ICOACT 2018

by Syahrul Mustafa

Submission date: 27-Sep-2022 09:22AM (UTC-0400)
Submission ID: 1910357170
File name: mustafa2018.pdf (408.91K)
Word count: 4912
Character count: 25085

Optimal capacitor placement and economic analysis for reactive power compensation to improve system's efficiency at Bosowa Cement Industry, Maros

Syahrul Mustafa[1,2,3], Ardiaty Arief[1,2] and Muhammad Bachtiar Nappu[1,2]

[1]Centre for Research and Development on Energy and Electricity, Hasanuddin University, Makassar 90245, Indonesia,
[2]Department of Electrical Engineering, Faculty of Engineering, Hasanuddin University, Gowa 92119, Indonesia
[3]Department of Electrical Engineering, Bosowa Polytechnic, Makassar 90241, Indonesia
E-mail: Syahrul.Mustafa88@gmail.com

***Abstract*— Good electric power system must have good power quality, including small power losses and voltage value at all buses do not exceed the tolerance limit. The tolerable limit of allowable voltage value is between 0.95 to 1.05 per unit. In this research, the quality of Bosowa Cement Industry, Maros' power system will be improved by using capacitors banks. This research will focus on optimum capacitor location determination and size using Genetic Algorithm (GA) to enhance low voltage and minimize power losses. It presents a model for simultaneously allocating bank capacitors for reactive power compensation in power system with a significant amount of dynamic rotating machine load. This research conducts several simulation of power flow before and after installation, optimization of capacitor placement with different bus candidates, to determine the location, number and capacity of capacitor then its economic analysis. The selection of a voltage dropped bus as a candidate only requires 7.400 kVar of 73 capacitor bank units with the value of each capacitor bank 100 kVar which aims to improve the quality of power at Bosowa Cement Industry, Maros, which is installed on several buses. Installation of capacitors can reduce power losses in the system from 901 kW to 801 kW.**

***Keywords:* Optimal capacitor placement, power factor correction, power losses, genetic algorithm**

I. Introduction

The continuity of power supply in a power system is important and can be easily maintained, however sometimes it may not be sufficient to retain the voltage stability in distribution network. Low voltage can happen in every part of the systems and it will change as the load flow [1][2]. In electrical power distribution system, bus voltage can decrease when power flows from electrical substation directly to consumers [3]. Especially since most of the power losses occur in the distribution system that is accounted for 13% of the total power generated [4]–[9]. One of the strategies to enhance the voltage profile of a power system is by placing the capacitors in the accurate location at distribution system.

Peak load may cause the demand of reactive power increases and can be bigger than the amount that are able to be provided by the system. One of the methods to overcome this issue in distribution system is by injecting reactive power in the system. The supply of reactive power in distribution network can be done by placing capacitor bank at the most sensitive point [10][11]. It is possible to obtain the system enhancement with power reactive addition, hence resulting in better voltage profile and minimize the power losses. Additionally, it can help deferring the network additional transmission network and avoiding system's congestion [12][13].

Capacitor bank allocation is in accordance with the important problems in electrical power distribution planning. They consist of arrangement of placement and each dimensions of capacitor bank in electrical power distribution with purpose to minimize the voltage distortion, distribution losses and loss of load. Characteristic of capacitor bank allocation research has the highest complexity to search for the optimal solution [14][15]. Optimal reactive power flow is changing the variable setting which is affecting reactive power flow so that power loss in transmission system turn into minimum [16].

