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APPLICATION OF STATCOMS TO IMPROVE STATIC VOLTAGE STABILITY FOR VIETNAM POWER SYSTEM WITH GRID CONNECTION OF LARGE NUCLEAR POWER PLANT

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ABSTRACT

The aim of this paper is to analyze static voltage stability of Vietnam power network at the level of 500 kV with the connection of the nuclear power plant and apply STATCOMs to improve the voltage stability of the system. Power system simulator for engineer (PSS/E), which is a powerful software for power system transmission analysis and generation performance in steady state and dynamics conditions, is employed for implementing and analyzing static voltage stability in this paper. To put it another way, P-V and Q-V analysis are carried out to assess both voltage stability and transfer capability of the power network corresponding to the normal operation mode and contingency modes. The purpose of the analysis is to define the unstable voltage buses and contingencies that potentially affect the voltage stability. Moreover, STATCOMs application to enhance voltage stability, power transfer as well as voltage quality of the Vietnam's power system is carried out.

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1 INTRODUCTION

In recent years, many studies about voltage stability, especially in the field of static voltage stability, have been carried out and made considerable progress because voltage instability goes on emerging in many countries. In Vietnam, voltage stability becomes a popular issue in a developing power network. Vietnamese network has been expanded with more complicated structure in recent years together with the fast growth of power load. In order to meet the demand of rapid increase in electrical load, especially in the South, according to the 7th Power Development Master Plan (2011 – 2020) with view 2030, the first nuclear power plant will be built in Ninh Thuan province and start generating power in 2020 together with the existing power plants in the South to support electric power for heavy load in this region (Dung, 2011). Therefore, in order to assure the reliability, security and economic operation of the system as well as the nuclear power plant, static voltage stability and power transfer capability of the network involving the nuclear power plant are carried out to find countermeasures for the enhancement of voltage stability and power transfer of the network.

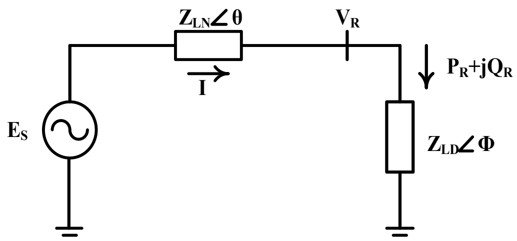
In this paper, static voltage stability and power transfer capability of the network involving the nuclear power plant are studied so as to evaluate the security, reliability and operation of Vietnam power system and the transmission lines connected to the nuclear power plant. Besides, reactive power compensation with STATCOMs is conducted for application in the network to enhance the voltage stability margin and power transfer capability. The research work is analyzed based on Vietnam's 500 kV power system model (2011 – 2020) with view 2030.

The structure of the paper is following. Sections 2 and 3 describe theory about voltage stability analysis and shunt compensation for transmission line, respectively. Section 4 illustrates static voltage stability analysis of Vietnam power system with grid connection of large nuclear power plant. Section 5 describes the application of shunt compensators for improving voltage stability and power transfer capability for the power network. Section 6 concludes the paper.

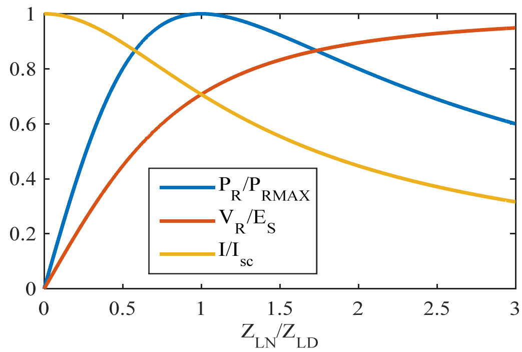
2 VOLTAGE STABILITY ANALYSIS

2.1 Voltage stability analysis by P-V curves

The simple radial power system is shown in Figure 1a. From the schematic diagram of the system, the quantities of current, voltage and power at receiving end are given by the following equations:



(a)



(b)

Fig. 1: Characteristics of a simple radial system (Kundur, 1994)

The current: (1) $I = \frac{1}{\sqrt{F}}\frac{E_S}{Z_{LN}}$

The receiving end voltage: (2) $V_R = \frac{1}{\sqrt{F}}\frac{Z_{LD}}{Z_{LN}}E_S$

The power supplied to the load: (3)

$$P_R = \frac{Z_{LD}}{\sqrt{F}}\left(\frac{E_S}{Z_{LN}}\right)^2 \cos\phi$$

Where (4)

$$F = 1 + \left(\frac{Z_{LD}}{Z_{LN}}\right)^2 + 2\left(\frac{Z_{LD}}{Z_{LN}}\right)\cos(\theta - \phi)$$

E_S: the voltage source

Z_{LN}: the series impedance

Z_{LD}: load

Q_R: the reactive power at receiving end

I_{sc}: the short circuit current

P_{RMAX}: the maximum power transfer at unity power factor

Figure 1b shows that when the load demand is risen by declining Z_{LD}, there is a dramatic rise in the power P_R at first, then followed by a gradual downward trend after reaching the highest value. On the whole, with a constant voltage source the active power may be maximally transmitted through an impedance, a circumstance in which the values of current as well as voltage corresponding to the highest value of transmitted power are defined as critical values.

