Impact of Capacitor Banks on Voltage Profile and Power Losses in Medium Voltage Power Systems

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***Abstract*— This paper studies the impact of capacitor banks on voltage profile and power losses in medium voltage power systems. Corresponding to compensative levels, some case studies are considered to evaluate the effect of capacitors to power systems such as no capacitor bank, a capacitor bank at a bus and some capacitor banks in whole system. A simple power system is consider to analyze values of bus voltage, power losses and power flows. The Newton-Raphson method is also made more detailed in case studies of having the participation of capacitor banks at any bus in complex systems. ETAP software is used to simulate and determine all parameters and evaluate the meaning of capacitor banks. Carried out by ETAP, voltage quality and power losses can be improved very much corresponding to the high value for capacitor banks at some buses. To have higher quality for values of bus voltage and smaller power losses, capacitor banks must be combined with other distributed power sources.**

***Index Terms*—Capacitor bank, compensation, ETAP software, power losses, reactive power, voltage quality.**

I. INTRODUCTION

Power sources in power system are designed to meet many different requirements of loads and transmission lines. There are many types of power sources, such as power plants, renewable sources, capacitors,... These sources can generate only active power, only reactive power or both active and reactive powers. In these sources, a parallel capacitor is considered as a reactive generator that helps to regulate bus voltage and power flows in whole system [1].

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 1.05pu (105%) for medium voltage power systems [2]. At time having high load levels, values of bus voltage can be out of above range and cause much power losses. A solution to overcome this problem is that uses parallel capacitors with continuous adjustment [1] or multi-level adjustment [3], [4], [5]. Continuous adjustment uses devices in FACTS (Flexible AC Transmission System) and requires high technique to regulate. Multi-level adjustment uses circuit breakers to switch on/off branches in capacitor banks. With multi-level adjustment, individual capacitor bank will be added in case of having lower voltage value than minimum threshold or released in case of having higher voltage value than maximum threshold. Multi-level compensation is suitable for medium voltage power system with low cost, easy to execute in acceptable efficiency. So, multi-level compensation will be main object in this study.

Due to the participation of capacitor banks, values of bus voltage and power flows in whole system change and must be determined to evaluate its parameters. ETAP software has been used recently to analyze power systems due to having high accuracy, and being easy to modify solvers and system structure. One of solver that is often to used in ETAP software is Newton-Raphson method with the assignment of values of loads, generations and bus types.

To make more detailed about the effect of capacitors to system parameters, section II will represent a simple method to determine values of bus voltage, power losses and power flows in transmission line in a power system with the participation of a capacitor at the end of transmission line. Moreover, section II will also represent equations and the Newton-Raphson algorithm applied in complex power systems with the participation of capacitor banks. Section III will use the Newton-Raphson method in ETAP software to analyze an complex power system example in different cases such as no capacitor, multi-level capacitor bank at a bus and capacitor banks at multi buses. The last section will give out some conclusions.

II. METHOD TO DETERMINE SYSTEM PARAMETERS

The structure of the hybrid power generation system is represented in Fig. 1. It has DC coupled structure with three main blocks for power circuit, forecasting, measurement, dispatch and control with [1-6].

A simple power system with the participation of a capacitor bank at bus j is considered in Fig. 1 [6].

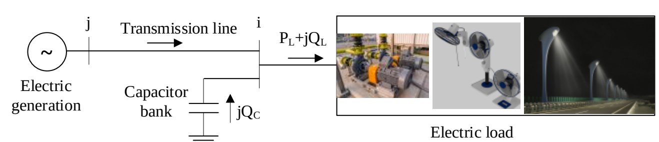

Fig. 1 A simple power system with the participation of a capacitor bank at the ith bus.

In Fig.1, a capacitor bank contributes a reactive power QC into bus i. This capacitor bank can have some levels to adjust compensative capacity corresponding to the requirement of dispatchers.

In this system, active and reactive power losses in transmission line can be determined by (1) [6]:

$$\begin{cases} \Delta P_{line} = \dfrac{P_L^2 + Q_L^2}{U_{rated}^2} R_{line} \times 10^{-3} \\ \Delta Q_{line} = \dfrac{P_L^2 + (Q_L - Q_C)^2}{U_{rated}^2} X_{line} \times 10^{-3} \end{cases} \quad (1)$$

where, P_L and ΔP_{line} (kW) are active power of load and active power loss in transmission line,

Q_C (kVAr) is the capacitive power integration into bus j,

Q_L and ΔQ_{line} (kVAr) are reactive power of load and reactive power loss in transmission line,

U_{rated} (kV) is rated voltage of the system,

R_{line} and X_{line} (Ω) are resistance and reactance of the transmission line.