The purposes of capacitor installation in distribution system are for enhancing the voltage regulation, improving power factor, reactive power compensation, increasing line capacity and decreasing electrical power losses [10][17]. It is a very important thing because if the analysis or calculation is incorrect, then it will affect the system. For example, if the capacitor dimension is installed more than it should have been, then it can cause overvoltage condition (accepted voltage is higher than it should be). In the distribution system design, reactive power compensation studies have an important role to improve the profile of the voltage as well as minimize the cost of compensation [18]–[20]. Furthermore, from the economic viewpoint, it is more advantageous for the utility if the capacitor installed rather than if they have to pay for power losses cost. although Ga is commonly used in capacitor placement as in[10], [21], [22] However, most of the research is simulating on most static load modeling, not focusing on systems with dominant motor loads. Therefore, the novelty of this study is the application of GA in determining the placement of capacitors in power systems with significant motor loads, such as the bosowa

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cement maros industry. Moreover, mostly in other studies there is no discussion of the economic impact of capasitor installation.

Bosowa Cement Industry, Maros is one of the largest cement factories in Indonesia, which is located in Maros Regency, South Sulawesi Province. Bosowa Cement Industry, Maros has problem with their power quality in electrical system, caused by the use of numerous of large motors for production process. One of the problems is the decreasing of power factor value whose effect is the excessive consumption power [23]. Therefore, the system needs to be analyzed to find solutions for their electrical system problem to minimize the potential impact that may arise. This research will focus on the determination of optimal location and capacitor optimum size by using power line and Genetic Algorithm (GA) to enhance low voltage and minimize power losses. The results are intended to be utilized as consideration in economic side. It presents a model to allocate simultaneous of capacitor bank for reactive power compensation with significant amount of dynamic load of power system.

II. Problems Formulations

A. Capacitor Placement

Function of optimal capacitor placement determination in an electrical power system is to minimize reactive power compensation and power losses in transmission lines. First step in this research is calculating power flow in electrical power system before it is compensated by using Newton-Raphson method. The purpose of this power flow analysis is find out the magnitude of voltage profile and power losses in electrical power system. After the power flow analysis is done and voltage magnitude and power losses are obtained, then the location and magnitude of capacitor value are determined by using Genetic Algorithm method. Capacitor is an equipment which produces reactive power at a point where the capacitor installed [24] and is installed parallel along the distribution line that control the voltage and increase the voltage profile on every bus. The capacitor should be installed in parallel with load which is having reduced power factor because capacitor is the source of some or all reactive power needed [25][17]. Capacitor decreases current line which is flowing into load and also decreasing voltage drop as in illustrated in Fig. 1.

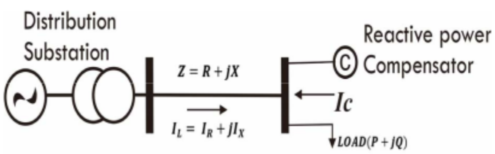

Fig. 1. Capacitor Installed in Parallel [25]

$$\Delta Vd = I_L \, . Z \quad (1)$$
$$\Delta Vd = I_R . R + jI_x . X_L \quad (2)$$

Voltage drop after capacitor installed in parallel:

$$\Delta Vd = I_R . R + j\, I_X . X_L - jI_C . X_L \quad (3)$$

Where I_L is current lines, Z is impedance, I_C is current from capacitor and ΔVd is voltage drop

B. Objective Functions of Economic Analysis

After the optimal capacitor placement, then the amount of bank capacitors which are needed to improve voltage quality in electrical system of Bosowa Cement Industry, Maros are obtained. The next step is economic analysis to find out estimation cost of bank capacitor installment. The purchase of bank capacitor should be made as minimum as possible, which will determine the cost estimation installation of bank capacitors. There are four aspects to be considered when purchasing the bank capacitor, which are [26]–[28]:

1. Installation cost of bank capacitor,
2. Purchase cost of bank capacitor,
3. Operational cost of bank capacitor (include maintenance and depreciation cost), and
4. Active power losses cost.

