Optimal Placements and Sizes of Capacitor Banks for Voltage Support and Minizing Total Cost

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***Abstract*: This paper presents a method to determine optimal placements and sizes for capacitor banks using constrains about bus voltage and cost function based on the OCP tool. The constrains are considered in three cases, including the limitation of rated compensation value, no compensated limitation of rated value and assigned some buses to compensate. This new approach can help dispatchers evaluate all information about the grid and give suggestions about the compensated process when compared to other cases. Above proposes were applied into a 35 kV grid and simulated on the ETAP software. Simulation results showed optimal placements and rated sizes for capacitor banks very detailed. After implementing capacitors, voltage values at all buses were in allowable range and cost function was minimum. Simulation results provided were also provided some additional information such as power losses in whole grid, installation and operation cost, loss reduction saving, yearly profit, accumulative profit in whole planning period to have total evaluation about the compensation problem.**

***Index Terms*: Capacitor bank, Compensation, ETAP software, Optimal placement, Optimal size, Optimal cost, Voltage quality.**

I. INTRODUCTION

Many researchers are interested in compensating reactive power in power systems. When implementing a capacitor into a grid, power flows in whole grid and bus voltage can be changed and it can be make some benefits. Placement and size of any capacitor banks will affect to economic and technical factors. So, it must be calculated and evaluated carefully.

Benefits of implementing capacitor banks can be: reduce active power consumption from power system; reduce power load for medium voltage transformers and lines; reduce power losses; improve voltage quality [1-7]. However, capacitor banks can create additional cost for purchasing capacitors, operating compensation station and power loss in self capacitors [1-7]. Compensation problems are often solved to determine the number of compensation stations, the optimal placements in the grid and the operating modes of capacitors to achieve the highest benefit or the minimum value for cost function.

Before establishing a compensation problem to determine placement, rated power and the number of capacitors for each station, it must be designed the way to implement and control capacitor banks. Objective function is often total algebra of benefit and cost factors that are calculated in a common money unit. Uncalculated factors and technical standards are considered as constrains and limitation. Although there are differential methods to solve, they have the same purpose that is to the minimum compensation cost based on ensuring technical standards, bus voltage in allowable range and minimum power losses. It must be noted that it can't be separated economic and technical compensation problems individually because economic compensation can help to reduce technical compensation. Combining two these problems in an unification can make high benefit for whole system [1-7].

The voltage deviation of all buses in power systems must be limited in an acceptable range. In Vietnam, its range is from 0.95 pu (95%) to 1.05 pu (105%) for medium voltage power systems. This paper will concentrate into voltage requirements in Vietnam corresponding to the limitation about sizes or placements using OCP tool in ETAP software. It is also important to minimize cost, while mathematically determining the capacitor size and location. Because this is an optimization issue, an optimization approach should be employed. It is an extremely powerful simulation tool specifically designed for this application. The OCP module allows you to place capacitors for voltage support and power factor correction while minimizing total cost. The advanced graphic interface provides the flexibility to control the capacitor placement process, while allowing you to view the results instantly. The precise calculation approach automatically determines the best location and bank sizes. In addition, it reports the branch capacity release and savings during the planning period due to var loss reduction [8].

II. METHOD TO DETERMINE OPTIMAL PLACEMENT AND SIZE OF CAPACITOR BANKS

A. Newton-Raphson method to analyze power flows and voltage buses in distribution systems

Almost buses in a distribution system are load buses (PQ buses). These buses can have the participation of capacitors. They can be considered as reactive power generators at the coupling buses. In this system, Newton-Raphson method is often used to analyze power flows and bus voltage.

To determine operating parameters for N-bus grid by using Newton-Raphson method, system of power balance equations at the ith bus can be defined by (1) and (2) [6]:

$$U_i^2 y_{ii} \cos\psi_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{N} U_i U_j y_{ij} \cos(\delta_i - \delta_j - \psi_{ij}) - P_{Li} = \Delta P_i \quad (1)$$

$$-U_i^2 y_{ii}\sin\psi_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{N} U_i U_i y_{ij}\sin(\delta_i - \delta_j - \psi_{ij}) - (Q_{Li} - Q_{Ci}) = \Delta Q_i \quad (2)$$

where: $i = \overline{1, N}$; $\dot{U}_i = U_i \angle \delta_i$; $Y_{ij} = y_{ij} \angle \psi_{ij}$