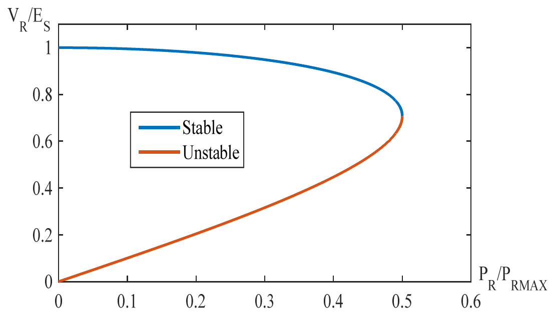


Fig. 2: The voltage and power characteristics of the simple radial system (Kundur, 1994)

The more traditional method plotting the family of normalized P-V curves is shown in Figure 2. The points above the critical operating points satisfy the operating conditions; moreover, the more leading power factors, the higher maximum transmitted power and the higher value of critical voltage (Bian *et al.*, 2013).

2.2 Voltage stability analysis by Q-V curves

The characteristics at different values of load power are illustrated in Figure 3, which can be used to consider requisites for reactive power compensation. The bottom of the curves, in which the derivative dQ_R/dV_R is zero, is not only referred to as voltage stability limit, but also specifies the minimal value of reactive power for stable operating condition (Huang *et al.*, 2007). The parts of the Q-V curves on the right hand side represent stable condition, where reactive power control devices are applied to raise the voltage corresponding to an increment in reactive power while the curves on the left side are associated with unstable operation region (Wang *et al.*, 2008).

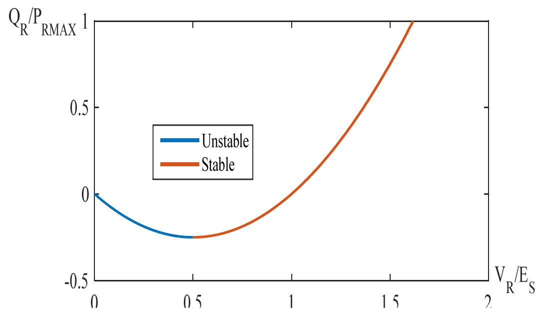


Fig. 3: V_R-Q_R characteristics of the system with different P_R/P_{MAX} ratio (Kundur, 1994)

3 SHUNT COMPENSATION FOR TRANSMISSION LINE

To control the voltage magnitude, enhance voltage quality as well as maintain voltage stability, shunt reactive compensation is one of the popular applications for power transmission system. In contrast, to absorb the reactive power due to over-voltage of transmission line, shunt-connected reactors are employed; whereas shunt-connected capacitors are applied to keep the levels of voltage by supplying reactive power for transmission line.

Figure 4 illustrates a simple transmission system connected by transmission line reactance X with shunt compensation, with assumption that the two buses have the same voltage V and different phase angle is δ. Moreover, the voltage at mid-point V_C, in which the controlled capacitor is connected, is kept constant as V.

The active power at bus 1 and 2 have the same value: (5) $P_1 = P_2 = 2\frac{V^2}{X}\sin\frac{\delta}{2}$

The reactive power of capacitor injected at mid-point: (6) $Q_C = 4\frac{V^2}{X}\left(1 - \cos\frac{\delta}{2}\right)$

Where

V: the voltage source

C: the capacitance

I_C: the current through the capacitor

P_{max}: the maximum active power

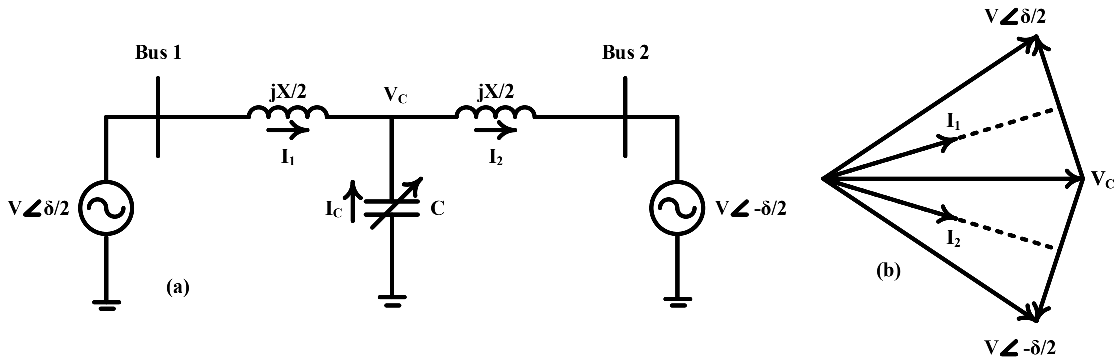


Fig. 4: Simple model (a) and phase diagram (b) of transmission system with shunt compensation

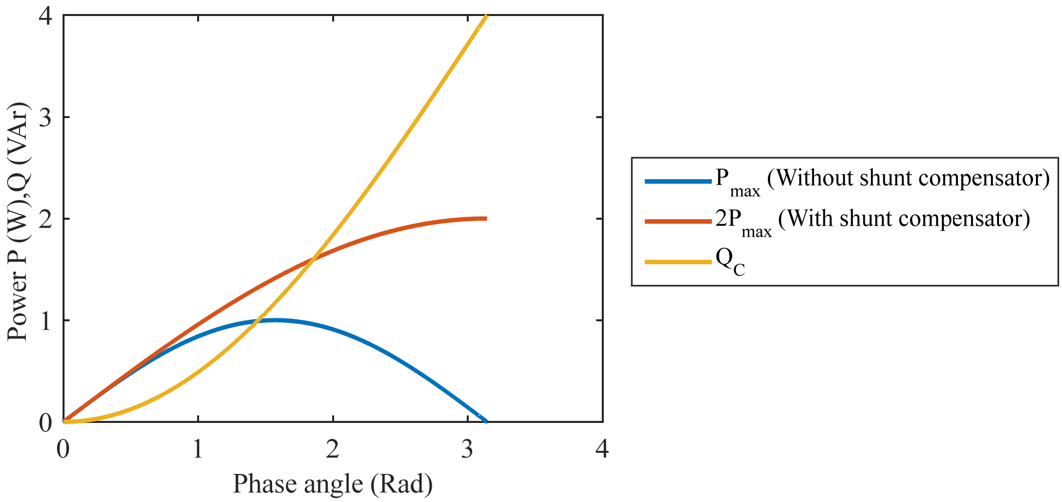


Fig. 5: The relationship between power and angle of a simple transmission system with shunt compensation

