

Research on Voltage Mechanism of Power System

Zhen Meng¹, Xiangbo Meng¹, Hao Liang¹, Yang Bai¹, Xing Zhao¹, Hong Zhang¹, Wei Ma², Yan Liu², Yadong Si³, Jianshi Bai⁴

¹ State Grid Jinzhou Power Supply Company, China

² State Grid Liaoyang Power Supply Company, China

³ State Grid Chaoyang Power Supply Company, China

⁴ Economic Research Institute of State Grid Liaoning Electric Power Co.,Ltd, China

306836433@qq.com

Keywords: electric system node, voltage, stability, margin

Abstract. With the increasing voltage classes of electric system, voltage stabling issue brings more and more severe constrains to the entire electric system. A throughout analysis of features and mechanism of voltage instability in electric system has guiding significance in assuring stability of the power grid. Taking the voltage of one node as an example, using functions to calculate the functional formula of the node's reactive power and voltage, can lead to the conclusion that by increasing reactive power compensation can not only increase the stability margin of supply voltage of this node, but also its neighboring nodes. This article summarizes several common effective measures of voltage instability, wish to provide references for electrical research and work.

Introduction

The problem of voltage stability is a research topic that scholars have paid close attention to in recent years. At present, the power system has not been strictly defined in academia. But no matter how to make the statement, the voltage stability problem is indeed an actual fact in electric system that is different from the power angle stability problem in generator rotor relative motion. Voltage stability means that the electric system can properly maintain a reasonable voltage level that is necessary in providing safe and reliable power to its load, and can be adjusted in appropriate ways under a variety of interference factors under collective effects.

In the late 1970s, it was confirmed that system collapses due to voltage stability issues occurred several times in the United States, Japan and some countries in Western Europe. There was similar records in China as well. The development of voltage instability may lead to collapse of the system, resulting in huge losses. Therefore, the voltage stability issue has aroused great concerns. Internationally well-known electrical organizations have all put voltage stability as the most vital issue among others. It can be seen that the study of voltage stability has great significance in assuring the safety and stability of the operation of eclectic systems.

Harmfulness of voltage stability failure of electric system

In reality, the power system is powered by the voltage source. The voltage of every node in the system should be within the specified range, and should not exceed a certain value. If the system works in the initial state with disturbance, when the disturbance is eliminated, node voltage in the system can return to its initial state with certain accuracy, then the system voltage is stable. If the voltage of a node or some nodes can not return to the initial state with certain accuracy, the system voltage is unstable, or also called stability failure.

After the voltage stability of an electric system is damaged, the voltage of a node or some nodes in the system will continue to rise or fall to an unacceptable value. This phenomenon is called voltage collapse. If we take no measure towards the development of the voltage collapse, it will affect more nodes within the system. Therefore, the damage process of voltage stability is similar to an

"avalanche" process. Compared with the system's frequency stability, generally speaking, voltage stability is a regional problem.

The mechanism of voltage stability failure

It's accustomed to say that "if the system lacks active power, the frequency will decrease and if the reactive power is insufficient, the voltage will decrease". Although the argument to a certain extent summed up the operating experience, but it's not very strict. The relationship between the node voltage and the reactive power balance is analyzed below.

(1) The relationship between the node voltage and the reactive power balance

Under the condition that the power supply voltage is basically constant, node voltage mainly depends on the voltage drop caused by the current flowing through the system impedance. As the grid impedance is mainly composed of reactance, the resistance is very small, so the voltage drop of system impedance is mainly generated by the flow through the reactive power(Q). This is the reason why the system voltage characteristic is mainly related to the reactive power distribution. Obviously, if the system impedance is composed of resistors (such as low voltage or cable lines), the system voltage characteristics are determined by the active power distribution.