P_{Li} and Q_{Li} are active and reactive load power at the i[th] bus; Q_{Ci} are active and reactive power of the capacitor bank at the i[th] bus,

In this problem, solutions are module and angle of bus voltage at the i[th] bus. Solutions at the (k+1)[th] step can be determined by (3) [6]:

$$\begin{bmatrix} \delta_i^{(k+1)} \\ U_i^{(k+1)} \end{bmatrix} = \begin{bmatrix} \delta_i^{(k)} \\ U_i^{(k)} \end{bmatrix} + \begin{bmatrix} \Delta\delta_i^{(k)} \\ \Delta U_i^{(k)} \end{bmatrix} \quad (3)$$

where, $\Delta U_i^{(k)}$ and $\Delta\delta_i^{(k)}$ are module and angle errors of bus voltage at the the i[th] bus and the k[th] step. These errors can be calculated by (4) at the k[th] step [6]:

$$\begin{bmatrix} \Delta\delta_i^{(k)} \\ \Delta U_i^{(k)} \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P_i^{(k)} \\ \Delta Q_i^{(k)} \end{bmatrix} \quad (4)$$

where, J^{-1} is the inversed matrix of Jacobian matrix,

$\partial P_i^{(k)}/\partial \delta_i^{(k)}$, $\partial P_i^{(k)}/\partial U_i^{(k)}$, $\partial Q_i^{(k)}/\partial \delta_i^{(k)}$ and $\partial Q_i^{(k)}/\partial U_i^{(k)}$ are elements of Jacobian matrix.

$\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ are active and reactive power errors at the k[th] step.

The difference of power at each bus at the k[th] step can be calculated from (1) and (2) equations. If errors are in the assigned value, values at the k[th] step are system roots. Newton-Raphson algorithm applied to determine operating parameters with the participation of capacitor banks is described in Fig. 4 [6].

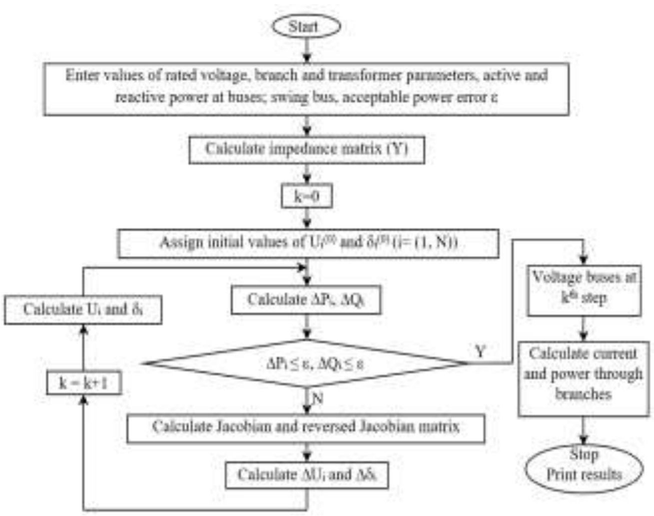


Fig. 1. Newton-Raphson algorithm to determine operating parameters in the grid

The Newton-Raphson method possesses a unique quadratic convergence characteristic. It usually has a very fast convergence speed compared to other load flow calculation methods. It also has the advantage that the convergence criteria are specified to ensure convergence for bus real power and reactive power mismatches. This criterion gives you direct control of the accuracy you want to specify for the load flow solution. The convergence criteria for the Newton-Raphson method are typically set to 0.001 MW and MVAr.

The Newton-Raphson method is highly dependent on the bus voltage initial values. A careful selection of bus voltage initial values is strongly recommended. Before running load flow using the Newton-Raphson method, ETAP software makes a few Gauss-Seidel iterations to establish a set of sound initial values for the bus voltages.

B. Objective Function of OCP

The objective of optimal capacitor placement is to minimize the cost of the system. This cost is measured in four ways: fixed capacitor installation cost, capacitor purchase cost, capacitor bank operating cost (maintenance and depreciation), cost of real power losses.