Voltage loss at bus j can be determined by (2):

$$\Delta U_{line} = \frac{P_L R_{line} + (Q_L - Q_C) X_{line}}{U_{rated}} \quad (2)$$

It is easy to see that power and voltage losses can be reduced when the capacitor bank contribute a mount of compensative power. It showed the its meaning in power systems. When the system becomes more complex with many branches and buses, power flows in branches and bus voltage are also more difficult than above simple system. In these cases, Newton-Raphson method can be used to solve this problem due to having fast convergence and high accuracy [7]. It means that the active effect of capacitor banks to the system will be made easier and clearer if it is implemented at many buses with suitable capacity.

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 (3) and (4) [6]:

$$U_i^2 y_{ii} \cos\psi_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{N} U_i U_j y_{ij} \cos(\delta_i - \delta_j - \psi_{ij}) = \Delta P_i \quad (3)$$

$$-U_i^2 y_{ii} \sin\psi_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{N} U_i U_j y_{ij} \sin(\delta_i - \delta_j - \psi_{ij}) = \Delta Q_i \quad (4)$$

where: $i = \overline{1, N}$; $\Delta P_i = P_{Li}$; $\Delta Q_i = Q_{Li} - Q_{Ci}$;

$\dot{U}_i = U_i \angle \delta_i$; $Y_{ij} = y_{ij} \angle \psi_{ij}$

P_{Li} and Q_{Li} are active and reactive load powers at the ith bus; Q_{Ci} are reactive power of the capacitor bank at the ith bus. Because the capacitor bank is considered as a reactive generator, integrating power between the capacitor bank and the system as defined by (5):

$$\begin{cases} P_{Gi} = 0 \\ Q_{Gi} = Q_{capacitor}\big|_{k\_bank} \end{cases} \quad (5)$$

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 (6) [6]:

$$\begin{bmatrix} \delta_i^{(k+1)} \\ U_i^{(k+1)} \end{bmatrix} = \begin{bmatrix} \delta_i^{(k)} \\ U_i^{(k)} \end{bmatrix} + \begin{bmatrix} \Delta\delta_i^{(k)} \\ \Delta U_i^{(k)} \end{bmatrix} \quad (6)$$

where, $\Delta U_i^{(k)}$ and $\Delta\delta_i^{(k)}$ are module and angle errors of bus voltage at the i^{th} bus and the k^{th} step. These errors can be calculated by (7) at the k^{th} step [6]:

$$\begin{bmatrix} \Delta\delta_i^{(k)} \\ \Delta U_i^{(k)} \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P_i^{(k)} \\ \Delta Q_i^{(k)} \end{bmatrix} \quad (7)$$

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

Newton-Raphson algorithm applied to determine operating parameters with the participation of capacitor banks is described in Fig. 2 [6].

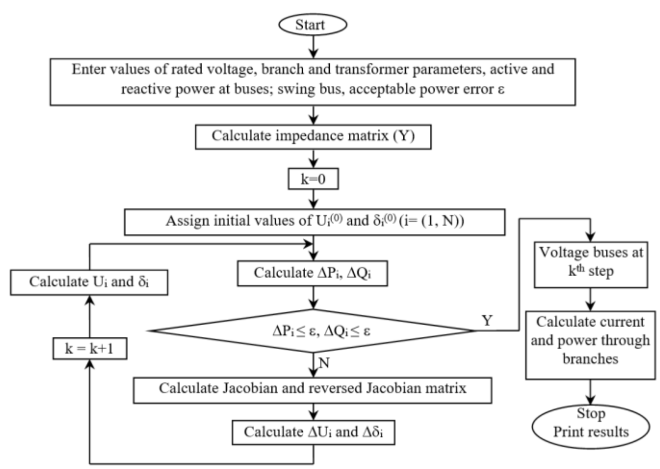

Fig. 2 Newton-Raphson algorithm to determine system parameters

III. Simulation Results

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

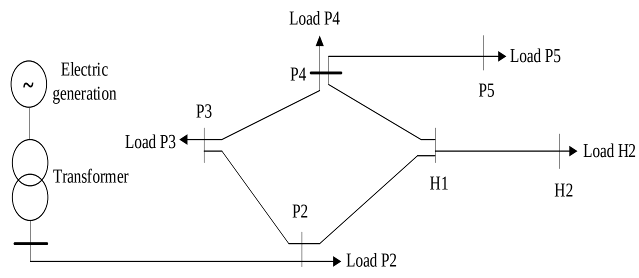

Fig. 3 Diagram of simulation system

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

TABLE I. 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

TABLE II. 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

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 III. 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 improve voltage quality, some case studies are considered as shown in Table 4 with some capacitor banks in P4, P5, and H1 buses.