The power-angle curve in Figure 5 shows that the transmitted power is dramatically improved, with the maximum power shifting from 90^0 to 180^0. The shunt compensation may be extended at the end of radial system, a situation in which the compensation becomes more effective in improving voltage stability.

4 STATIC VOLTAGE STABILITY ANALYSIS OF THE POWER NETWORK WITH GRID CONNECTION OF LARGE NUCLEAR POWER PLANT

4.1 Introduction about Vietnamese power system

With reference to the annual report 2012 – 2013 of Viet Nam Electricity (EVN), the total amount of generation capacity installed made up 30597 MW by the end of 2013, which is contributed from various types of generation such as hydropower, gas turbine, wind power, coal fired as well as oil fired power, etc. (Vietnam Electricity, 2013). However, to keep pace with the high growth of power load new power plants will be built from the North to the South of Vietnam. As a matter of fact, the capacity of load in the South of Vietnam constitutes about half of the total load capacity of the nation, which may cause challenges for building new power plants because the power resources from gas and coal in the South are unstable. The result of such problems, the nuclear power plant is the priority and possible choice. The nuclear power plant (NPP) that will be simulated operates with the rate of power at 2000 MW, power factor at 0.85, the terminal voltage at 27 kV and the revolution at 2500 rpm (revolutions per minute).

The power network in Vietnam with vision to 2030 at the level of 500 kV is built according to the 7^{th} Master Plan (2011 – 2020), including 1680 generators, 18 substations, 43 buses and 78 transmission lines.

According to the geography in Vietnam, the national power system is dived into such three regions as North region, Central region and South region. The power network in three regions is electronically connected by parallel transmission lines. Most of power load centers are located in the North and in the South together with smaller amount of power load in the Central region. In addition, the nuclear power plant (G_NPP at bus 9), which will be integrated into Vietnam's 500 kV power network in 2020, is built in Ninh Thuan province as shown in Figure 6.

