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Analysis of the Effect of Capacitor Placements at High and Low Voltage Transformer Sides as Voltage Profile and Total Cost in Distribution Systems

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ABSTRACT

This study mentions the problem of determining optimal placements and sizes for capacitor banks by comparing different schemes that allow implemented buses at both high and low voltage side, only high voltage side or low voltage side of transformers in distribution systems. Criterions evaluated for each scheme are active and reactive power losses in whole system, voltage value at all buses, installation and operation cost and accumulative profit saving. Standard with and without transformer branches in distribution systems and Newton-Raphson method are introduced to make clear about the way to analyze power flows in whole system. Optimal placements and sizes for capacitor banks are determined by using a proposed algorithm and optimal capacitor placement tool in ETAP software. Simulation results can help to show the comparisons, evaluations and make decision about optimal capacitor placements and sizes. The contribution shows the best scheme that install capacitors at low voltage side of transformers because it has the lowest implemented capacity, highest economic factors while voltage quality is always in allowable range. Achieved results can be applied in any distribution system, help managers have overall review and decide optimal placements and sizes for capacitor banks.

Keywords: Capacitor bank, OCP Tool, ETAP software, Optimal placement, Optimal size, Voltage quality, Optimal cost.

I. INTRODUCTION

Distribution systems are increasingly under pressure regarding requirements of high transmitted power and long transmission lines. At times with high consumed electric loads, voltage quality at buses often decreases due to power losses in transmission lines. Capacitor compensation is considered by many managers and engineering staffs to be one of the best solutions to improve voltage quality.

Capacitors can affect directly to voltage quality and power losses in whole system [1-2]. When distribution system becomes more complexly with many branches and nodes, many researches have been dealt with the problem of determining optimal capacitor placements and many methods have been proposed such as voltage drop increase [1], generic algorithm [2-3], metaheuristic algorithms [4], hybrid mathematical formulation [5], voltage profile improvement and loss reduction [6], voltage support and minimum total cost [7], etc. General purpose for these methods is to reduce the active power required from the power system; reduce load for transformers and medium voltage transmission lines; reduce power loss and electric energy; improve voltage quality; optimize the cost function according to conventional constraints [1-10]. These methods provide new approaches to determine optimal capacitor placements but they can't be applied in large grids with many buses because they have large calculation and it must be reprogrammed for each detailed grid. At the other side, managers need a suitable method to determine optimal capacitor placements with a reliable simulation tool that can help them overall evaluate whole real systems.

In steady operating mode, capacitors can affect directly to power flows in whole system and power losses if they are installed at different nodes. In distribution system, consumption voltage is often 400 V for three-phase loads or 220 V for single-phase loads. These loads are supplied by connecting to the low voltage (LV) side of transformers and voltage quality for them are often adjusted by the onload tap charger in each transformer [11-14]. Moreover, the number of motors consuming medium voltage at high voltage (HV) side of transformers directly is very small. Therefore, it needs to show analysis about the effectiveness of capacitor compensation when considering economic factors (installation and operation costs) corresponding to their locations in the grid at high voltage side or low voltage side of transformers. In particular, it is necessary to mention the differences of price and operation cost of capacitor banks according to voltage and power losses in whole grid.

Recently, controlled capacitor banks applied in distribution system such as D-SVC, D-STATCOM can help to compensation capacity continuously as required of loads to meet voltage constraints in allowable limits [15-22]. However, installed capacity of the capacitors at each bus needs to be determined according to the maximum load consumption and minimum economic function. Moreover, managers need to have calculation tools that are reliable and have been commercialized when applied to large real distribution systems. Currently, optimal capacitor placement (OCP) tool in ETAP software is considered as the best tool to analyze power flows and execute the economic capacitor problem. In this tool, many parameters can be set such as rated and cost for each capacitor bank, constraints for voltage or/and power factor [23-25]. Moreover, compensation buses can be assigned to have detailed evaluations about expected compensation schemes.

This paper will focus on the problem of optimal placements and sizes of capacitor banks by using voltage restraint and comparing effectiveness of placing them at HV and/or LV side of transformers. The next section will present Newton-Raphson method to analyze power flows in case of considering transmission lines and standard transformer branches. Section III will present contents of OCP tool. Section IV will present simulation results and evaluations about the effectiveness of placing capacitor banks at HV and/or LV side of transformers. The last section will show some conclusions about the contributions of this paper that have some suggestions for managers to choose placements and sizes of capacitor banks for any distribution systems.

II. Newton-Raphson method to analyze distribution system with the participation of line and transformer branches

A. Mathematical model of transmission line and power transformer in distribution systems

Mathematical model of medium voltage transmission lines is described in Fig. 1 [7].

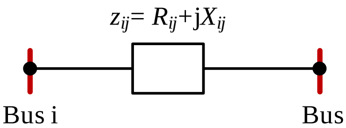
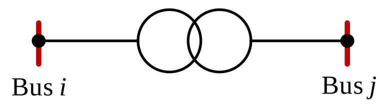


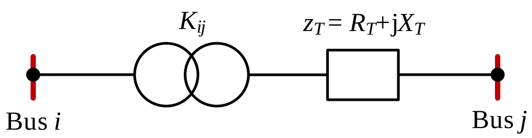
Fig. 1 Mathematical model of transmission line in medium voltage systems

Where: R_{ij} (Ω) is resistance and X_{ij} (Ω) is reactance of the transmission line connecting bus i and bus j.