As we can see from figure 2-1, the relation between the voltage of node b and the node's reactive power load Q_L . Under normal steady state, the reactive power of node b is balanced, $Q_L=Q_S$. The voltage $U_2(U_2=U_1-\Delta U)$ will be a certain value. If load power Q_L rises, unbalanced power $\Delta Q=Q_S-Q_L$ will occur at node b momentarily, also called short term power insufficiency. In order to maintain the power balance of node b, the power need to provide more reactive power to node b, which will result in more voltage drop at X_S , and U_2 decreases. This is the physical explanation of the reason why the voltage will decline when node's reactive power is insufficient. This explanation is only true if the system impedance is mainly based on reactance.^[1]

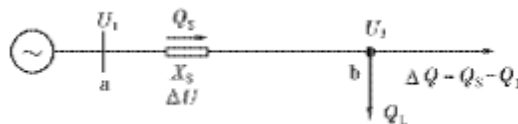


Figure 2-1 Analysis System

(2) The basic condition of node voltage stability

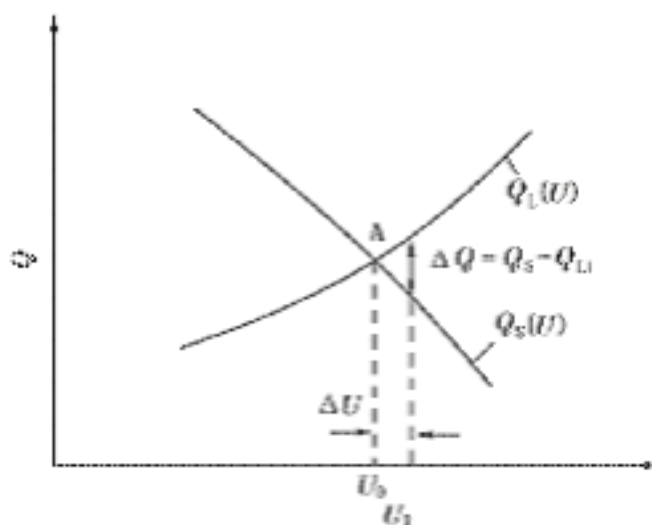


Figure 2-2 Voltage Stability Condition

Only the relationship between the node voltage and the node power balance is described above. Whether the voltage at the initial point is stable depends on the voltage change after the disturbance. Figure 2-2 shows the condition of voltage stability at the initial point. In figure 2-2, $Q_S(U)$ and $Q_L(U)$, respectively, stand for the voltage characteristics of node system reactive power and load reactive

power. It is obvious that the voltage of node b is stable, because if there is a disturbance, such as voltage changes (ΔU), the voltage increases, then there's node b reactive power shortage, when the disturbance is eliminated, the voltage will be back to the initial state (U_0). Therefore, as for node b, in the initial state, if $\frac{\Delta Q}{\Delta U} < 0$, then the voltage is stable.

Therefore, the node voltage stability is similar to system frequency stability, its stability depends on the system and the voltage characteristics of load reactive power.

Reactive Power - Voltage Characteristics of Eclectic System

According to the single generator power supply equation, equations can be listed below:

$$\frac{PX_{eq}}{E_{eq}^2} = \frac{U}{E_{eq}} \sin \delta \quad (3.1)$$

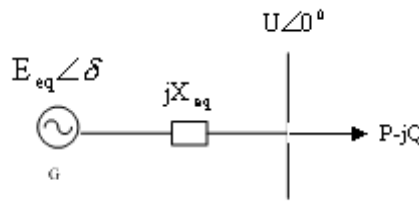


Figure 3-1 Single Generator-infinite System

And

$$\frac{QX_{eq}}{E_{eq}^2} = \frac{U}{E_{eq}} \cos \delta - \left(\frac{U}{E_{eq}}\right)^2 \quad (3.2)$$

We can deduce that

$$\left(\frac{PX_{eq}}{E_{eq}^2}\right)^2 + \left[\frac{QX_{eq}}{E_{eq}^2} + \left(\frac{U}{E_{eq}}\right)^2\right]^2 = \left(\frac{U}{E_{eq}}\right)^2 \quad (3.3)$$

Then the relationship between the voltage and the load power of the terminal can be calculated:

$$\left(\frac{U}{E_{eq}}\right)^2 = \frac{1}{2} \left[1 - 2 \frac{QX_{eq}}{E_{eq}^2} \pm \sqrt{1 - 4 \frac{QX_{eq}}{E_{eq}^2} - 4 \left(\frac{PX_{eq}}{E_{eq}^2}\right)^2} \right] \quad (3.4)$$

In equation (3.4), each quantity is the standard value of a certain voltage and a certain capacity. In particular, when the load is absorbing reactive power by the system, Q is positive, and when the load is sending reactive power to the system, Q is negative. All the P and Q are the corresponding standard values to certain voltage value U , rather than the value of the rated voltage.