The mathematical equations for objective function of bank capacitor cost are:

$$Min\_Cost = \sum_{i=1}^{N_{Bus}} (X_i C_{0i} + Q_{0i} C_{1i} + C_{21} T) + C_2 T_i \sum_{i=1}^{N_{Load}} P_l^i \quad (4)$$

Where:

N_{bus} = Candidate bus number
X_i = 0/1,0 means no activate placement capacitor bank on bus i
C_{0i} = Installation cost of capacitor bank/unit
C_{1i} = Capacitor bank price/kVar
C_{2i} = Maintenance cost of capacitor bank/year
Q_{ci} = Capacitor bank capacity (kVAr)
T = Planning period (year)
C_2 = Losses cost/kWh,in $/kWh
N_{load} = Load level (Maximum, Medium, or average)
T_i = Load duration on level i (hour)
P_1 = Total of system losses load level i

C. Application of Genetic Algorithm (GA)

Genetic Algorithm (GA) is based on organism genetic development process in natural population, that slowly follow the principal nature selection, where the strongest individual will survive [29]. The algorithm works with a population of individuals, where each individual represents a possible solution to the existing problem. Individuals represent a fitness value which will be used to find out best solution [30][31]. GA method can help solve various problems in power system. Coding in GA generally in binary that become a string which compiling gens is forming the chromosomes. Then it will find out solution and best fitness according to the objective function that is used. Parameters used inside GA is generation (maximum amount of generations), *popsize* (amount of population), probability of crossover and mutation. Commonly used genetic parameters include population size (N), crossover probability (Pc), and mutation probability (Pm). The results of genetic operation will be evaluated where the objective function is used to obtain the chromosome included in iteration process. Process of GA evolution will stop when it achieves the specified generation [32].

D. Implementation of GA

Implementation of GA in this research is to determine the bus where the capacitors will be installed. The determination of parallel capacitor location and number their size will installed and it is expected to obtain optimal improvement in system. Optimal in this work refers to enhancing voltage drop in system power losses decreased while the capacitors installed are as minimum as possible. The tested system is 42-bus electrical system at Bosowa Cement Industry, Maros, Southern Sulawesi. To implement GA in finding capacitor placement in the system, the chromosome identifies location and size of capacitors. Chromosome represents every injection of reactive power into system. Therefore the chromosome used consist of 42 gens, which following the number of buses in the tested system. The optimization process using Genetic Algorithm (GA) can be seen in figure 3.

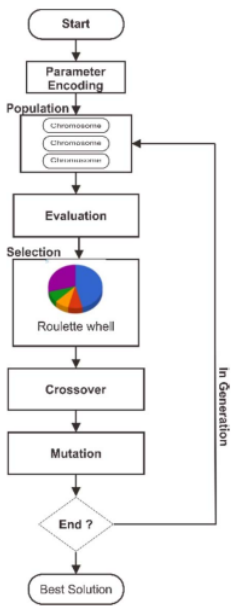

Fig. 2. Flowchart of the Genetic Algorithm Program [33]

E. Parameter and Objective Function

There are two parameters in this research, in Fig.2 indicates they are location and size of capacitor. Gen in capacitor contains two values. First value is determination of the chromosome location, which is number 0 or 1. Number 0 is to identify absence of capacitor in that bus whereas number 1 is to identify installed capacitor on that bus. Then the second value contains information about the size of capacitor. This value is in integer value by multiplication of 10 according to bank capacitor used, 10MVAr. Gen value contains of 0 until 400 MVAr.

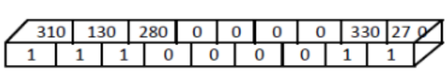

Fig. 3. Chromosome Model on a System [33]

After the number of gen value in chromosome are determined, then the reliability needs to be tested. Does the chromosome can repair the electrical system or not? Chromosome contains information of location and size of injected reactive power on the bus system. The testing of chromosome value is the objective function. The objective function used is power losses, where the formula is written below:

$$Min\ F = \boldsymbol{S_{loss}}$$

$$= \sum_{i=1}^{N} \sum_{i=1(j<i)}^{N} |V_i V_j Y_{ij}| \angle\theta_{ij} + \delta_j - \delta_i \quad (5)$$

