Static Voltage Stability Analysis of Power System Using the Combination of P-V Curve and the Modal Analysis

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Abstract. Acorrding to the poor effect of traditional voltage stability method in the actual power network, a new method, combination of the P-V curve and modal analysis, was put forward. First, Kp(power reserve coefficient) was calculated to measure the power system static voltage stability margin through P-V curve. Then, on the basis of that, the modal method was used to get a detailed analysis. The participation factors under the minimum singular value of each node were calculated to find out the weak area, the key branch and key generators of the power system. These results may guide operators to note the weak areas, timely adjust the power flow, and arrange reactive power compensation and so on after a major disturbance. The study of a large power grid, with the help of the PSD-Vsap, a static voltage stability program, verifies the validity and practicability of the method.

Introduction

Voltage stability refers to the ability to maintain the voltage of power system, that is in power system, every bus voltage in normal or disturbed after a dynamic process can be controlled within its rated voltage tolerance range. The occurrence of the United States and Canada blackout in August 14, 2003, the Moscow blackout in May 25, 2005, the Europe blackout in November 4, 2006 and a series of accidents, caused a wide attention of all countries in the world on the voltage stability[1]. In the background of the rapid growth of electricity load, how to ensure the safe and stable operation of the power grid to ensure reliability of power supply has become an urgent problem to be solved. Current methods of voltage stability analysis mainly include the maximum power method[2], sensitivity method[3, 4], the eigenvalues and singular value decomposition method[5, 6], the multi-solution of power load method[7], the differences analysis[7] etc. These static analysis methods are mostly applied in theoretical research, but when extended to the real complex system, the effect also need to be verified [8, 9].

This paper uses P-V curve and the modal analysis to study the combined application method of power system static voltage stability problem. First calculate the power reserve coefficient Kp from the P-V curve, which measures the power system static voltage stability margin. Then on the basis, apply the modal analysis method, from the perspective of the whole power system, get detailed information relating to the analysis of the weak areas and provide a basis for best location choice to compensate reactive power.

The P-V curve method is an method based on power flow simulation to study the voltage stability of power system[10], it is the effective tool for judging system static voltage stability margin. We use PSD-Vsap static voltage stability analysis program to draw PV curve. The applications of modal analysis method in other areas are more mature, but less on static voltage stability analysis [11, 12]. Modal analysis method can be used for the analysis of actual system, the actual example analysis shows that, the method is effective and practical.

PV and QV Curves and Voltage Stability Margin

In the power system, PV and QV curves of load nodes can be used as an effective tool to determine the system static voltage stability margin. P-V or Q-V curve, as shown in Fig.1, the abscissa represents total load P or Q of a node, the vertical axis represents the voltage amplitude corresponding to the load. P-V and Q-V curve inflection point is the critical point of stable operation. The load Pmax corresponding to inflection point is the ultimate load, and the voltage Vcr corresponding to the inflection point is the limit voltage of the stable operation. The difference between the ultimate power and load of the actual operating point, as well as the voltage difference between the limit and actual voltage operating point can be integrated to reflect the static voltage stability margin of the node.

In practical applications, the power reserve coefficient *Kp* and voltage reserve factor *Kv* are often used to reflect the static voltage stability margin of the system .The power reserve coefficient *Kp* and voltage reserve factor *Kv* are defined as Eq.1 and Eq.2:

$$K_p = \frac{P_{\max} - P}{P} \tag{1}$$

$$K_v = \frac{V_o - V_{cr}}{V_{cr}} \tag{2}$$

In Eq.1 and Eq.2 , *Pmax* is the limit of active power, *P* is the active power under normal operation, *Vo* is the normal operating voltage, *Vcr* is the critical operating voltage.