Using capacitor banks are proposed to locate at P5 bus with three rated levels: 600 kVAr, 1200 kVAr, and 1800 kVAr. Simulation results in theses cases are represented in Fig. 5, Fig. 6, and Fig. 7.

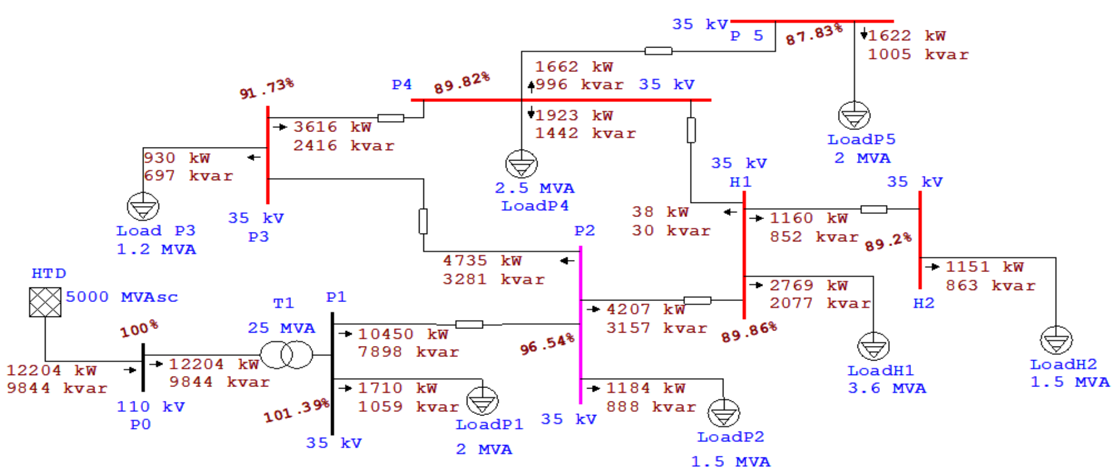

Fig. 4 Simulation results with no capacitor bank

TABLE IV. CASE STUDIES WITH CAPACITOR BANKS

	1st case	2nd case	3rd case	4th case		5th case		
Location	P5	P5	P5	P4	P5	P4	P5	H1
Rated capacity	600 kVAr	1200 kVAr	1800 kVAr	1800 kVAr	1800 kVAr	1800 kVAr	1800 kVAr	1800 kVAr
Rated capacity/reactive load power	9.05%	18.1%	27.15%	54.3%		81.45%		