Mathematical model of two-winding transformer is described in Fig. 2.



a. Power transformer



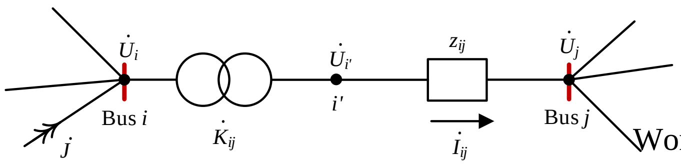
b. Equivalent circuit

Fig. 2 Mathematical model of two-winding transformer

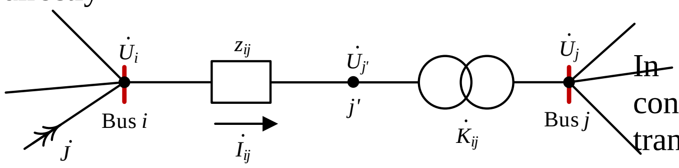
Where: R_T (Ω) is resistance and X_T (Ω) is reactance of the transformer; K_{ij} is voltage ratio between bus i and bus j of ideal transformer (without power loss). In Fig. 2b, voltage value of bus i is higher than voltage value of bus j, so bus i is called HV bus and bus j is called LV bus.

B. Establish the admittance matrix for a distribution system

A general distribution system includes (N+1) buses, where N buses are normal buses and a bus is ground. Any branch in the system can be classified to the standard line or transformer branch. These branches can be defined by a general standard branch as depicted in Fig. 3 [7].



a. Bus i connecting to the ideal transformer directly



b. Bus i connecting to the ideal transformer indirectly through an impedance

Fig. 3 Diagram of general standard branch

In Fig. 3a and Fig. 3b, the current source $\dot{J}_i$ (from generations) is injects to bus i. If the branch describes a transformer, voltage ratio can be calculated forward to bus i that is $\dot{K}_{ij} = \frac{\dot{U}_{i'}}{\dot{U}_{i'}}$. If the branch describes a transmission line, voltage ratio is $\dot{K}_{ij} = 1$.

Applying Kirchhoff 1, current balancing equation at bus i can be determined by (1) [7]:

$$\sum_{\substack{j=0 \\ j\neq i}}^{N} \dot{I}_{ij} = \dot{J}_i \qquad (1)$$

Using I'$_{ij}$, equation (1) can be converted to equation (2):

$$\sum_{\substack{j=0 \\ j\neq i}}^{N} \dot{K}_{ij}\dot{I}'_{ij} = \dot{J}_i \qquad (2)$$

Using Ohm's law for i'j branch, equation (2) can be converted to equation (3) [7]:

$$\dot{Y}_{ii}\dot{U}_k + \sum_{\substack{j=0 \\ j\neq i}}^{N} \dot{Y}_{ij}\dot{U}_j = \dot{J}_i \qquad (3)$$

where: $\dot{Y}_{ii}$ is individual admittance of bus i and $\dot{Y}_{ij}$ is interactive admittance of branch ij. $\dot{Y}_{ii}$, $\dot{Y}_{ij}$ can be determined by equation (4) and (5) [7].:

$$\dot{Y}_{ii} = \sum_{\substack{j=0 \\ j\neq i}}^{N} \left(\frac{\dot{K}_{ij}^2}{\dot{Z}_{ij}} \right) \qquad (4)$$

$$\dot{Y}_{ij} = -\frac{\dot{K}_{ij}}{\dot{Z}_{ij}} \qquad (5)$$

Working the same with Fig. 3b, $\dot{Y}_{ii}$ can be defined by equation (6):

$$\dot{Y}_{ii} = \sum_{\substack{j=0 \\ j\neq i}}^{N} \frac{1}{\dot{Z}_{ij}} \qquad (6)$$

In general case study, bus i can be connected to m buses directly through ideal transformers and k buses indirectly through ideal transformers. $\dot{Y}_{ii}$ can be determined by equation (7) [7]:

$$\dot{Y}_{ii} = \sum_{\substack{j=0 \\ j\neq i}}^{k} \frac{1}{\dot{Z}_{ij}} + \sum_{\substack{j=0 \\ j\neq i}}^{m} \frac{\dot{K}_{ij}^2}{\dot{Z}_{ij}} \qquad (7)$$

Current balancing equations for whole system can be described in system of equations (8).

$$\begin{cases} \dot{Y}_{11}\dot{U}_1 + \dot{Y}_{12}\dot{U}_2 + \ldots + \dot{Y}_{1N}\dot{U}_N = \dot{J}_1 \\ \dot{Y}_{21}\dot{U}_1 + \dot{Y}_{22}\dot{U}_2 + \ldots + \dot{Y}_{2N}\dot{U}_N = \dot{J}_2 \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \dot{Y}_{N1}\dot{U}_1 + \dot{Y}_{N2}\dot{U}_2 + \ldots + \dot{Y}_{NN}\dot{U}_N = \dot{J}_N \end{cases} \qquad (8)$$

From equation (8), matrix admittance can be derived as (9):

$$Y = \begin{bmatrix} \dot{Y}_{11} & \dot{Y}_{12} & ... & \dot{Y}_{1N} \\ \dot{Y}_{21} & \dot{Y}_{22} & ... & \dot{Y}_{2N} \\ ... & ... & ... & ... \\ \dot{Y}_{N1} & \dot{Y}_{N2} & ... & \dot{Y}_{NN} \end{bmatrix} \quad (9)$$

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

Almost buses in distribution systems are PQ buses (load buses). Capacitors can be implemented at these buses and considered as reactive generators. In these systems, Newton-Raphson method is often used to determine power flows and voltage buses.