Cost can be represented mathematically as [8]:

$$\sum_{i=1}^{N}\left(x_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T\right) + C_2 \sum_{i=1}^{N} T_\ell P_L^\ell \quad (5)$$

where:

N is the number of bus candidates,
x_i=0 or x_i=1 (x_i=0 means no capacitor installed at bus i[th])
C_{0i} is installation cost,
C_{1i} is per kVAr cost of capacitor banks,
Q_{ci} (kVAr) is capacitor bank size,
B_i is the number of capacitor banks,
C_{2i} is operating cost of per bank, per year,
T is planning period (years),
C_2 (USD/kWh) is cost of each kWh loss,
ℓ is load levels (maximum, average and minimum),
T_ℓ (hour) is time duration of load level ℓ,
P_L^ℓ is total system loss at load level ℓ.

C. Constraints

The main constraints for capacitor placement are to meet the load flow constraints. In addition, all voltage magnitudes of load (PQ) buses should be within the lower and upper bars. Load Power Factor (PF) should be greater than the minimum. It may be a maximum power factor bar.

The constraints can be represented mathematically as [8]:

$\Delta P_i = 0$ and $\Delta Q_i = 0$ in constrains of allowable bus voltage that are $U_{min} \le U \le U_{max}$ for all buses.

In this method, it has no limitation for the number of capacitor banks. It means that maximum and minimum limitations of capacitor banks does not exist. The calculation process only stops after the constrains are met.

D. Proposed algorithm

The proposed algorithm is represented in Fig. 2.

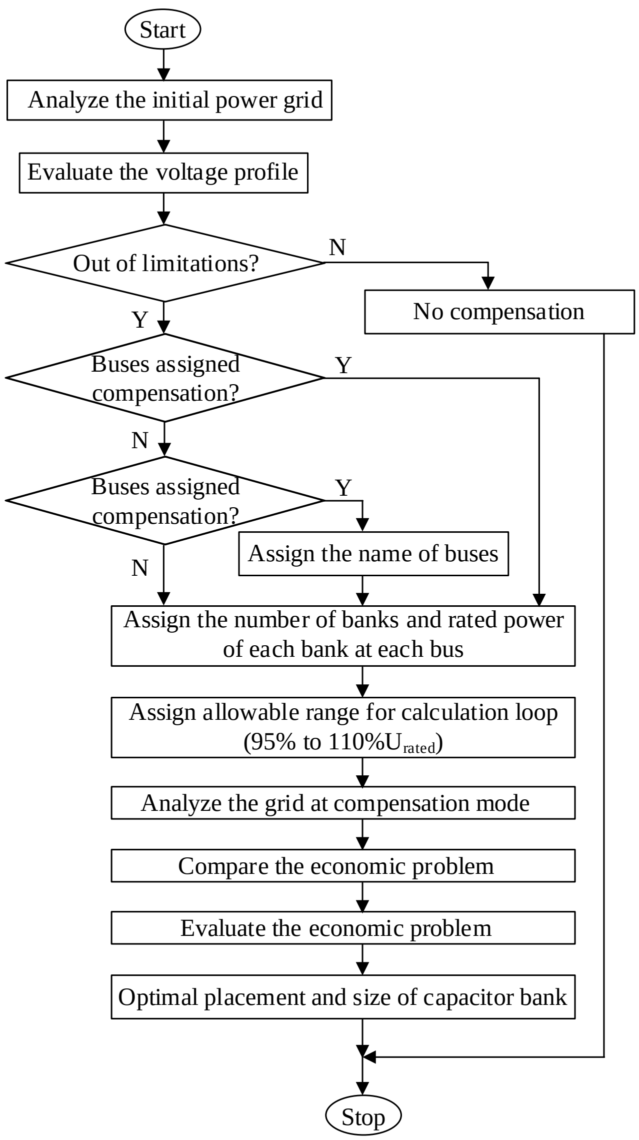


Fig. 2. Method to determine optimal placements and size of capacitors

III. SIMULATION RESULTS

The diagram of the system is depicted in Fig. 3 [6].

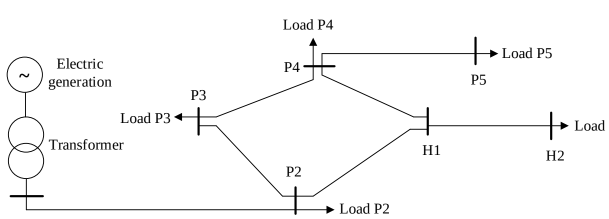


Fig. 3. Diagram of simulation system

Parameters of electric source and transformer in Table 1, transmission lines in Table 2, electric load at bused in Table 3 [6].