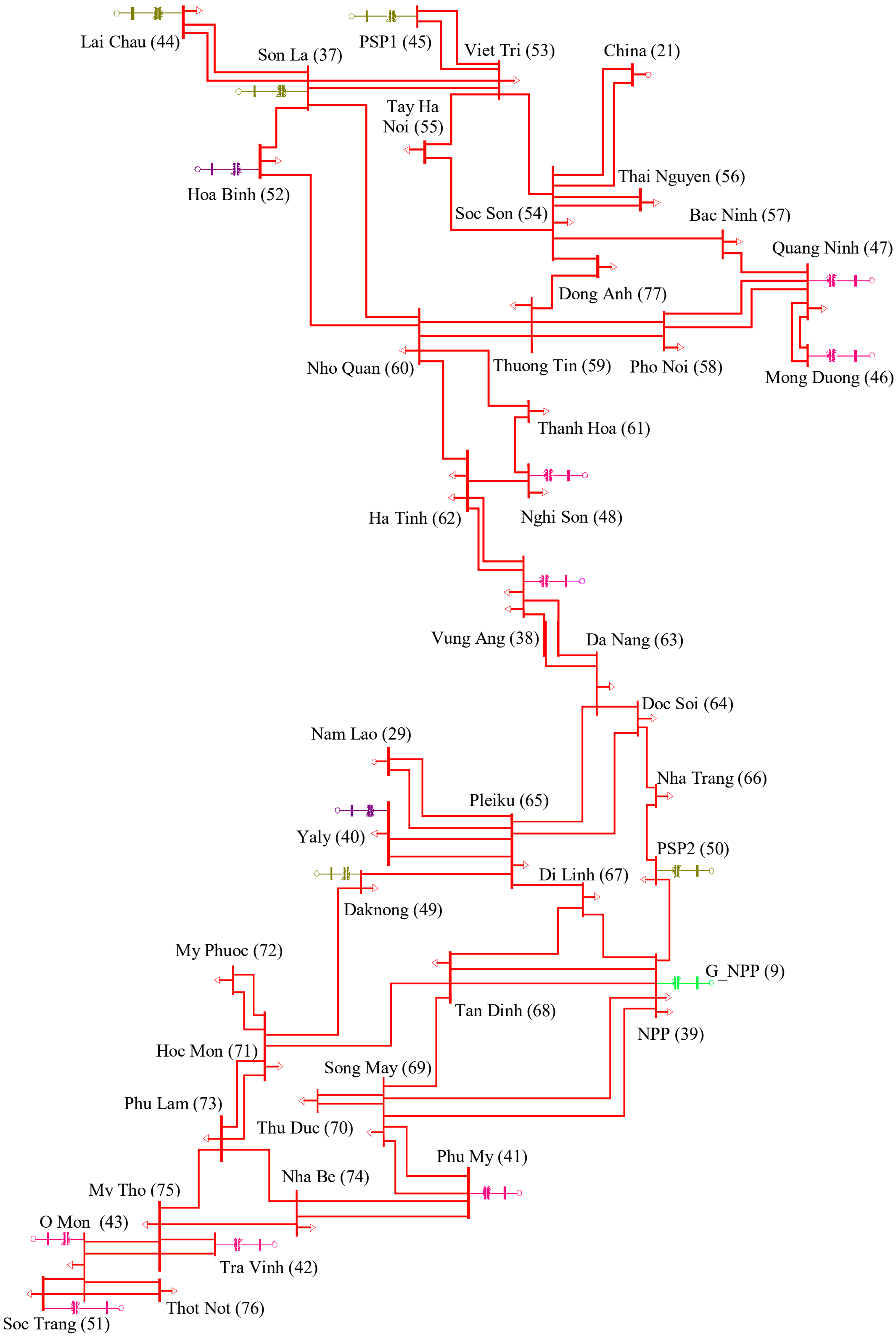


Fig. 6: Vietnam's 500 kV power system in period 2011 – 2020 with view 2030

4.2 Voltage stability analysis by P-V and Q-V curves in base case mode

Base case mode is defined as normal operation of the power system in which the P-V characteristic of Vietnamese network is implemented with the incremental power transferred from the North having power stations with high generation capacity to the South, of which is heavy power load and can suddenly witness a great load increment.

It can be seen from Figure 7 that power load centers locate in the North and the South of Vietnam, which are expressed by yellow region; in contrast, blue region indicates the locations where power plants are settled. Furthermore, the buses in the Central region, which is displayed by dark-yellow color, have low value of voltage because they are connected by long transmission lines.

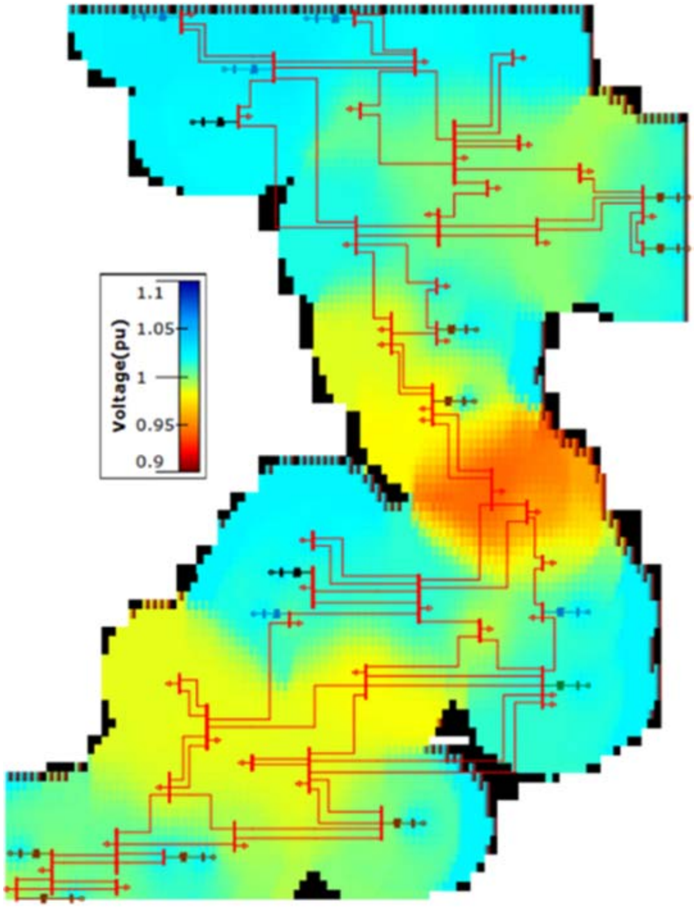


Fig. 7: Contour-diagram of Vietnam's 500 kV power system at normal operation mode

In the normal operation, the amount of active power transferred from the North to the South by the parallel transmission lines between Vung Ang and Da Nang is about 1132 MW on each single line. The voltage value at buses continues declining with the increase of the transmission power illustrated in Figure 8. Moreover, when the system load margin at buses rises to 1187.5 MW, the voltage collapse occurs rapidly. At the margin of the stability limit, Da Nang bus has the lowest value of voltage at 0.806 pu. The second lowest voltage at 0.852 pu is Doc Soi bus, followed by Vung Ang bus and Ha Tinh bus with the value being 0.886 pu and 0.91 pu, respectively. Beyond this limit, power-flow solution fails to converge; a situation may lead to voltage instability for the power system.