To determine operating parameters for N-bus grid by using Newton-Raphson method, system of power balancing equations at bus i can be defined by (10) and (11) [7]:

$$U_i^2 y_{ii} \cos\psi_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{N} U_i U_j y_{ij} \cos(\delta_i - \delta_j - \psi_{ij}) - P_{Li} = \Delta P_i \quad (10)$$

$$-U_i^2 y_{ii} \sin\psi_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{N} U_i U_i y_{ij} \sin(\delta_i - \delta_j - \psi_{ij}) - (Q_{Li} - Q_{Ci}) = \Delta Q_i \quad (11)$$

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 bus i; Q_{Ci} are active and reactive power of the capacitor bank at the bus i.

From solutions at the kth step including $\delta_i^{(k)}$ and $U_i^{(k)}$, values of $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ can be calculated. Moreover, values of $\Delta\delta_i^{(k)}$ and $\Delta U_i^{(k)}$ at the kth step can be calculated by using reversed Jacobian matrix as described in equation (12) [7], [26-27]:

$$\begin{bmatrix} \Delta\delta_i^{(k)} \\ \Delta U_i^{(k)} \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P_i^{(k)} \\ \Delta Q_i^{(k)} \end{bmatrix} \quad (12)$$

where: J is Jacobian matrix.

Jacobian matrix at the ith step: $J = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}$

Solutions at the next step can be determined by equation (13) [7], [26-27]:

$$\begin{bmatrix} \delta_i^{(k+1)} \\ U_i^{(k+1)} \end{bmatrix} = \begin{bmatrix} \delta_i^{(k)} \\ U_i^{(k)} \end{bmatrix} + \begin{bmatrix} \Delta\delta_i^{(k)} \\ \Delta U_i^{(k)} \end{bmatrix} \quad (13)$$

This process will be stopped if both values of ΔP_i and ΔQ_i are smaller than allowable value ε [7], [26-27]. Fig. 4 describes the Newton-Raphson method to analyze a distribution system [7], [26-27].

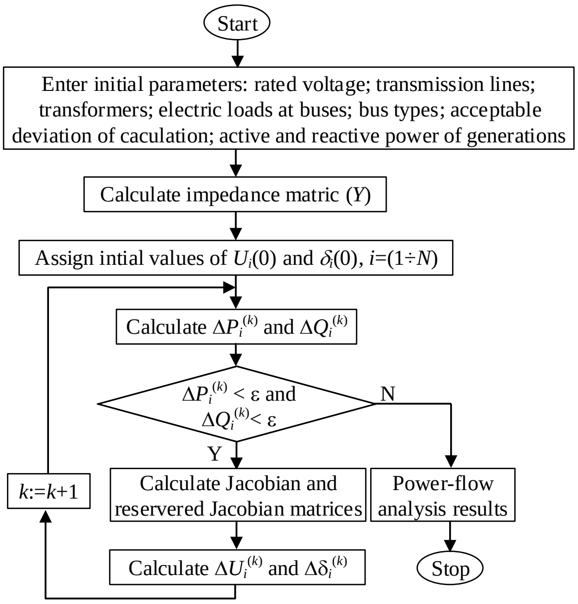


Fig. 4. Newton-Raphson algorithm to analyze whole grid

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.

It must be noted that there are some methods to analyze power systems such as Newton-Raphson, Gauss-Seidel, Fast Decoupled Load Flow, Laurent Power Flow, Backward Forward Sweep, etc. Newton-Raphson method is highly dependent on the bus voltage initial values. A careful selection of bus voltage initial values is strongly recommended. In power system, values of voltage buses are always approximately rated voltage value. So, Newton-Raphson method provides a reliable tool to analyze power system with fast convergence and small amount of calculation.

III, Method to determine optimal placement and size of capacitor banks

A. Problem of capacitor compensation at high and low voltage sides of transformers

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 [23], [25], [28]:

$$\sum_{i=1}^{N}\left(x_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T\right) + C_2 \sum_{i=1}^{N} T_\ell P_L^\ell \quad (14)$$

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)

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.

B. 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 should be greater than the minimum. It may be a maximum power factor bar.

For the voltage constraint, voltage values at all buses are in allowable range, that is $U_{min} \le U \le U_{max}$.

C. Proposed algorithm

The proposed algorithm is represented in Fig. 5.