Table 1. Parameters Of Transmission Lines

Name	Sectional area (mm^2)	Type	Length (km)
P1-P2	183	Pirelli-twisted 19 strands	12
P2-P3	111	Pirelli-twisted 7 strands	20
P4-H1	49.5		11
P4-P5	34.4		10
P3-P4	77.3		8
P2-H1	111		30
H1-H2	49.5		6

Table 2. Parameters Of Source And Transformer

Type	Parameters
Grid	Rated voltage: 110 kV; Short-circuit power: 5000 MVA; Reactance/Resistance = ∞.
Power transformer	Voltage ratio: 110/35 kV; Rated power: 25 MVA; Impedance: Z=10%; Reactance/Resistance = 20.

Simulation results for the case of no capacitor bank are shown in Fig. 4. It can be easy to see that almost voltage values are much smaller than allowable value (<95%). Buses at the end of transmission lines such as P5 and H2 are considered the weakest buses because they are near to the limitation of voltage collapse.

Table 3. Parameters Of Electric Load At Buses

Name	Apparent power (MVA)	cosφ	Type
LoadP1	2	0.85	80% constant kVA, 20% constant Z
LoadP2	1.5	0.8	
LoadP3	1.2	0.8	
LoadP4	2.5	0.8	
LoadP5	2	0.85	
LoadH1	3.6	0.8	
LoadH1	1.5	0.8	

To execute OCP problem, values of bus voltage are limited from 95% to 110%; electric energy cost is 0,09 USD/kWh; planning period is 5 year; objective purpose is only voltage support.

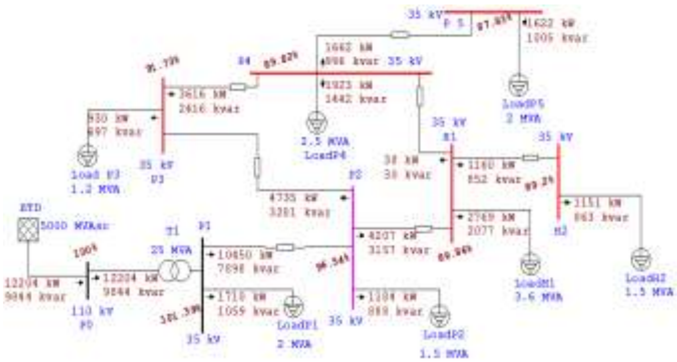
Moreover, capacitor parameters are assigned: rate voltage grid is 35 kV; capacitor bank is 200 kVAr; maximum value of banks at each bus are 10; capacitor cost is 40 USD/kVAr; cost for implement is 1200 USD; operating cost is 400 USD/bank year.

In case of not compensating, simulation results are shown in Fig. 4. They presented voltage profile at P3, P4, P5, H1, H2 buses are lower than allowable limitation (smaller than 95%U_{rated}). It means that it must be had some solutions to improve voltage quality. To apply capacitors, it must be determined sizes and placements at all buses to achieve the purpose that including the voltage improvement and economic factor (cost for implementing and operating is minimum).

In the 1st case, the number of capacitor banks is limited at 10 banks and rated power of each bank is 200 kVAr. Simulation results are depicted in Fig. 5.

In the 2nd case, rated power of each bank is 200 kVAr while the number of capacitor banks is not limited. Simulation results are depicted in Fig. 6.

In the 3rd case, rated power of each bank is 200 kVAr while 4 buses (P4, P5, H1, H2) are assigned to compensate and without limiting sizes at each bus. Simulation results are depicted in Fig. 7.