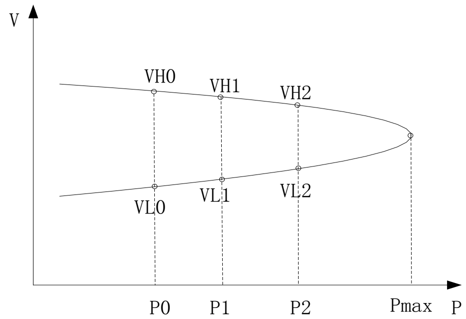

Fig.1 Typical P-V Curve

With linear simulation method, we can quickly get PV and QV curves to calculate the power reserve coefficient *Kp* and voltage reserve coefficient *Kv.* Of the two, the system static voltage stability and power reserve factor *Kp* are in good agreement, and when the P-V curve is relatively flat, voltage reserve coefficient Kv can not well reflect the static voltage stability.So our main method to measure static voltage stability of the system is the *Kp*.

Application of Modal Analysis Technology in Voltage Stability Analysis

Static voltage stability of the system is derived from a PV curve, power system voltage static linear equation can be expressed as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = J \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{3}$$

In Eq.3, ΔP and ΔQ are bus active power and reactive power incremental change, $\Delta\theta$ is the incremental change of bus voltage angle, ΔU is the incremental change of bus voltage magnitude, J is the Jacobi matrix of the system. We can get the relationship among the power incremental change,right eigenvector and state variables shown in Eq.4 and Eq.5 after mode method is applied to the power flow equations:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = K_i U_i \tag{4}$$

$$\begin{bmatrix} \Delta\theta \\ \Delta U \end{bmatrix} = \lambda_i^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{5}$$

In Eq.4 and Eq.5, $\Delta\theta$ and ΔU are incremental change of voltage angle and magnitude, λ_i is the convergent Jacobi matrix eigenvalues, ΔP and ΔQ are power incremental change.In modal analysis of static voltage stability, the right eigenvectors corresponding to the minimum eigenvalue u_m reflect the most sensitive perturbation direction of active and reactive power relative to the minimal model ,when the power perturbation direction consistent with u_m, the changes of state caused is maximum. At this time, the branches reactive power loss which are more sensitive to changes can be considered a greater impact on the minimum model,these kind of branches are defined as the key branch. In the minimal model, the generator whose reactive power changes in larger unit is defined as the key generator. Besides, according to the contribution degree to the node voltage sensitivity, we can find the load node in strong correlation with minimum singular mode,which is defined as the key node. The key nodes constitute weak area, and often are the best location for reactive power compensation.

Case Analysis

Take a northwest power grid in China for example, the power grid include 4 500kV substations, 16 220kV substations, and the total installed capacity is 9818MW.The northwest power grid is the load center of a regional power grid. Power reference value is 100MVA.

Static Voltage Stability Margin Analysis of Normal Operation Mode

Research on the modeling of the power grid, under the high load operation mode in the summer of 2013, large part of static stability indices of main results are shown in Table 1. Table 1 shows the voltage stability index of main load bus: the power reserve coefficient Kp. According to "Guidelines for power system security and stability"published by China Electric Power Research Institute, aiming at different power systems under the normal mode of operation, static stability reserve coefficient is calculated according to the power angle criterion should satisfy 15% -20%. From Table 1 : under the high load operation mode in the summer of 2013, power reserve coefficient Kp is above 31%, so there is a larger margin.Gu North regional power reserve coefficient is low, the power reserve is relatively weak.

Table 1 The Main Static StabilityResults of the 115kV Nodes

Node	Voltage Level[kV]	Power Limit[p.u.]	Kp [%]
Baogang 52	115.0	3.488	98.39
Gu North11	115.0	2.495	31.64
Hezi 11	115.0	3.145	97.67
Kuang West 11	115.0	1.607	83.53
Shibao 11	115.0	1.798	72.43
Huabian 11	115.0	1.257	96.42
Dou West 11	115.0	2.058	84.88

Fig.2 shows the P-V curves of the Huabian 115kV bus, under the high load operation mode in the summer of 2013. The Kp of Huabian 115kV bus is 96.42%. According to the power reserve coefficient under different operation modes, there is a certain distance between the operation point of the system and the power limit , so the grid has enough static voltage stability margin.