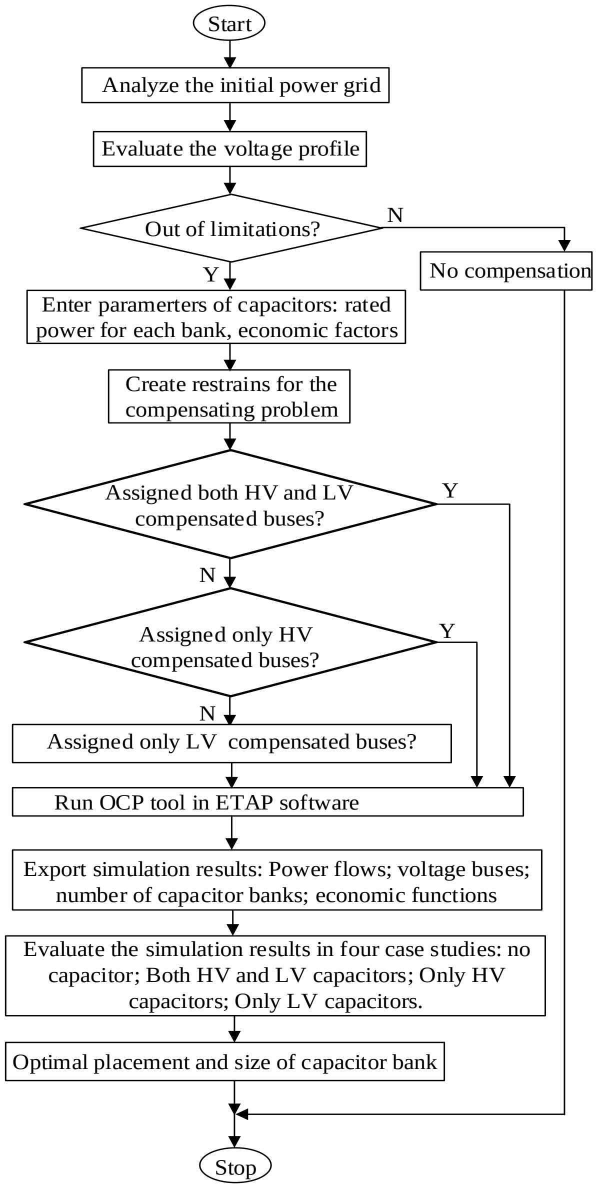


Fig. 5. Proposed process to determine optimal placements and size of capacitors

IV. Simulation results

The diagram of the simulation system is depicted in Fig. 6.

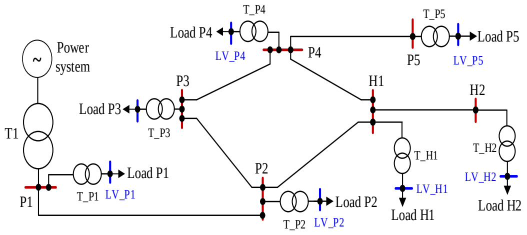


Fig. 6 Diagram of simulation system

Parameters of transmission lines in Table I, power source in Table II, transformers in Table III, electric load at bused in Table IV.

Table- I 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- II Parameters of source

Type	Parameters
Power system	Rated voltage: 110 kV; Short-circuit power: 5000 MVA; Reactance/Resistance: ∞

Table- III Transformers

Location	Parameters
T1	Voltage ratio: 110/35 kV; Rated power: 25 MVA; Impedance: Z=10%; Reactance/Resistance=20
T_P1	Voltage ratio: 35/0,4 kV; Rated power: 2,5 MVA; Impedance: Z=6,25%; Reactance/Resistance=6
T_P2, T_P3, T_H2	Voltage ratio: 35/0,4 kV; Rated power: 2,0 MVA; Impedance: Z=6,25%; Reactance/Resistance=6
T_P4, T_P5	Voltage ratio: 35/0,4 kV; Rated power: 3,0 MVA; Impedance: Z=6,25%; Reactance/Resistance=6
T_H1	Voltage ratio: 35/0,4 kV; Rated power: 5,0 MVA; Impedance: Z=7,15%; Reactance/Resistance=8,5

Table- IV 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	

Parameters of OCP tool [29-30]:

U_{max} = 1.05 p.u (105%); U_{min} = 0.95 p.u (95%);

Cost for electricity =0,09 USD/kWh;

Planning period = 5 year;

Objective: voltage support;

Capacitor at 35 kV side: bank size 400 kVAr; 7000 USD/bank. Capacitor at 0,4 kV side: bank size 400 kVAr; 4500 USD/bank [12-13].

Simulation results in case of without compensating are described in Fig. 7. From Fig. 7a, voltage values of P3, P4, P5, H1, H2, LV_P2, LV_P3, LV_P4, LV_H1, LV_H2 buses are lower than allowable value (0.95 p.u). It means that voltage quality must be improved and capacitors are proposed to use and adapt to economic factors.

There are three considering compensation case studies:

For the first case study, both HV and LV buses are considered as good candidates to implement capacitors. These buses are P1, P2, P3, P4, P5, H1, H2, LV_P1, LV_P2, LV_P3, LV_P4, LV_52, LV_H1, LV_H2. Simulation results for this case study is represented in Fig. 8.

For the second case study, only HV buses are considered as good candidates to implement capacitors. These buses are P1, P2, P3, P4, P5, H1, H2. Simulation results for this case study is represented in Fig. 9.

For the third case study, only LV buses are considered as good candidates to implement capacitors. These buses are LV_P1, LV_P2, LV_P3, LV_P4, LV_52, LV_H1, LV_H2. Simulation results for this case study is represented in Fig. 10.

Simulation results in Fig. 8, Fig. 9, Fig. 10 are used to evaluate economic and technical factors when comparing compensation schemes.

Compensation capacity in three case studies in described in TABLE V.