$\boldsymbol{S_{loss}}$ is the total network loses calculated using the Newton-Raphson power flow method

$$P_i = \sum_{k=1}^{n} [V_i V_k Y_{ik}] \cos(\delta_i - \delta_k - \theta_{ik}) \quad (6)$$

$$Q_i = \sum_{k=1}^{n} [V_i V_k Y_{ik}] \sin(\delta_i - \delta_k - \theta_{ik}) \quad (7)$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (8)$$

ΔP = Difference in net power injection off

ΔQ =Difference in net reactive power injection

$\Delta\delta$ =Vector of phase angle correction with voltage.

$\Delta|V|$ =Vector correction of voltage magnitude

H, L, M, N are the diagonal and diagonal elements of the Jacobian submatrix formed by defining equations (6) and (7).

$$H_{ik} = \frac{\partial P_i}{\partial \delta_k} \qquad N_{ik} = \frac{\partial P_i}{\partial |V_k|}$$

$$M_{ik} = \frac{\partial Q_i}{\partial \delta_k} \qquad L_{ik} = \frac{\partial Q_i}{\partial |V_k|}$$

The limit used in GA process is voltage. The voltage limit should in allowed tolerance [34], [35]:

$$V^{Min} \leq V_i \leq V^{Maks} \qquad For\ \ i = 1, \dots \dots \dots n \quad (9)$$

Where, i is bus number, V^{Min} is value 0.95 pu and V^{Maks} is value 1.05 pu

III. Results And Discussions

A. System Data

In this study the system tested is a 42-bus system of Bosowa Cement Industry, Maros which only consists of two bus types; ie bus 1 is a swing bus and the rest of the other buses are load buses. Single line diagram of the tested system can be seen in Fig. 4. From the data obtained, power flow study is conducted to compare between system's performance before injection of

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reactive power in the form of capacitor bank where location and size of capacitor bank are determined by using method GA Optimization.

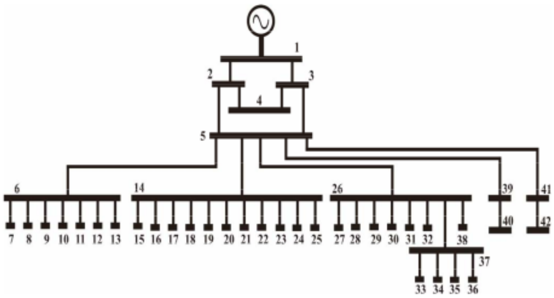

Fig 4. Single Line Diagram of Electrical System in Bosowa Cement Industry, Maros

B. *The Calculation Result Initial Condition of System*

In Table I Information According to the load flow analysis of the program that runs with Newton Raphson Method, there are several buses whose voltage is above the standard limit of 5 % of the reference voltage. It does not meet the allowed standard voltage limits and needs to be upgraded. This system can be increased through the addition of bank capacitors in buses calculated using GA. The optimal capacitor placement results from this case study can be seen in Table II.