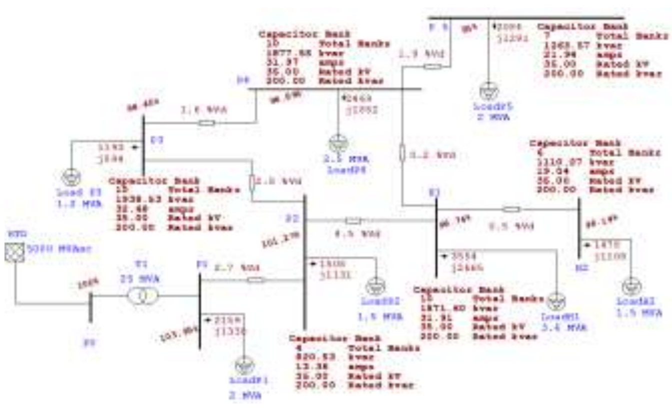
a. Power flows in whole system

Branch Losses Summary Report

CKT / Branch ID	From-To Bus Flow MW	From-To Bus Flow Mvar	To-From Bus Flow MW	To-From Bus Flow Mvar	Losses kW	Losses kvar	% Bus Voltage From	% Bus Voltage To	Vd % Drop in Vmag
15	1.160	0.852	-1.151	-0.863	9.3	-10.8	89.9	89.2	0.66
DZ P1-P3	-3.968	-2.959	4.207	3.157	239.0	197.4	89.9	96.5	6.67
DZ P1-P10	0.018	0.018	-0.018	-0.060	0.0	-29.8	89.9	89.8	0.07
T1	12.204	9.844	-12.160	-8.958	44.3	886.4	100.0	101.4	1.39
DZ P1-P2	10.450	7.898	-10.126	-7.325	324.4	573.2	101.4	96.5	4.86
DZ P1-P14	4.735	3.281	-4.545	-3.113	190.2	168.0	96.5	91.7	4.81
DZ P1-P16	3.616	2.416	-3.547	-2.378	68.9	37.1	91.7	89.8	1.91
DZ P1-P17	1.662	0.898	-1.622	-1.005	40.2	-8.2	89.8	87.8	1.98
					916.3	1812.2			

b. Branch losses summary report

Fig. 4. Simulation results with no capacitor bank



a. Power flows in whole system

Optimal Capacitor Placement Cost Summary

Year	Cost ($) Installation	Cost ($) Operation	Saving ($) Loss Reduction	Saving ($) Yearly Profit	Saving ($) Accumulative Profit
1	383200.00	18800.00	288233.80	-113766.20	-113766.20
2	0.00	18800.00	288233.80	269433.80	155667.70
3	0.00	18800.00	288233.80	269433.80	425101.50
4	0.00	18800.00	288233.80	269433.80	694535.40
5	0.00	18800.00	288233.80	269433.80	963969.30

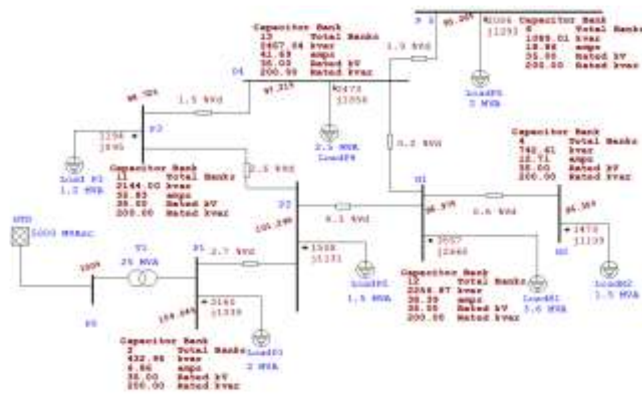
a. Optimal capacitor placement cost summary

Branch Losses Summary Report (Max. Loading)

CKT / Branch ID	From-To Bus Flow MW	From-To Bus Flow Mvar	To-From Bus Flow MW	To-From Bus Flow Mvar	Losses kW	Losses kvar	% Bus Voltage From	% Bus Voltage To	Vd % Drop in Vmag
15	1.488	-0.016	-1.478	0.002	8.4	-13.9	96.7	86.2	8.55
DZ P1-P3	-5.091	-0.280	5.312	0.444	220.9	163.4	96.7	101.3	4.54
DZ P1-P15	0.051	-0.497	-0.050	0.464	1.0	-33.7	98.7	98.8	0.15
T1	15.325	3.114	-15.281	-2.232	44.1	881.7	100.0	104.0	3.95
DZ P1-P2	13.122	0.894	-12.811	-0.351	310.6	543.5	104.0	101.3	2.68
DZ P1-P14	5.992	-0.403	-5.805	0.559	186.4	155.4	101.3	98.5	2.82
DZ P1-P16	4.613	0.486	-4.545	-0.453	67.8	32.6	98.5	96.9	1.56
DZ P1-P17	2.125	0.015	-2.084	-0.028	41.2	-13.1	96.9	95.8	1.89
					881.2	1716.0			