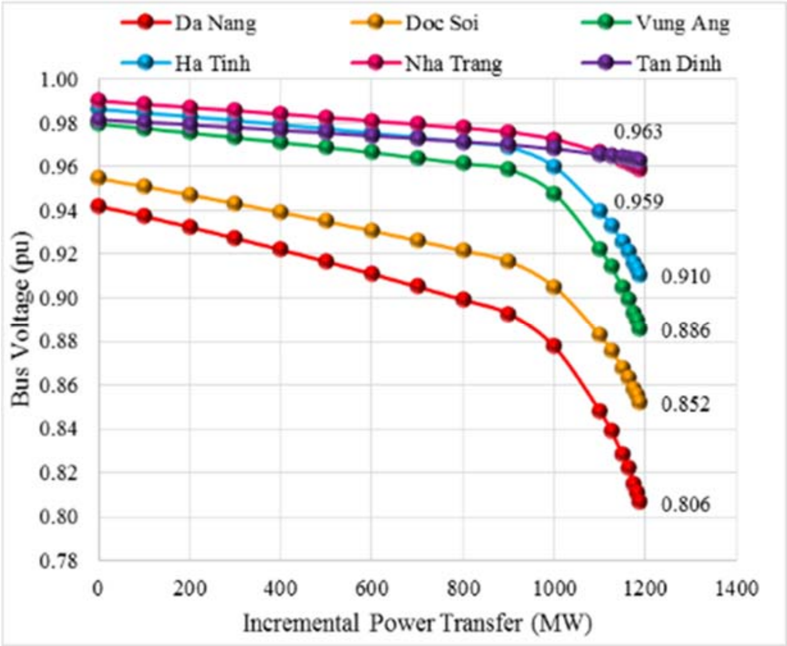


Fig. 8: P-V characteristics of buses at base case mode

It is shown in Figure 9 that two buses having the lowest value of reactive power margin are Da Nang and Doc Soi, with the former being of a slightly lower level than the latter (274.23 MVAr and 362.91 MVAr, respectively). This is followed by Vung Ang (637.73 MVAr) and Nha Trang (687.450 MVAr), leaving Daknong at 707.190 MVAr and Ha Tinh at 762.460 MVAr.

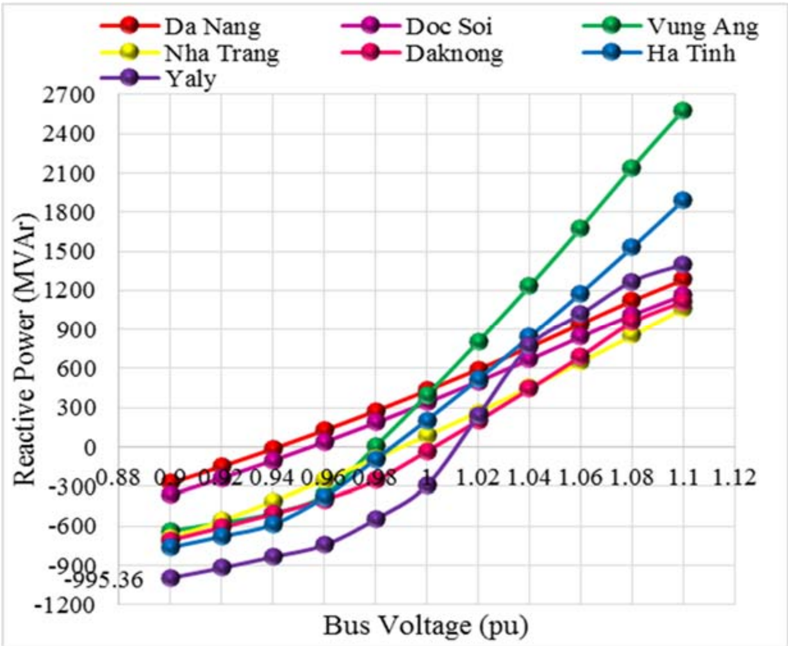


Fig. 9: Q-V curves of buses with value of reactive power margin lower than 1000 MVAr at base case

As a result of analyzing P-V and Q-V characteristic, power system in Vietnam has some such weak buses as Da Nang, Doc Soi, Vung Ang and Ha Tinh. They are not only of low voltage value at the margin of the stability limit but also have low reactive power margin.

4.3 Voltage stability analysis by P-V and Q-V curves at branch contingency mode

P-V characteristic of the network is analyzed with the most severe branch contingencies. Obviously, the transfer power limit of the system varies due to the change of the network structure.

The characteristics of P-V curves at Da Nang whose voltage value decreases dramatically in most of branch contingencies are shown in Figure 10. It can be seen that the branch contingency between Phu Lam (bus 73) and My Tho (bus 75) causes the most significant decline of the transfer power limit at 737.5 MW with the voltage value at 0.855 pu. The second lowest voltage is Doc Soi at 0.887 pu, followed by Vung Ang and Ha Tinh with the former having a slightly lower level than the latter (0.93 pu and 0.946 pu, respectively).

