

As presented in the introduction, the current software cannot calculate the placement of electric equipment. Therefore, with results obtained from this software (location and capacitor capacity), costs for installation and placement will be calculated with formula (8,9,10 and 11) with the hypothesis that the amount of reactive power 1.2 MVAr is moved from existing location in the network to new location. The obtained results are displayed in column "Actual Software with location modification" in table…

From Table 5, there are the following comments: the amount of reactive power compensation from the proposed method is higher than the result of current software: 0.3 MVAr. Therefore, the losses of the proposed method are smaller. The proposed method has a higher profit than the method from the current software.

The reason for the difference is that software considers capacitors installed as new equipment, hence the more capacitors are installed the less profit is obtained. In fact, there is 0.6 MVAr which is newly installed, 1.2 MVAr is from the replacement of capacitors from buses to buses. The proposed method takes this factor into account, therefore it has found the solution with greater compensation capacity, which reduces more when it comes to losses.

4. Conclusion

The reduction of loss in power system is one of the main missions of Vietnam power utilities. The paper studies the proposal to reallocate the placement of existing capacitors in the network when conducting economic compensation of reactive power in the distribution network.

From the results, the proposed model finds the measure to compensate where it provides higher profit and it is more practical in the network in Da Nang.

However, this is just the first step in this study.It is necessary to use strong hypotheses such as using the time for maximal losses without considering losses that vary by time. For the further research, the authors will continue to develop the objective function, forecast long-term load diagram (over one year) to determine the optimal location, the size of capacitors, avoiding rapid change and installation of capacitors.

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