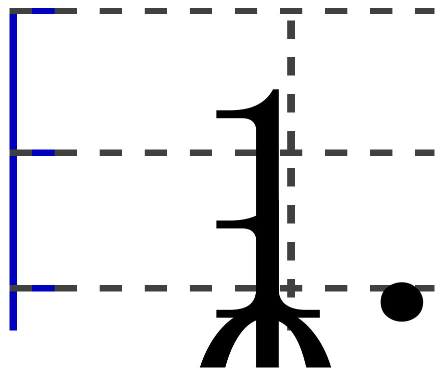

Fig.2 P-V Curve of the Hubian 115 kV Bus

Calculation Results of Modal Analysis

The major part of related factors calculation results of load bus, transmission lines and generators, under the high load operation mode in the summer of 2013, are shown in Table 2 to 4.

The buses whose related factor is relatively big belong to voltage stability weak point, and the greater its value, the greater the contribution to the node voltage sensitivity; the greater line participation factor, the more sensitive to reactive power loss; the greater generator participation factor, the greater issued reactive power change.

For the high load operation mode in summer, Barun, Kuang West , Baiyun, Gu North are the voltage stability relatively weak points; Gu North 220-Chunkun 220 lines, Tuyou 220-Daqi 220, Zhao Temple 220-Sha River 220, Baobai 115-Gu North 115, G1 and G2 generator of River West, are the corresponding key branches and key generators.

Table 2 The Main Related Factor Results of Buses

Number	Node	Voltage Level[kV]	Related Factor
1	Barun 12	115.0	0.551465
2	Kuang West 11	115.0	0.503995
3	Baiyun 11	115.0	0.501605
4	Shibao 11	115.0	0.349154
5	Guyang 12	115.0	0.346726
6	Goden Mount 11	115.0	0.336117
7	Baobai T2	115.0	0.334535

Table 3 The Main Related Factor Results of Transmission Lines

Number	Voltage Level[kV]	Node 1	Node 2	Related Factor
1	220	Gu North 21	Chunkun 21	0.132382
2	220	Zhao Temple 21	Sha River 21	0.042807
3	220	Gu North 21	Red Tower 21	0.038627
4	220	Wang Sea 22	Red Tower 21	0.028005
5	110	Barun 11	Wang Sea12	0.013853
6	110	Xingqing T1	Happiness 11	0.009733
7	110	Baobai T1	Baobai T2	0.009688
8	110	Shashi T1	Sha River11	0.007306

Table 4 The Main Related Factor Results of Generators

Number	Generator	Voltage Level[kV]	Related Factor	Reactive power reserve[p.u.]
1	River West G1	20	0.3734	1.706
2	River West G2	20	0.3668	1.706
3	Bao Third G1	20	0.2506	0
4	Daqi G2	24	0.2283	0.504
5	Daqi G1	24	0.2283	0.504

Analysis of the Computation Result

According to the static voltage stability margin analysis ,we can effectively evaluate the existing power grid's capability of bearing load growth. The power limit of northern ,southern, western, eastern power grid is about 1.5pu (907MW), 2.0pu (1950MW), 1.9pu (3425MW), 2.2pu (4635MW) respectively. Barun, Kuang West, Baiyun, Gu North are relatively weak point of voltage stability, and they can be choosen as the preferred position for reactive power and voltage compensation.

Conclusions

This paper presents a new method based on PV curve method combined with modal applications. By studying the results of the actual grid shows that the method is simple and effective. Operating personnel in the normal scheduling and monitoring, should pay attention to the key lines, reduce the load on the key lines and make reasonable adjustments on tide way when a major disturbance occured in the system. Besides,key generators plays a key role for the stability of the system, Operating personnel should consider arranging adequate reserves for them to avoid systems lossing voltage stability.

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