Taking $\frac{PX_{eq}}{E_{eq}^2}$ as determined values, a series of function curves $\frac{U}{E_{eq}} = f\left(\frac{QX_{eq}}{E_{eq}^2}\right)$ can be calculated. As shown in Figure 3-2, we can see the following characteristics:

1) Generally speaking, on the $\frac{U}{E_{eq}} = f\left(\frac{QX_{eq}}{E_{eq}^2}\right)$ curve when $\frac{PX_{eq}}{E_{eq}^2}$ is a set value, one $\frac{QX_{eq}}{E_{eq}^2}$ value can have 2 corresponding $\frac{U}{E_{eq}}$ value that meet the requirement. And obviously only the intersections of the right side of the curve are stable operation points, and in the left, are the unstable operation points

2) The lowest point of the curve is voltage when $\sqrt{1 - 4 \frac{QX_{eq}}{E_{eq}^2} - 4 \left(\frac{PX_{eq}}{E_{eq}^2}\right)^2} = 0$. So the critical

voltage for steady operation is $(\frac{U}{E_{eq}})_{\min} = \sqrt{0.25 + (\frac{PX_{eq}}{E_{eq}^2})^2}$. The higher the active load, the higher the required safe and stable operating voltage.

3) When $\frac{PX_{eq}}{E_{eq}^2} > 0.5$, $(\frac{U}{E_{eq}})_{\min}$ is above the horizontal axis of the curve. That is, if the receiving

active power is too large, or the system power transmission reactance is too large, or the system power supply source voltage is too low, in order to maintain stable operation of the receiving load, the receiving area must have sufficient over-compensation reactive power. In addition to the reactive power of loads in compensation area, we must also send certain reactive power to the system to maintain a high enough operating voltage level for the receiving bus voltage to run stably. When $\frac{PX_{eq}}{E_{eq}^2} < 0.5$, the receiving-end system can absorb some reactive power by the system or send some reactive power to the system, depending on the specific voltage level. In any case, receiving-end bus voltage must be higher than the allowable minimum value to cope with the system and disturbance of the load of receiving end, to obtain a stable operation. [2]

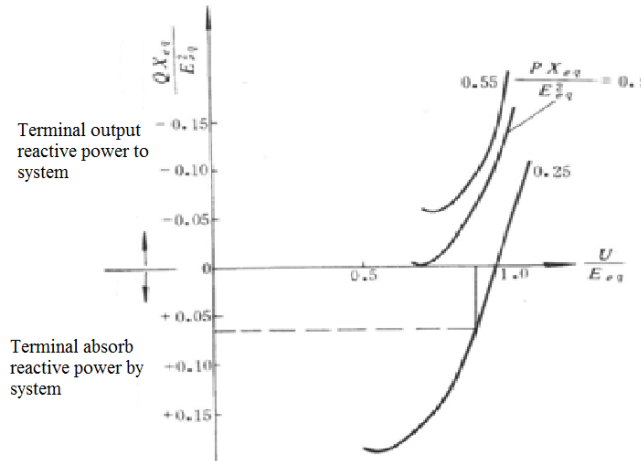


Figure 3-2 Voltage-reactive power character of receiving end

After analyzing equation (3.4), you can further obtain a concise voltage stability criteria as follows:

Regardless of the complexity of the system structure, see the system from one node, at any moment, the external system can be equivalent to a single generator system whose power source electromotive force powers nodes through transmission impedance. The only assumption in equation (3.4) is that only the reactance component is considered in the transmission impedance, which is generally acceptable^[5].