Table- V Compensation capacity in three case studies

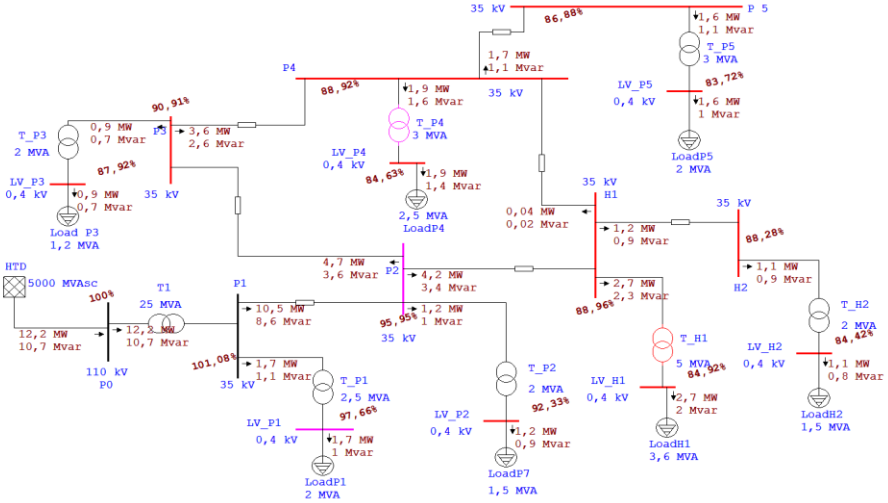
	Case 1	Case 2	Case 3
Number of HV capacitor banks	26	35	0
Number of LV capacitor banks	14	0	31
Total installation capacity	16 MVAr	14 MVAr	12,4 MVAr

Voltage values in case of without capacitors and three case studies are represented in Fig. 11.

The comparison about active and reactive power losses in case of without capacitors and three case studies are represented in Fig. 12.

The comparison about operation and installation cost in three case studies are represented in Fig. 13.

The comparison about accumulative profit saving in three case studies are represented in Fig. 14.

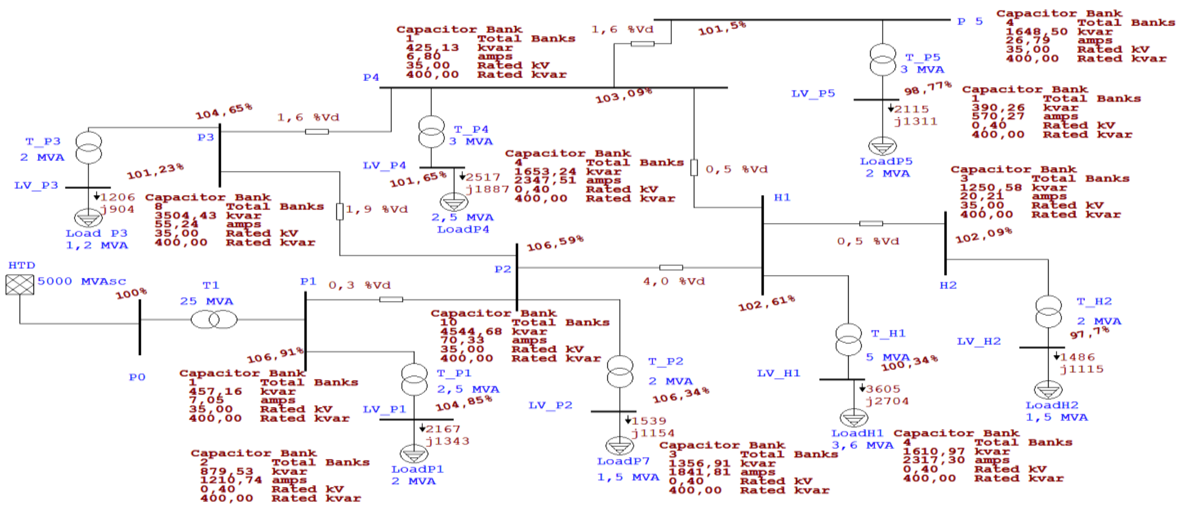


a. Power flows in whole system

CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
15	1.155	0.925	-1.145	-0.935	10.0	-10.1	89.0	88.3	0.68
DZ P1-P3	-3.939	-3.216	4.196	3.437	257.3	221.2	89.0	96.0	6.99
DZ P1-P19	0.037	0.024	-0.037	-0.053	0.0	-29.2	89.0	88.9	0.04
T_H1	2.746	2.267	-2.719	-2.040	26.8	227.6	89.0	84.9	4.04
T_H2	1.145	0.935	-1.131	-0.848	14.4	86.5	88.3	84.4	3.86
T_P1	-1.684	-1.044	1.701	1.145	16.9	101.5	97.7	101.1	3.42
T_P2	-1.165	-0.873	1.177	0.950	12.8	76.6	92.3	96.0	3.62
T_P3	-0.916	-0.687	0.925	0.740	8.7	52.3	87.9	90.9	2.99
T_P4	-1.886	-1.415	1.913	1.574	26.6	159.6	84.6	88.9	4.29
T_P5	-1.598	-0.991	1.616	1.094	17.3	103.7	83.7	86.9	3.16
T1	12.209	10.676	-12.161	-9.727	47.4	948.3	100.0	101.1	1.08
DZ P1-P2	10.460	8.582	-10.112	-7.963	348.3	619.0	101.1	96.0	5.12
DZ P1-P14	4.738	3.576	-4.534	-3.390	204.5	186.3	96.0	90.9	5.04
DZ P1-P16	3.609	2.650	-3.534	-2.608	74.4	42.3	90.9	88.9	1.99
DZ P1-P17	1.659	1.087	-1.616	-1.094	42.9	-7.5	88.9	86.9	2.03
					1108.2	2778.0			