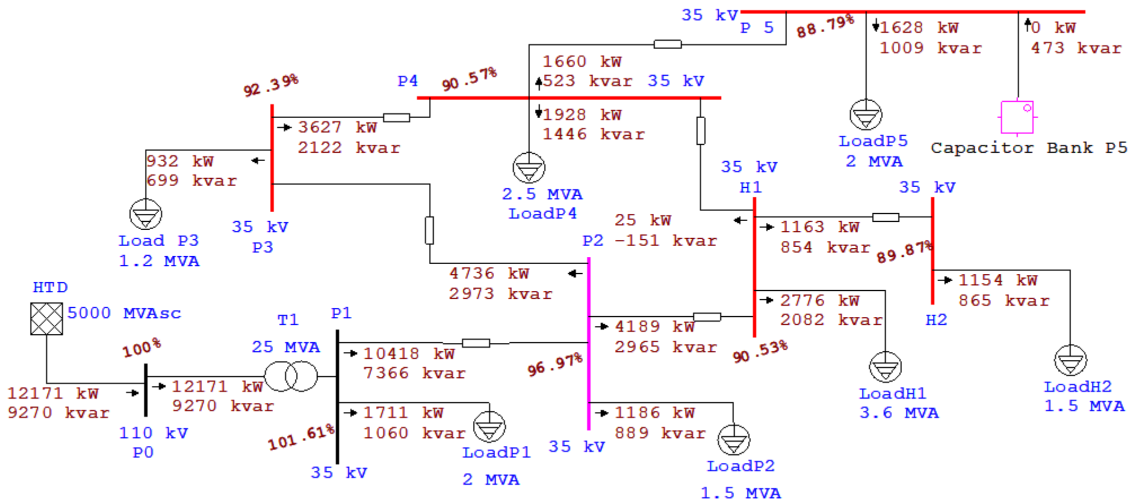

Fig. 5 Simulation results in the 1st case

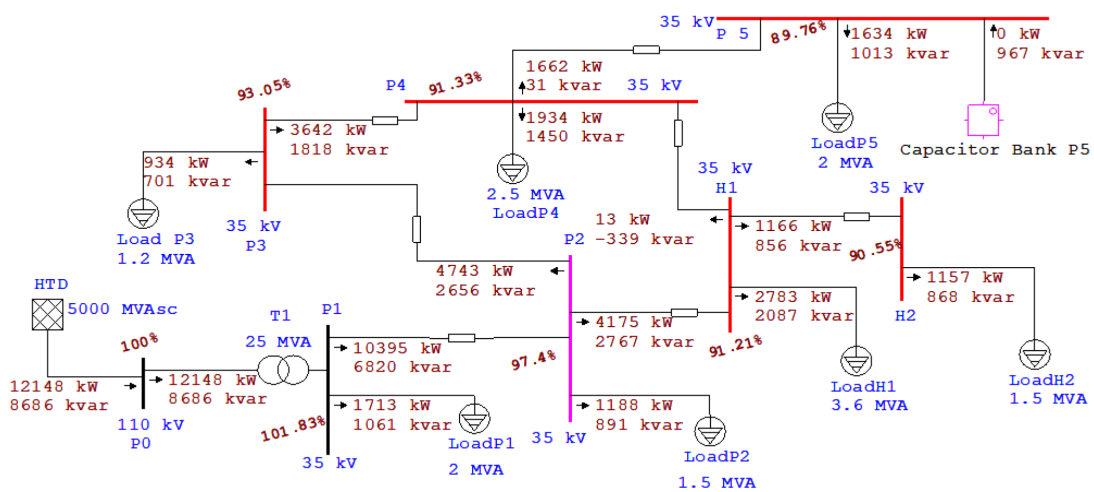

Fig. 6 Simulation results in the 2nd case

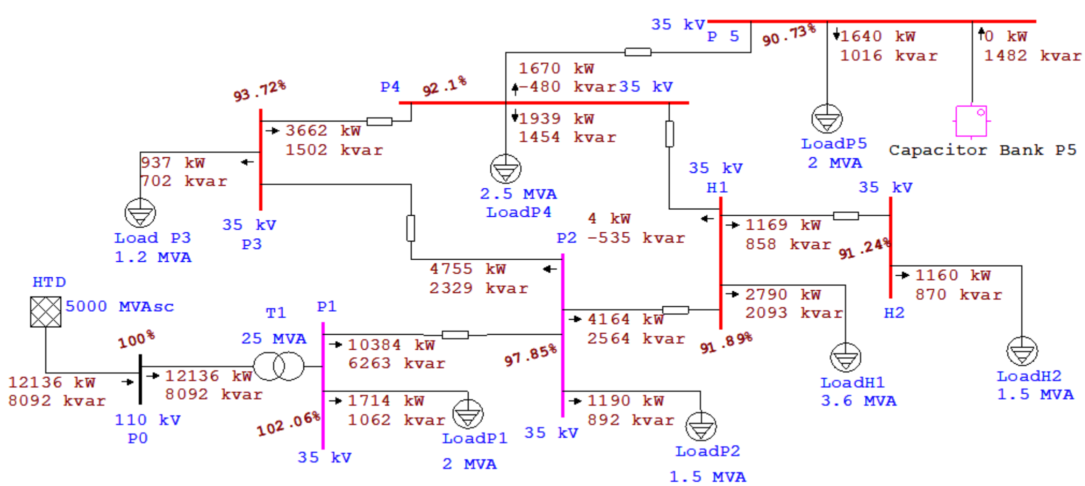

Fig. 7 Simulation results in the 3rd case

From above simulation results, we can see the meaning of each capacitor bank at bus P5. It helps to improve the voltage quality at all buses in the power system because the smaller reactive load power flows are transmitted that make voltage losses reduce. In fact, the compensation at a bus can not bring high efficiency because it must be improve voltage values of at generation-side buses and neighbor buses. To make more detailed about this, this study will assume two additional cases simulated and represented: capacitor banks are implemented at P4 and P5 buses in Fig. 8; at P4, P5, and H2 buses in Fig. 9.