c. Branch losses summary report

Fig. 5. Simulation results in the 1st compensation case



a. Power flows in whole system

Optimal Capacitor Placement Cost Summary

Year	Cost ($) Installation	Cost ($) Operation	Saving ($) Loss Reduction	Saving ($) Yearly Profit	Saving ($) Accumulative Profit
1	391200.00	19200.00	286364.40	-124035.60	-124035.60
2	0.00	19200.00	286364.40	267164.40	143128.80
3	0.00	19200.00	286364.40	267164.40	410293.20
4	0.00	19200.00	286364.40	267164.40	677457.60
5	0.00	19200.00	286364.40	267164.40	944622.00

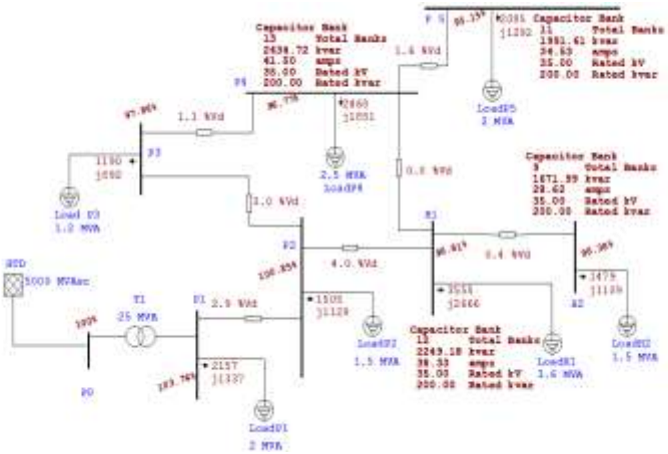
b. Optimal capacitor placement cost summary

Branch Losses Summary Report (Max. Loading)

CKT / Branch ID	From-To Bus Flow MW	From-To Bus Flow Mvar	To-From Bus Flow MW	To-From Bus Flow Mvar	Losses kW	Losses kvar	% Bus Voltage From	% Bus Voltage To	Vd % Drop in Vmag
15	1.487	0.353	-1.478	-0.366	8.8	-12.7	97.0	96.3	0.83
DZ P1-P3	-5.083	-0.068	5.301	0.229	218.7	160.4	97.0	101.3	4.32
DZ P1-P10	0.038	-0.695	-0.035	0.662	3.2	-33.8	97.0	97.2	0.24
T1	15.341	2.882	-15.297	-2.004	43.9	878.5	100.0	104.0	4.04
DZ P1-P2	13.137	1.098	-12.825	-0.553	311.5	545.3	104.0	101.3	2.75
DZ P1-P14	6.016	-0.807	-5.826	0.966	190.3	159.8	101.3	98.7	2.57
DZ P1-P16	4.632	0.282	-4.565	-0.250	67.6	32.2	98.7	97.2	1.51
DZ P1-P17	2.127	0.190	-2.086	-0.204	41.4	-13.2	97.2	95.3	1.89
					883.5	1716.4			

c. Branch losses summary report

Fig. 6. Simulation results in the 2nd compensation case



a. Power flows in whole system

Optimal Capacitor Placement Cost Summary

Year	Cost ($)		Saving ($)		
	Installation	Operation	Loss Reduction	Yearly Profit	Accumulative Profit
1	364800.00	18000.00	281844.30	-100955.70	-100955.70
2	0.00	18000.00	281844.30	263844.30	162888.60
3	0.00	18000.00	281844.30	263844.30	426732.90
4	0.00	18000.00	281844.30	263844.30	690577.30
5	0.00	18000.00	281844.30	263844.30	954421.60

b. Optimal capacitor placement cost summary

Branch Losses Summary Report (Max. Loading)

CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	% Drop in Vmag
19	1.488	-0.576	-1.470	0.563	0.7	-13.2	96.8	96.4	0.43
DZ P1-P5	-5.170	0.300	5.398	-0.128	228.1	172.5	96.8	100.9	4.05
DZ P1-P10	0.127	-0.141	-0.127	0.107	0.2	-34.5	96.8	96.8	0.04
T1	15.335	3.677	-15.290	-2.780	44.8	896.6	100.0	103.7	3.74
DZ P1-P2	13.133	1.443	-12.818	-0.892	314.7	551.7	103.7	100.9	2.88
DZ P1-P4	5.915	-0.108	-5.732	0.261	182.5	151.4	100.9	97.9	2.99
DZ P1-P6	4.542	-1.153	-4.472	1.188	70.8	34.7	97.9	96.8	1.08
DZ P1-P7	2.131	-0.711	-2.085	0.700	46.8	-11.1	96.8	95.1	1.62
					896.0	1748.0			

c. Branch losses summary report

Fig. 7. Simulation results in the 3rd compensation case

Simulation results in Fig. 5, Fig. 6 and Fig. 7 are used to evaluate economic and technical factors when comparing cases. Bus voltage profiles in three cases are represented in Fig. 8. The 1st case used 47 banks corresponding to 9400 kVAr rated reactive power. The 2nd case used 48 banks corresponding to 9600 kVAr rated reactive power. The 3rd case used 45 banks corresponding to 9000 kVAr rated reactive power.

The comparison about active power and reactive power loss is represented in Fig. 9. Total loss reduction saving is depicted in Fig. 10. Accumulative profit saving is shown in Fig. 11.