TABEL 1. CALCULATION RESULTS OF POWER FLOW ANALYSIS BEFORE INTEGRATION OF CAPACITOR BANK

BUS ID	KV	Volt (%)	Load		BUS ID	KV	Volt (%)	Load	
			MW	MVar				MW	MVar
1	150	100	54.2	-8.2	22	11	101.25	0.748	0.342
2	11	101	27.1	-6.2	23	11	101.25	0.748	0.342
3	11	101	27.1	-6.2	24	0.7	100	2.231	0.896
4	0.4	101	0	0	25	0.7	100	2.235	0.906
5	11	101	54.23	-12.4	26	11	101.25	20.4	9.8
6	11	101	14.3	7.2	27	0.4	100	0.805	0.309
7	0.4	94.2	2.230	1.254	28	0.4	94.5	1.822	1.122
8	0.4	94.1	2.816	1.604	29	11	101.25	3.498	1.385
9	11	101	0.482	0.203	30	11	101.25	3.498	1.385
10	11	101	1.408	0.579	31	0.7	100	0.429	0.188
11	11	101	5.813	2.262	32	11	100	5.287	2.065
12	11	101	0.908	0.375	33	0.4	94.2	1.486	0.880
13	0.69	100	0.400	0.186	34	11	101.25	0.482	0.221
14	11	101	14.7	7.5	35	11	101.25	0.376	0.174
15	0.4	94.1	1,087	0.650	36	0.4	93.8	0.968	0.555
16	0.4	94.0	1,116	0.671	37	11	101.25	3.5	2
17	0.69	94.3	1,000	0.620	38	0.4	93.5	1.325	0.760
18	0.69	100	1,332	0.601	39	11	101.25	0.03	0.01
19	11	101	0.759	0.315	40	0.4	101.25	0.03	0.01
20	0.66	105	0.855	0.354	41	11	101.25	1.9	1.2
21	0.4	94.2	2.042	1.188	42	04	93.3	1.761	1.013

In Table II, it is shown that the total capacitors that should be installed to improve the system voltage are 73 units at 11 buses. The total capacitor's capacity for all the 11 buses is 7.400 kVar. By referring to the results of the calculation of power flow after the installation of the capacitor, the voltage profile on the system can be back to normal situation.

TABEL II. OCP RESULTS FOR BUS CANDIDATES AND NUMBER OF BANKS IN POWER DISTRIBUTION NETWORK AT BOSOWA CEMENT INDUSTRY, MAROS

Bus ID	Voltage Before OCP (%)	Voltage After OCP (%)	Rated		Total Capacitor	Total KVar
			Kvar/Bank	KV		
7	94.2	97.3	100.0	0.4	9	900
8	94.1	96	100.0	0.4	2	200
15	94.1	97.9	100.0	0.4	6	600
16	94.0	97.8	100.0	0.4	8	800
17	93.4	100.9	100.0	0.7	7	700
21	94.2	98.1	100.0	0.4	8	800
28	94.5	98.2	100.0	0.4	7	700
33	94.2	97.1	100.0	0.4	5	500
36	93.8	97.1	100.0	0.4	8	800
38	93.5	97	100.0	0.4	6	600
42	93.3	97.4	100.0	0.4	8	800
Total					73	7400

This means the capacitor can help to improve the system voltage back to the standard and also reduce the power system's losses. The voltage after capacitor installation is different for each simulation performed. The simulation results of the power flow study show no longer red buses like the previous condition before the integration of capacitor. The entire buses color are black which indicates that the system is in a normal state and there is no significant voltage drop.

C. *Comparison of simulation results before and after addition of capacitor bank in system*

Based on the calculation of the Newton-Raphson power flow program, the addition of capacitor bank in the system can reduce the power loss and also improve the system voltage so that they are between the tolerance limit as shown in Fig. 5.

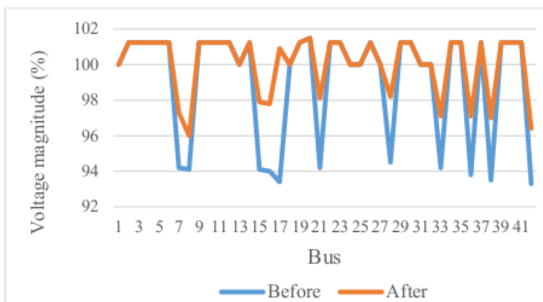

Fig.5. The system bus voltage comparison chart before and after the Bank Added 42 Bus Capacitors

By seeing from the results of all the graphs in Fig.5, the voltage profile after the installation of the capacitor bank improved better than before the installation of capacitors bank. After the installation of the capacitor bank, the voltage range is between 0.95 p.u - 1.05 p.u. After installation of this capacitor bank also resulted in the reduction of power loss in the system due to reduced reactive power supplied from the source, then the active power also decreased and the cost decreases. Installation of the capacitor will improve the power factor so that by itself reduces the amount of reactive power supplied from the source. Table III compares total power losses with and without capacitor.