From simulation results in Fig. 5, Fig. 6, Fig. 7, Fig. 8, and Fig. 9, the change of power flows in transmission lines is represented in Table. 5.

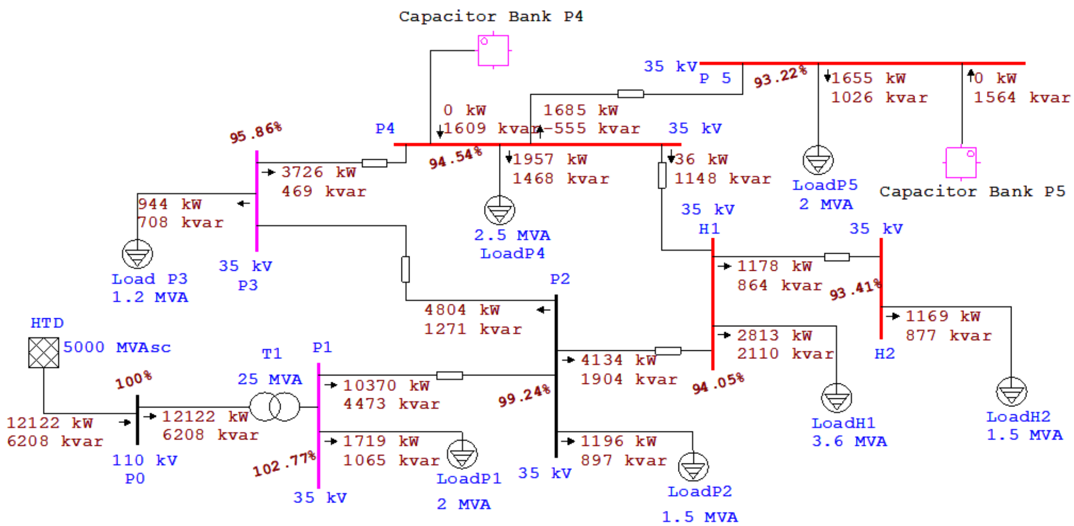

Fig. 8 Simulation results in the 4th case

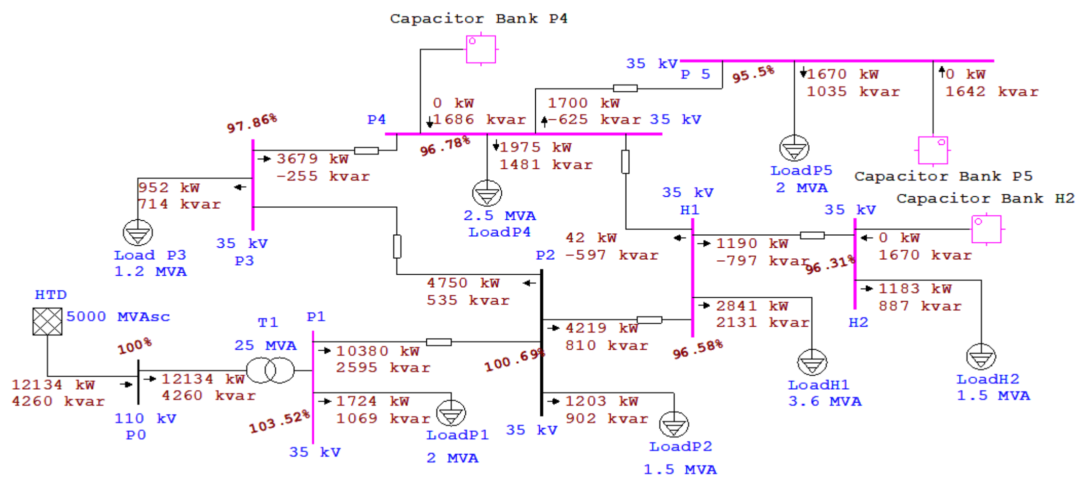

Fig. 9 Simulation results in the 5th case

TABLE V. POWER FLOWS IN TRANSMISSION LINES

Power flows (kW+jkVAr) / Transmission lines	No compensator	The 1st case	The 2nd case	The 3rd case	The 4th case	The 5th case
P1-P2	10450+j7898	10418+j7366	10395+j6820	10384+j6263	10370+j4473	10380+j2595
P2-P3	4735+j3281	4736+j2973	4743+j2656	4755+j2329	4804+j1271	4750+j535
P4-H1	38+j30	25-j151	13-j339	4-j535	36+j1148	42-j597
P4-P5	1662+j996	1660+j523	1662+j31	1670-j480	1685-j555	1700-j625
P3-P4	3616+j2416	3627+j2122	3642+1818	3662+j1502	3726+j469	3679-j255
P2-H1	4207+j3157	4189+j2965	4175+j2767	4164+j2564	4134+j1904	4219+j810
H1-H2	1160+j852	1163+j854	1166+j856	1169+j858	1178+j864	1190-j797
P0-P1	12204+j9844	12171+j9270	12148+j8686	12136+j8092	12122+j6208	12134+j4260
Total power loss	916.3+j1812.2	856.3+1691.9	806+j1582	766.1+j1483.4	666.3+j1228.2	586+j1037.9