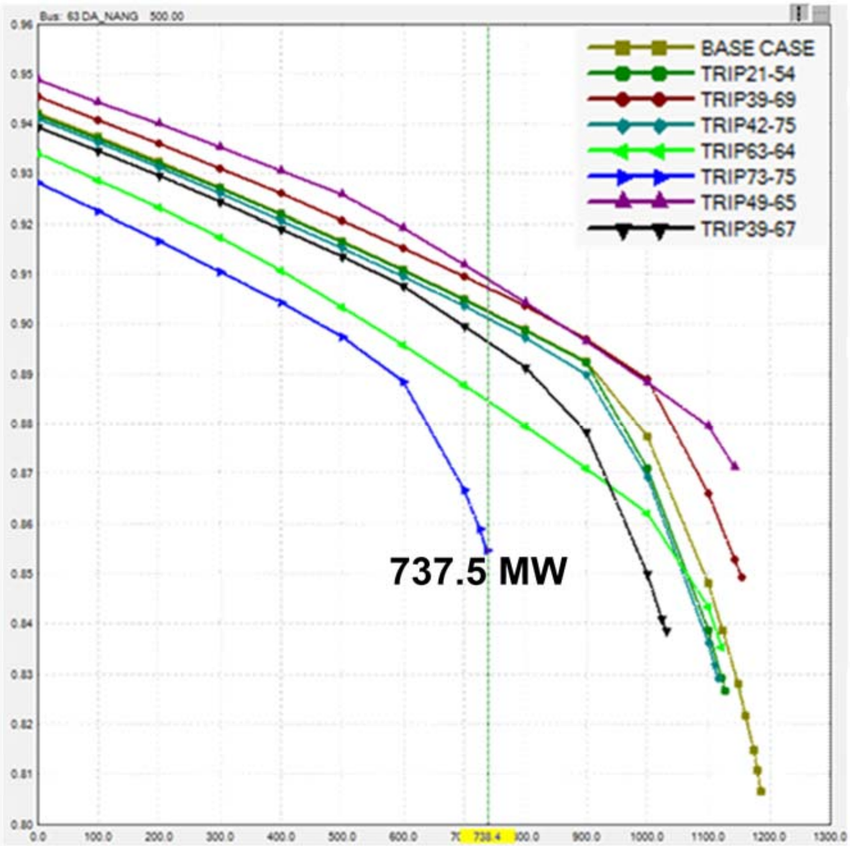


Fig. 10: P-V curves of Da Nang bus at base case and branch contingencies

In addition, the single branch failures of transmission lines deriving from NPP are taken careful consideration. The branch failure between NPP and Di Linh causes the transfer power limit to decrease to 1031.3 MW, leading to low voltage at such buses as Da Nang, Doc Soi, Vung Ang, Di Linh and Ha Tinh in Figure 11.

The transferred power margin changes fractionally (1154.7 MW) when single branch contingency between NPP bus and Tan Dinh or NPP bus and Song May occurs; however, the value of voltage reduces significantly due to the former contingency as shown in Figure 12. The location of buses having the lowest voltage is the same such as Da Nang (0.843 pu), Doc Soi (0.877 pu), Vung Ang (0.919 pu), Ha Tinh (0.937 pu) and Tan Dinh (0.946 pu).

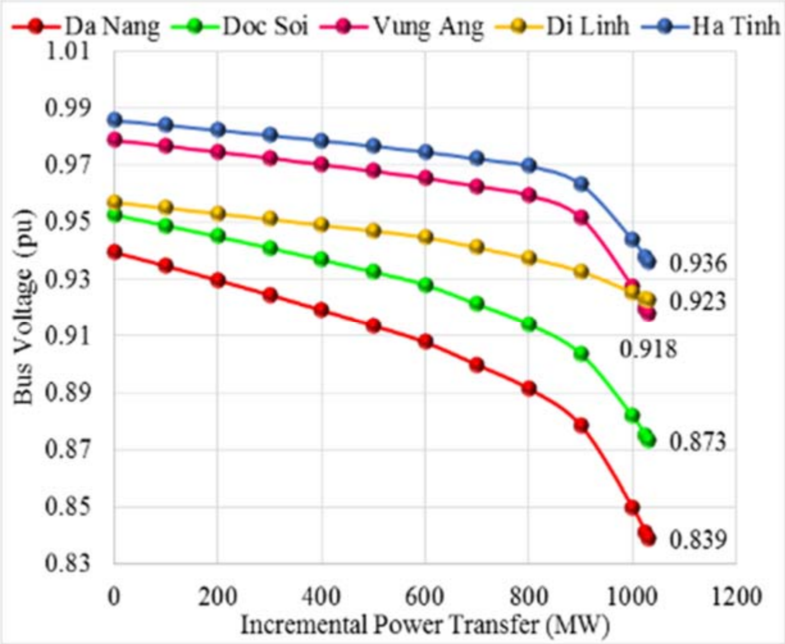


Fig. 11: P-V curves of low-voltage buses at branch contingency between NPP bus and Di Linh bus

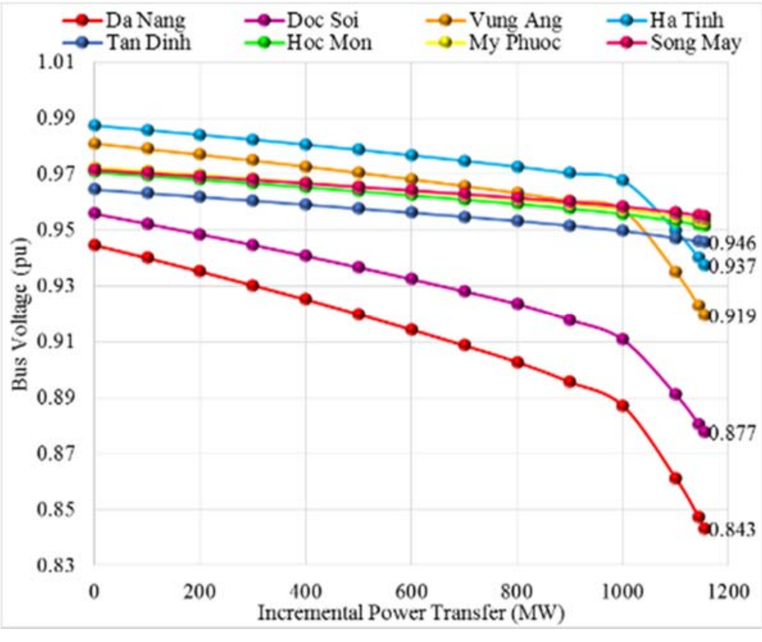


Fig. 12: P-V analysis of buses at single branch contingency between NPP bus and Tan Dinh bus

When transmission line failures occur, the transferred reactive power limits change. It can be seen from Table 1 that Da Nang bus is of the lowest value of reactive power margin at branch outages. The amount of reactive power reserve varies slightly with most of single transmission line failures; however, the reactive power margin at this bus dramatically reduces with the outage of branch between Da Nang (bus 63) and Doc Soi (bus 64) at 157.07 MVAr, Phu Lam (bus 73) and My Tho (bus 75) at 179.08 MVAr. When the transmission line from Daknong (bus 49) to Hoc Mon (bus 71), which connects between the power sources and load centers in the South, is tripped, the value of reactive power margin in most of buses in the South decreases considerably.