b. Branch losses summary report

Fig. 7 Simulation results with no capacitor bank



a. Power flows in whole system

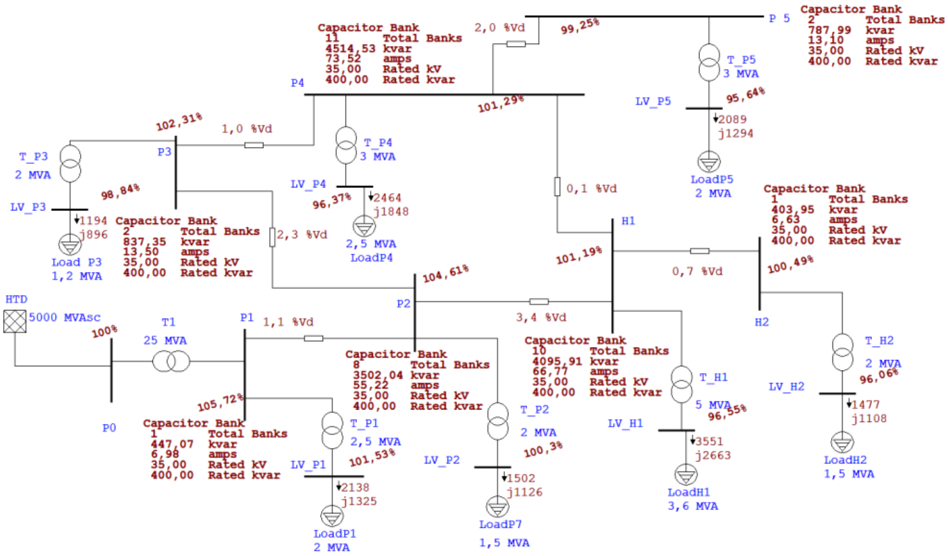
	Cost ($)		Saving ($)		
Year	**Installation**	**Operation**	**Loss Reduction**	**Yearly Profit**	**Accumulative Profit**
1	273800.00	12200.00	393186.90	107186.90	107186.90
2	0.00	12200.00	393186.90	380986.90	488173.90
3	0.00	12200.00	393186.90	380986.90	869160.80
4	0.00	12200.00	393186.90	380986.90	1250148.00
5	0.00	12200.00	393186.90	380986.90	1631135.00

b. Optimal capacitor placement cost summary

CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
15	1.513	-0.041	-1.505	0.024	7.8	-16.6	102.6	102.1	0.52
DZ P1-P3	-5.130	0.059	5.329	0.065	199.1	124.6	102.6	106.6	3.98
DZ P1-P19	-0.011	-1.311	0.021	1.278	10.4	-33.1	102.6	103.1	0.49
T_H1	3.628	1.293	-3.605	-1.093	23.5	200.2	102.6	100.3	2.26
T_H2	1.505	1.226	-1.486	-1.115	18.6	111.5	102.1	97.7	4.38
T_P1	-2.167	-0.464	2.186	0.574	18.4	110.2	104.9	106.9	2.05
T_P2	-1.539	0.202	1.550	-0.137	11.0	65.7	106.3	106.6	0.25
T_P3	-1.206	-0.904	1.217	0.973	11.4	68.3	101.2	104.6	3.42
T_P4	-2.517	-0.234	2.538	0.361	21.2	127.1	101.7	103.1	1.44
T_P5	-2.115	-0.920	2.133	1.032	18.7	112.0	98.8	101.5	2.73
T1	15.687	-4.663	-15.638	5.628	48.3	965.6	100.0	106.9	6.91
DZ P1-P2	13.453	-5.745	-13.090	6.384	362.6	638.7	106.9	106.6	0.31
DZ P1-P14	6.210	-1.768	-6.016	1.924	194.1	156.2	106.6	104.6	1.94
DZ P1-P16	4.799	0.608	-4.734	-0.581	65.4	26.9	104.6	103.1	1.56
DZ P1-P17	2.175	-0.633	-2.133	0.616	41.2	-17.2	103.1	101.5	1.59
					1051.5	2640.0			

c. Branch losses summary report

Fig. 8 Simulation results in the first compensation case study



a. Power flows in whole system

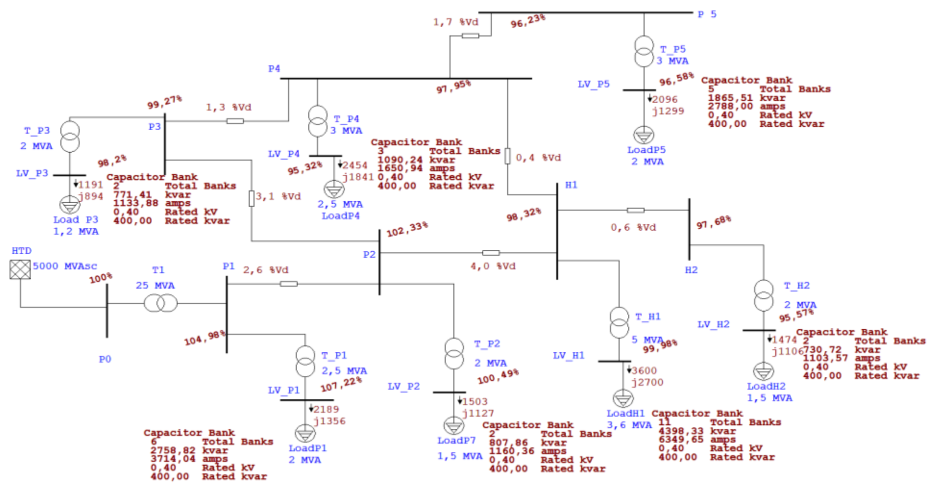
	Cost ($)		Saving ($)		
Year	**Installation**	**Operation**	**Loss Reduction**	**Yearly Profit**	**Accumulative Profit**
1	260400.00	14000.00	392492.10	118092.10	118092.10
2	0.00	14000.00	392492.10	378492.10	496584.10
3	0.00	14000.00	392492.10	378492.10	875076.20
4	0.00	14000.00	392492.10	378492.10	1253568.00
5	0.00	14000.00	392492.10	378492.10	1632060.00