TABEL III. COMPARISON OF TOTAL POWER LOSSES

	Active Power Losses (MW)	Reactive Power Losses (MVar)
Without Capacitor	0.902	18.135
With Capacitor	0.801	12.778

D. Economic analysis

After the analysis of capacitor mounting is done, then the number of capacitor bank needed to improve the quality of voltage in the electricity system of Bosowa Cement Industry Maros are obtained. Furthermore, economic analysis is needed to see the estimated cost of installing the bank capacitor which is shown by Table IV.

TABEL IV. THE COST OF INSTALLING A BANK CAPACITOR

Bus id	Rated		Total capacitor	Cost ($)			
	Kvar/ bank	Kv		Total kvar	Installation	Purchase	Oper./year
7	100	0.4	9	900	600	9000	900
8	100	0.4	2	200	600	2000	200
15	100	0.4	6	600	600	6000	600
16	100	0.4	8	800	600	8000	800
17	100	0.69	7	900	600	9000	900
21	100	0.4	8	800	600	8000	800
28	100	0.4	7	700	600	7000	700
33	100	0.4	5	500	600	5000	500
36	100	0.4	8	800	600	8000	800
38	100	0.4	6	600	600	6000	600
42	100	0.4	8	800	600	8000	800
Total				7600	6600	76000	7600

Based on Table IV, the total cost required for installation capacitor bank is US $ 90,200.00. Based on the total price, then the break even point can be determined, which is the point where the company gets back the cost incurred for the installation of capacitors and starts to gain profits. One of the advantages that company gets with the installation of capacitors is the reduction of power losses in the system. Installation of the capacitor reduces the initial power losses from 902 kW to 801 kW that can be seen in Table III. Fig. 6 informs the profit of Bosowa Cement Industry with capacitor placement internal of network losses. In connection with the loss of power loss will automatically reduce maintenance cost and this will affect the profit each year.

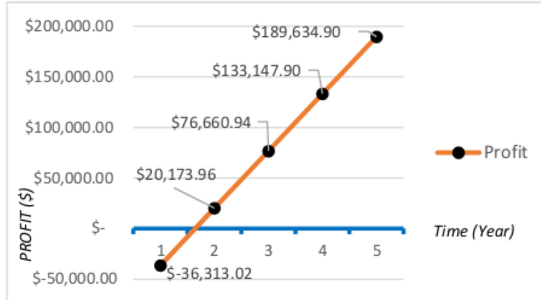

Fig 6. Profit during planning period in Bosowa Cement Industry, Maros

As can be seen from Fig. 6, the installation of capacitors at Bosowa Cement Industry will achieve its break even point to restore installation cost in less than 2 (two) years. This means that Bosowa Cement Industry Maros will benefit from the installation of this capacitors in the 2nd year.

IV. CONCLUSIONS

Based on the result of power flow analysis before placement of capacitor bank for peak load conditions, the system voltage value of Bosowa Cement Industry, Maros is below 95% of nominal voltage. To improve the power quality of Bosowa Cement Industry, Maros, it is required 7.400 kVar of 73 units of capacitor bank with value of each 100 kVar, where the locations of the capacitor placement are Bus 7, Bus 8, Bus 15, Bus 16, Bus 17, Bus 21, Bus 28, Bus 33, Bus 36, Bus 38, and Bus 42. The calculation process to determine the location and size of the capacitor employs GA method. Installation of bank capacitor reduces power losses in the system. In the simulation where the bus that experienced a voltage drop used as a bus candidate obtained reduced system losses which initially amounted of 902 kW decrease to 801 kW. Results (capacity release, total generation, loading, demand, power losses, number of capacitor banks, costs and annual benefits) are obtained and analyzed. In addition, economic factors are also taken into consideration and would be beneficial to future studies of the distribution system.

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