Table 1: Reactive power margin of buses at branch contingencies

Bus	Reactive Power Margin (MVAr) at branch contingencies				
	49-71	39-68	63-64	73-75	39-67
Vung Ang	782.39	664.38	620.66	516.35	613.11
Ha Tinh	908.5	788.8	748.77	639.95	741.62
Da Nang	320.25	292.62	157.07	179.08	255.78
Doc Soi	283.84	367.12	187.04	276.88	325.43
Di Linh	625.95	913.15	1024.58	931.37	284.38
Tan Dinh	885.51	1057.2	1543.39	1040.02	1335.77
Song May	926.62	1094.27	1479.89	1065.89	1330.72
Thu Duc	765.3	893.56	1194.44	879.04	1077.55
Hoc Mon	967.41	1205.38	1622.95	1029.61	1465.61
My Phuoc	802.23	986.23	1300.43	867.3	1182.05
Phu Lam	1090.19	1333.36	1732.79	1057.49	1591.55

The reactive power reserve margin at buses around the nuclear power plant reduces compared to normal operation with the outage of single branches around the power plant. The failure of the single branch between NPP (bus 39) and Tan Dinh (bus 68) or from NPP to Di Linh (bus 67) not only causes the decline in reactive power margin at buses connected to NPP but also their proximate buses. The former contingency leads to substantial decrease at Di Linh, Tan Dinh, Song May, Thu Duc, Hoc Mon, My Phuoc and Phu Lam while the latter contingency results in somewhat reduce in reactive power reserve at Vung Ang, Ha Tinh, Da Nang and Doc Soi.

5 APPLICATION OF SHUNT COMPENSATORS FOR IMPROVING VOLTAGE STABILITY AND POWER TRANSFER CAPABILITY FOR VIETNAM NETWORK

After the analysis of static voltage stability and power transfer capability of power system is taken careful consideration, the Vietnamese network is voltage stable in normal operation; however, some weak buses in the power system can cause instability for the network when contingencies occur. Therefore, static var compensators are employed to increase the static voltage stability margin. The application of STATCOMs in this paper is only based on technical specifications without considering economic aspect (Kamarposhti and Alinezhad, 2009).

The calculation and choosing locations for installing STATCOMs are established on P-V and Q-V characteristics at various operating modes including base case mode as well as N – 1 contingency mode (Hossain *et al.*, 2014). In addition, buses, which are of dramatic decline in voltage value and low reactive power margin, are chosen to install STATCOMs with the constraint of voltage value of reactive-power-compensated buses staying in the range between 0.95 pu and 1.05 pu (Hai and Huu, 2011). Having considered the effect of STATCOMs on improving the voltage stability and power transfer capability of the power network, the locations chosen to install shunt compensators are shown in Table 2.

Table 2: Reactive power values of STATCOMs at buses

Bus Name	Reactive power values (MVAr)
Vung Ang	200
Ha Tinh	100
Da Nang	350
Doc Soi	300
Di Linh	50
Song May	250

The P-V characteristic of the power network in Vietnam at several buses with the installation of static synchronous compensators is illustrated in Figure 13. The system load margin in normal operating mode rises considerably at 2131.25 MW, with the amount of increment in power transfer capability being 943.75 MW. The power transfer limit in base case mode is the highest in comparison with other operating modes. Installation of STATCOMs not only leads to increment in power transfer capability in base case, but also improving the maximum transfer ability at single branch contingency between Phu Lam (bus 73) and My Tho (bus 75). The amount of increase in transfer capability in operation modes accounts for more than 900 MW.

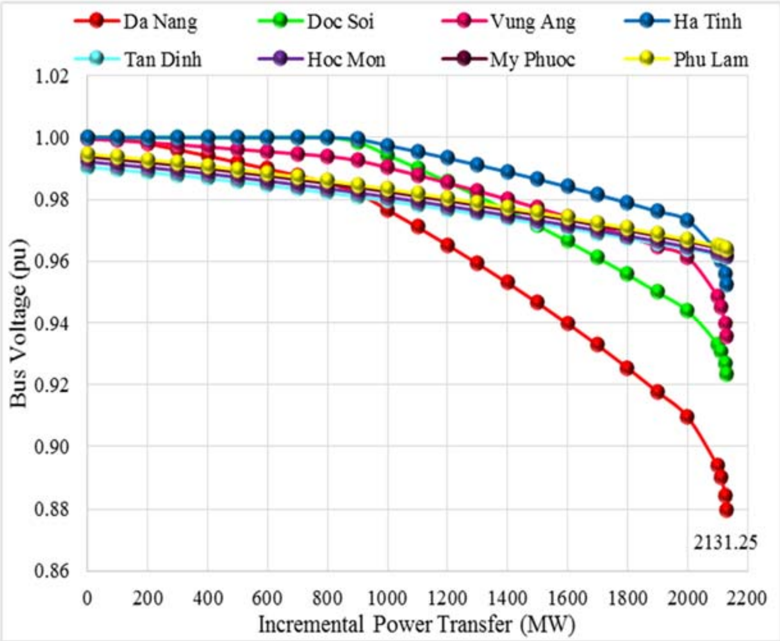


Fig. 13: P-V curves of buses at base case mode with STATCOMs

It can be seen from Table 3 that reactive power margin at buses is significantly risen with the arrangement of STATCOMs at the chosen locations in various operation modes. Basically, the increase in reactive power limit at buses corresponding to operation modes does not have substantial difference.