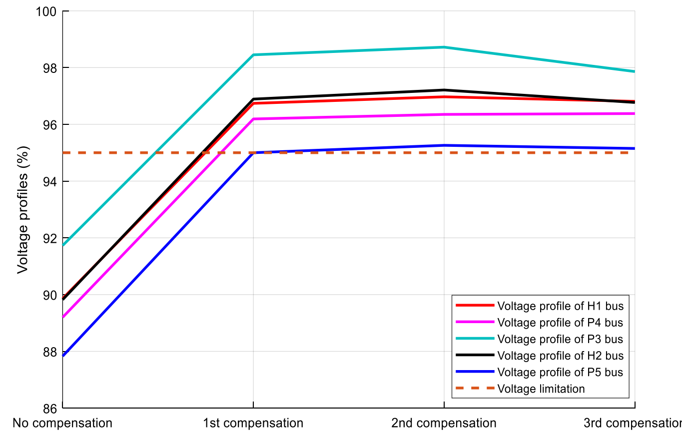


Fig.8. Bus voltage profiles in cases

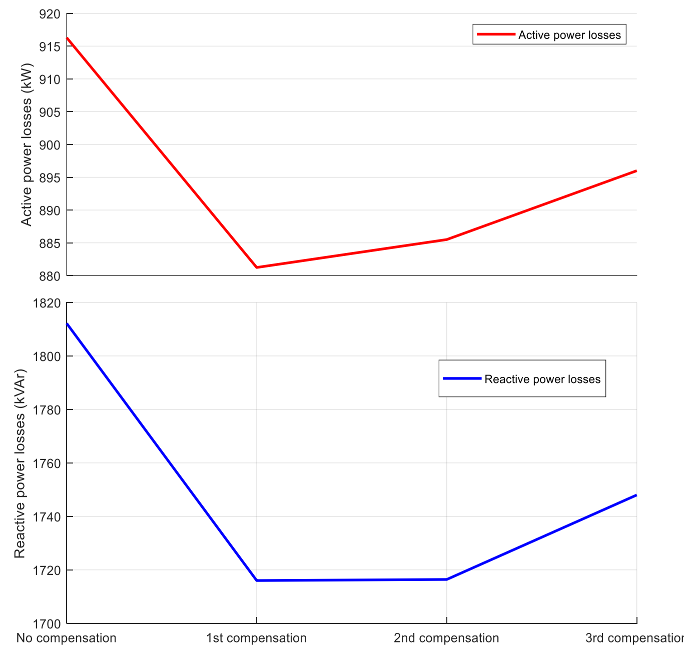


Fig.9. Active and reactive power loss

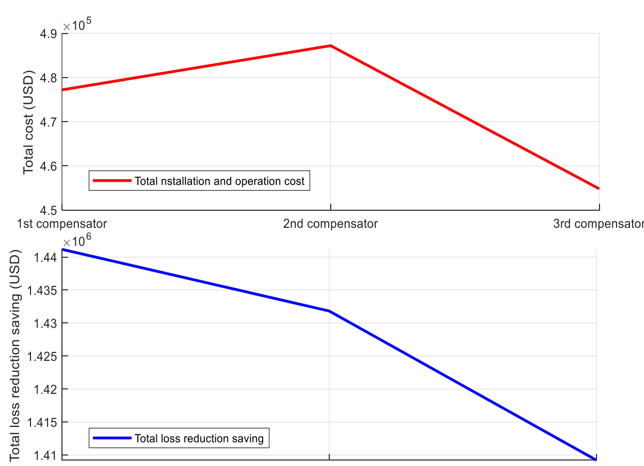


Fig.10. Diagrams of installation and operation cost and loss reduction saving

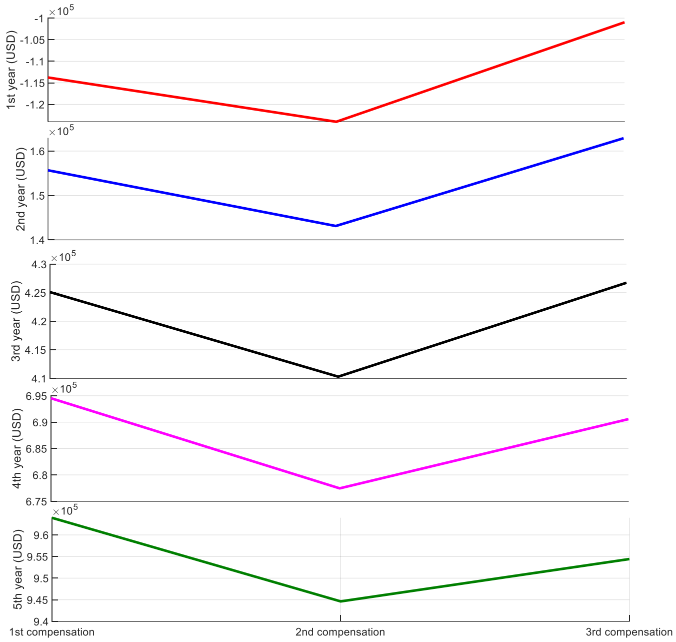


Fig.11. Diagrams of accumulative profit saving

Diagrams in Fig.11 showed that voltage values at all buses are lower than allowable values (smaller than 95%). After compensating in both three cases, voltage values at all buses are higher than 95%. It means that compensation solution in the grid with constrains for OCP tool can be achieved completely corresponding to assigned values. Diagrams in Fig.9 showed the meaning of active and reactive power reduction. Moreover, the 1st and 2nd compensation cases present higher meaning than the 3rd compensation case and no compensation case.

Diagram in Fig.10 showed the 2nd case had the highest total installation and operation cost. The 3rd case had minimum total cost and total reduction saving. It means that the assigned compensation buses brings highest benefit for factors of implementing, operating and power losses.

Diagrams in Fig.11 showed the accumulative profit in the first year was negative while 4 final years were positive. In the 1st, 2nd and 3rd years, values of accumulative profit saving present that the 3rd compensation case can make the highest profit while the 1st compensation case has accumulative profit saving higher. It means that the 1st compensation case can make the highes profit in long time.

Considering totally, the 3rd case has the lowest implementing power and makes highest profit in long time. It can be the optimal case when evaluating economic and technical factors.

IV. CONCLUSION

This paper proposed a method to determine optimal placements and sizes for capacitor banks in distribution systems. Based on the OCP tool of ETAP software, the author established some cases to determine the best propose for capacitor banks. The new contribution is a combination of constrains about the limitation of rated power at each bus or the assignation of compensation buses. The OCP tool helps to give out results about voltage profile, proposed compensation power at each bus and economic factor in each case.

Simulation results showed all compensation cases were calculated and evaluated about power losses in whole system, installation and operation cost, loss reduction saving, yearly profit, accumulative profit in the planning period. Due to adapting to allowable voltage range, capacitor sizes at all buses meet economic and technical requirements well. So, this research can bring the best suggestion for compensation problem.

This paper was proposed three cases to solve the optimal compensation problem. Received reports in each case are optimal compensation value to meet assigned constrains. When changing constrains, the optimal parameters also change. To have the best parameters, it must be evaluated by using additional factors. In the future, the constrains will be added to make higher total meaning for compensation problem.

ACKNOWLEDGMENTS

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