b. Optimal capacitor placement cost summary

CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
15	1.506	0.803	-1.496	-0.818	10.2	-14.6	101.2	100.5	0.70
DZ P1-P3	-5.198	0.801	5.414	-0.652	215.7	148.6	101.2	104.6	3.42
DZ P1-P19	0.105	-0.472	-0.104	0.435	1.4	-37.1	101.2	101.3	0.10
T_H1	3.586	2.964	-3.551	-2.663	35.3	300.2	101.2	96.5	4.64
T_H2	1.496	1.221	-1.477	-1.108	19.0	113.8	100.5	96.1	4.43
T_P1	-2.138	-1.325	2.163	1.476	25.2	151.4	101.5	105.7	4.19
T_P2	-1.502	-1.126	1.520	1.234	18.0	108.0	100.3	104.6	4.31
T_P3	-1.194	-0.896	1.206	0.966	11.7	70.3	98.8	102.3	3.47
T_P4	-2.464	-1.848	2.499	2.058	35.0	210.0	96.4	101.3	4.92
T_P5	-2.089	-1.294	2.111	1.430	22.6	135.7	95.6	99.2	3.61
T1	15.469	-1.544	-15.425	2.415	43.6	871.3	100.0	105.7	5.72
DZ P1-P2	13.262	-3.444	-12.936	4.014	325.5	569.5	105.7	104.6	1.11
DZ P1-P14	6.003	-1.094	-5.823	1.236	180.1	142.5	104.6	102.3	2.31
DZ P1-P16	4.616	-1.365	-4.549	1.395	67.6	30.1	102.3	101.3	1.01
DZ P1-P17	2.154	0.627	-2.111	-0.642	42.2	-15.5	101.3	99.2	2.05
					1053.1	2784.2			

c. Branch losses summary report

Fig. 9 Simulation results in the second compensation case study



a. Power flows in whole system

Year	Cost ($)		Saving ($)		
	Installation	Operation	Loss Reduction	Yearly Profit	Accumulative Profit
1	155800.00	3100.00	411695.20	252795.20	252795.20
2	0.00	3100.00	411695.20	408595.20	661390.30
3	0.00	3100.00	411695.20	408595.20	1069986.00
4	0.00	3100.00	411695.20	408595.20	1478581.00
5	0.00	3100.00	411695.20	408595.20	1887176.00

b. Optimal capacitor placement cost summary

CKT / Branch	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop
ID	MW	Mvar	MW	Mvar	kW	kvar	From	To	in Vmag
15	1.496	0.439	-1.487	-0.453	9.0	-14.2	98.3	97.7	0.64
DZ P1-P3	-5.288	0.369	5.519	-0.195	231.7	173.7	98.3	102.3	4.02
DZ P1-P19	0.165	0.666	-0.162	-0.700	3.4	-33.7	98.3	97.9	0.37
T_H1	3.626	-1.473	-3.600	1.699	26.5	225.1	98.3	100.0	1.66
T_H2	1.487	0.453	-1.474	-0.375	13.0	78.1	97.7	95.6	2.11
T_P1	-2.189	1.402	2.213	-1.258	24.2	144.9	107.2	105.0	2.24
T_P2	-1.503	-0.319	1.515	0.391	12.0	72.1	100.5	102.3	1.84
T_P3	-1.191	-0.122	1.199	0.168	7.6	45.9	98.2	99.3	1.07
T_P4	-2.454	-0.750	2.479	0.899	24.8	149.0	95.3	97.9	2.63
T_P5	-2.096	0.566	2.114	-0.462	17.3	103.9	96.6	96.2	0.35
T1	15.516	0.414	-15.472	0.454	43.4	868.6	100.0	105.0	4.98
DZ P1-P2	13.260	0.803	-12.949	-0.261	310.7	542.7	105.0	102.3	2.64
DZ P1-P14	5.915	0.064	-5.738	0.079	177.3	143.0	102.3	99.3	3.06
DZ P1-P16	4.538	-0.247	-4.474	0.275	64.0	28.8	99.3	97.9	1.33
DZ P1-P17	2.157	-0.475	-2.114	0.462	43.5	-12.9	97.9	96.2	1.71
					1008.4	2515.0			

c. Branch losses summary report

Fig. 10 Simulation results in the third compensation case study

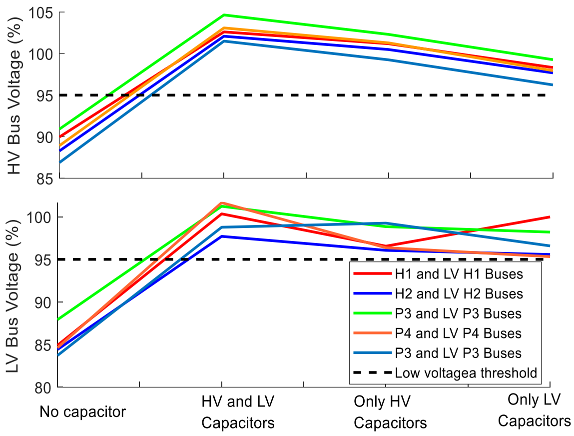


Fig. 11. Voltage values in case of without capacitor and three compensation case studies