From received results in Table 5, the participation of capacitor banks changes the power flows in whole system. They help to reduce power mobilized from electric source and can reverse reactive power in transmission lines. The active effect of capacitor banks to active and reactive powers is depicted in Fig. 10.

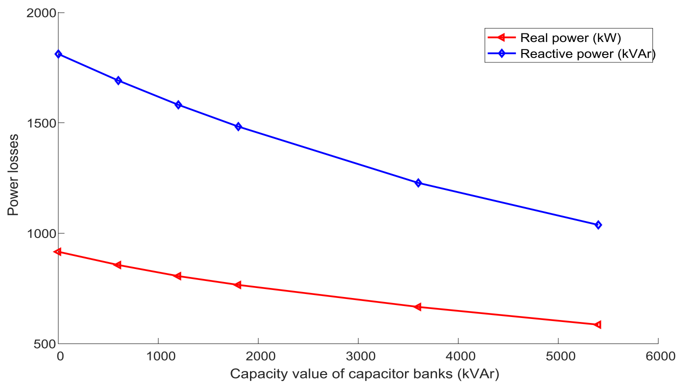

Fig. 10. Relation of power losses and capacity value of capacitor banks

The relation of bus voltage and capacity value of capacitor banks is shown in Fig. 11. All values of bus voltage in whole system are only higher than 95% in the 5th case (corresponding to 81.45% total load power). It means that it has to implement capacitor banks at some buses to improve voltage quality and must be combined with other solutions to have higher effects.

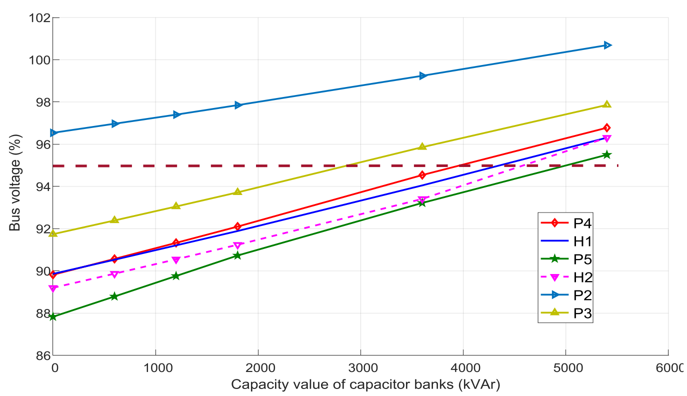

Fig. 11. Variation of bus voltage corresponding to capacity value of capacitor banks

IV. CONCLUSION

The contribution of this paper is to analyze the effect of capacitor banks in medium voltage system. A simple power system is considered to make clear about power flows and voltage at a bus having the participation of capacitor banks. Equations for balancing power at all buses and Newton-Raphson method to determine system parameters such as voltage, power flows in transmission lines are represented in this paper. Above method is used in ETAP software for 35kV power system having 8 buses to evaluate voltage quality and power losses in transmission lines in cases of having capacitor banks with three-level compensation at a bus and at three buses in the system.

Simulation results received from ETAP software showed that capacitor bank at only one bus can not make high benefit although compensative capacity is higher than reactive load power at the bus having the participation of the capacitor bank. In cases of using capacitor banks at some buses with 81.45% total load power, values of bus voltage are higher than allowable value. Moreover, power losses in whole system decreases very much due to the decrease of values and direction of power flows in transmission lines.

The intervening of capacitor banks helps to improve voltage quality and power losses in power systems. Capacitance of capacitors must be changed corresponding to the model of FACTS model to make flexible for capacitor capacity. To meet requirement of low cost, multi-level capacitor banks can be executed by circuit breakers. This study show the meaning of capacitor banks to improve voltage quality at all buses but it must be combined with renewable sources such as wind, photovoltaic,...

ACKNOWLEDGMENTS

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