Table 3: Reactive power margin at buses in base case and contingency modes with and without STATCOMs

Bus Name	Reactive Power Margin (MVAr) of buses corresponding to different operating modes with and without STATCOM					
	Without STATCOM			With STATCOM		
	Base case	73-75	39-69 (Parallel)	Base case	73-75	39-69 (Parallel)
Yaly	995.36	736.19	878.93	1473.83	1194.59	1370.64
Phu My	1695.13	1156.48	739.04	1917.08	1382.84	979.61
Daknong	707.19	448.33	475.93	768.05	529.75	569.5
Pleiku	1042.11	765.50	915.88	1562.34	1257.29	1448.21
Nha Trang	687.45	557.84	605.49	839.83	695.36	741.91
Tan Dinh	1533.14	885.51	498.95	1770.92	1121.96	750.18
Hoc Mon	1637.87	967.41	634.48	1872.36	1192.08	883.78
Phu Lam	1757.28	1090.19	743.31	1988.92	1320.41	998.36
Nha Be	1835.72	1203.89	827.2	2063.05	1435.03	1081.99

In addition, the increasing in reactive power reserve at buses is associated with the rise in their voltage values as depicted in Table 4. Before the establishment of STATCOMs, the weak voltage buses as Da Nang, Doc Soi, Vung Ang and Ha Tinh have very low value of voltage when the network reaches the maximum transfer ability (1187.5 MW) at base case. Nevertheless, at the same value of power transfer limit (1187.5 MW) their voltage is improved dramatically such as Da Nang (0.966 pu), Doc Soi (0.986 pu), Vung Ang (0.986 pu) and Ha Tinh (0.993 pu) when STATCOMs are installed at candidate locations.

Table 4: Voltage values at buses corresponding to different operating modes with and without STATCOMs

Bus Name	Voltage values (pu) at buses corresponding to different operating modes at the maximum power transfer limit before installing STATCOMs					
	Without STATCOM			With STATCOM		
	Base case 1187.5 MW	49-71 1182.03 MW	39-69 (Parallel) 1171.09 MW	Base case 1187.5 MW	49-71 1182.03 MW	39-69 (Parallel) 1171.09 MW
Vung Ang	0.886	0.962	0.943	0.986	0.996	0.992
Phu My	0.985	0.966	0.932	0.996	0.978	0.966
Daknong	0.985	1.002	0.948	1.000	1.017	0.979
Ha Tinh	0.910	0.971	0.956	0.993	1.000	0.999
Da Nang	0.806	0.882	0.866	0.966	0.982	0.98
Doc Soi	0.852	0.885	0.89	0.986	0.983	0.994
Di Linh	0.972	0.933	0.935	0.992	0.953	0.96
Tan Dinh	0.963	0.934	0.899	0.977	0.950	0.932
Song May	0.969	0.944	0.903	0.986	0.963	0.942
Hoc Mon	0.965	0.939	0.909	0.978	0.953	0.94
Phu Lam	0.968	0.944	0.917	0.981	0.958	0.947
Nha Be	0.977	0.955	0.927	0.988	0.968	0.957

Furthermore, STATCOMs improve the voltage at buses significantly when the single branch failure between Daknong (bus 49) and Hoc Mon (bus 71) or parallel branch contingency between NPP (bus 39) and Song May (bus 69) occurs. Many buses, of which are low voltages at the maximum transfer ability due to the contingency, have voltage risen at the same value of power transfer limit. Their voltage values are higher than 0.95 pu (the lowest safe voltage margin) in case of single branch failure, a circumstance in which the system is considered voltage stability. To put it another way, STATCOMs help the system overcome the voltage instability with the occurrence of the most severe single branch contingency.

6 CONCLUSION

Through P-V and Q-V analysis, the power system in Vietnam operates stably in normal condition with the integration of the large nuclear power plant. Besides, weak buses in the system and contingencies that potentially affect the voltage stability are identified. With the installation of STATCOMs at Vung Ang, Ha Tinh, Da Nang, Doc Soi, Di Linh and Song May, Vietnamese power system and the area around the nuclear power plant are more stable because the maximum power transfer ability, reactive power limit and voltage values of weak buses are risen significantly at various operation modes.

The characteristic of the nuclear power plant is different from the normal power plants. Therefore, the research about the mutual impacts between the power plant and Vietnam's 500 kV network should be studied more in depth. Reactive power compensation should be optimized in steady state as well as transient analysis about the locations and capacity of compensators in terms of technique and economic aspects to improve the voltage stability margin and power transfer capability of the network better in various operating conditions. Furthermore, designing and constructing the suitable transmission lines, especially the transmission lines connected between the nuclear power plant and the network, are not only to get the optimal power rate transferred from the nuclear power plant to the system, but also to limit the short circuit current of the network. Moreover, the dynamic stability will be studied for future entity, analyzing the frequency of the system as well as critical clearing time of the nuclear power plant when N – 1 contingency of the transmission lines connected from the nuclear power plant to the power system occurs.

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