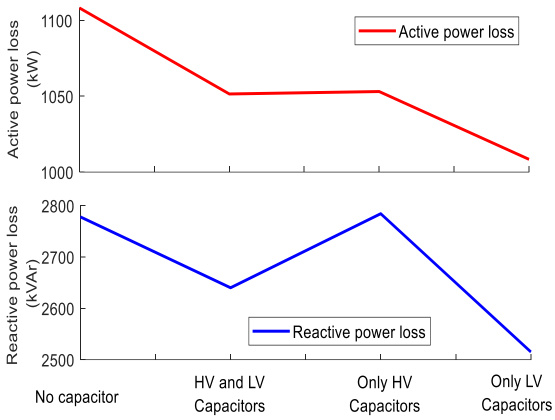


Fig. 12. Active and reactive power losses

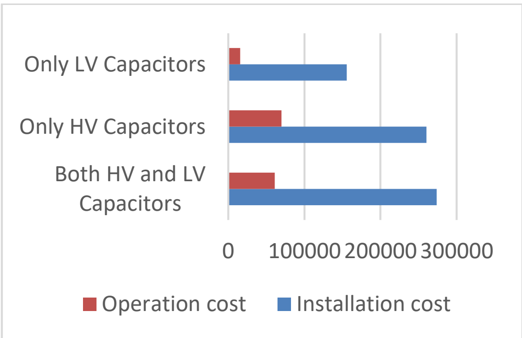


Fig. 13. Installation and operation cost

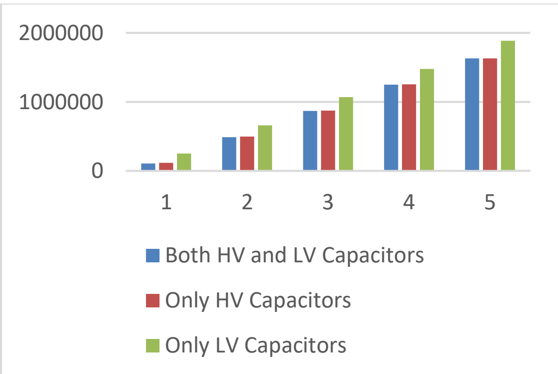


Fig. 14. Accumulative profit saving

Fig. 11 showed almost voltage values were smaller than allowable value (0.95 p.u) in case of without capacitors. After using OCP tool in both case studies, voltage values were higher than 0.95 p.u.

Capacitor placements in each compensation scheme affect much to voltage buses. In the first compensation case study, voltage values of almost buses are approximately rated voltage. In the third compensation case study, voltage values of almost buses are only higher than allowable value a bit. In the second compensation case study, voltage values of almost buses are better than the third case study but worse than the first case study.

When evaluating compensation capacity, TABLE V showed that the capacity in the first case study is highest and the capacity in the third case study is lowest. The reason for this is that the voltage buses is directly related to reactive power distribution. In case of allowing at both HV and LV buses, power losses in transmission lines is significantly reduced because reactive power in transmission lines were reduced and power load also met directly by large capacity of capacitors at LV buses that reduced power flow through transformers as depicted in Fig. 12. In case of allowing at only LV buses, power losses are lowest because almost reactive power requirements met by capacitors with smallest capacity. Above analysis showed the meaning of compensation problem with voltage restraint using OCP tool.

Fig. 13 showed that the third case study had smallest installation and operation cost very much. Reason is that cost for capacitors and controllers of LV capacitor banks is always lower than those in HV. At the same time, smaller power losses also lead to smaller operation cost and highest accumulative profit saving when compared with remaining compensation schemes as depicted in Fig. 14. The above analysis shows that the third case study has the lowest total installed capacity and brings the highest efficiency. It means that this case study can be considered the most optimal one in terms of economic and technical aspects.

V. CONCLUSION

The contribution of this article is to compare the economic and technical factors of the capacitor compensation problem in three case studies. Candidate placements for capacitors are both HV and LV buses, only HV buses and only LV buses. OCP tool in ETAP software is used to set voltage restraint, limitation for number of capacitor banks, capacity of each capacitor bank, cost for electricity, costs for capacitor installation and operation. Through setting the constraint and economic-technical parameters of the optimization problem, the article has shown that LV buses are considered the most suitable candidates for capacitor installation.

The results of the article are achieved through the use of Newton-Raphson method to analyze power flows in whole system and OCP tool in ETAP software to determine the optimal compensation capacity. These capacitor banks help voltage buses be improved with the lowest installation and operation costs and the highest overall benefits. The results obtained from the simulation process in ETAP software have been compiled into graphs, thereby providing an overall view of economic and technical factors when comparing compensation schemes. This is considered one of the scientific contributions of the article.

The idea of determining the optimal compensation placements and sizes shown in this article can help manager make schemes to calculate compensation for any distribution system. Moreover, they can use OCP tool in ETAP software to get a fast calculation that ensures enough reliability. The results of this research can be further developed to apply controlled capacitor banks, thereby improving the operating efficiency of the power system, reducing power losses while still improving power quality, reducing operating costs for the whole power system.

Declaration by Authors

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