From (3.4), the stable critical voltage ratio of the power supply node in the system: $(\frac{U}{E_{eq}})_{\text{crit}}$, can be calculated:

$$(\frac{U}{E_{eq}})_{\text{crit}} = [\frac{1}{2}(1 - 2Q\frac{X_{eq}}{E_{eq}^2})]^{\frac{1}{2}} \quad (3.5)$$

The basic requirement for maintaining the voltage of the power supply node from collapsing is:

$$1 - 4\frac{QX_{eq}}{E_{eq}^2} - 4(\frac{PX_{eq}}{E_{eq}^2})^2 = 0 \quad (3.6)$$

Therefore, we can get the critical system of the power supply system equivalent electromotive force:

$$\frac{E_{eq.crit}^2}{X_{eq}} = 2[Q + \sqrt{P^2 + Q^2}] \quad (3.7)$$

Take equation (3.7) into equation (3.5), the bus voltage stability threshold of one power node in the grid U_{crit} can be derived:

$$U_{crit}^2 = X_{eq} \sqrt{P^2 + Q^2} \quad (3.8)$$

It is quite convenient to use equation to analyze the stability of the grid supply voltage. E.g.:

1) The critical value of the supply voltage of a node in the grid is a function of the inspecting power of the load connected to the node and also a function of the equivalent impedance of the system connected to the node. Different nodes in the power grid have different power supply voltage threshold, and therefore need to check point by point.

2) When the load of a node $\sqrt{P^2 + Q^2}$ is fixed, the steady-state voltage threshold of the node U_{crit} is determined by the short-circuit impedance of the external system structure (the connection mode of the power grid, the number of access machines, etc.) X_{eq} regardless of the operation mode of the synchronous unit. But the operation mode of the synchronous unit determines the potential value of the equivalent unit of the system connected to the node E_{eq} , thus determining the actual operating voltage U of the node. As long as the bus voltage value U is greater than the U_{crit} value calculated by X_{eq} after the event the (N-1)th event after, we can reckon that there will not be voltage collapse at the node.

3) When the bus voltage is U , the supply voltage stability margin M of the node is:

$$M = \frac{U - U_{crit}}{U_{crit}} \times 100\% \quad (3.9)$$

As a result, it is possible to check which node has the smallest margin in a particular incident and which nodes need to take specific measures. For example, increase reactive power compensation. In the power grid, increase the reactive power compensation of a node can not only improve the node's power supply voltage stability margin (Q 's absolute value decreases, and the node voltage increases), but also improve the voltage of adjacent nodes, increasing the stability of the supply voltage of the adjacent node.

4) In a region where the load is concentrated, if the reactive power compensation capability is insufficient or the external supply voltage is too low, the voltage at the grid point is continuously reduced during operation, the best means of terminating the occurrence of voltage collapse is to reduce suitable amount of load at some regions. Its effect is double-sided: ① can effectively reduce the critical voltage U_{crit} . In the case of a general load, the absolute value of P is always significantly greater than Q , therefore the reduction of P (including the portion of Q it contains) is particularly significant for the reduction of U_{crit} . ② because the required active power of the grid is reduced, the voltage U at the receiving-end hub node is increased at the same time, so that the voltage stability margin M can be significantly increased.

For further analysis, equation (3.8) has more general meanings. Equation (3.8) is obtained by the fact that the connection impedance between the power supply and the receiving bus is purely inductor. If the connection impedance is $Z_{eq} \angle 90^\circ - \theta$, that is, with the resistance component, according to the same principle, we can get:

$$\frac{E_{eq.crit}^2}{Z_{eq}} = 2[P \sin \theta + Q \cos \theta + \sqrt{P^2 + Q^2}] \quad (3.10)$$

$$\left(\frac{U}{E_{eq}}\right)_{crit}^2 = \frac{1}{2} \left[1 - 2(P \sin \theta + Q \cos \theta) \frac{Z_{eq}}{E_{eq}^2}\right] \quad (3.11)$$

Take (2.17) into the formula (2.18), we can get:

$$U_{crit}^2 = Z_{eq} \sqrt{P^2 + Q^2} \quad (3.12)$$

Equation (3.8) is still correct, but at this time it is necessary to replace X_{eq} with the absolute value of the connected impedance Z_{eq} .

Measures to Improve Voltage Stability of Electric System

The ultimate goal of the study of voltage stability is to propose a practical method to analyze the voltage stability in response to the actual situation of the electric system, to forecast the risk of voltage collapse in time, and to find measures to improve the voltage stability in order to prevent the occurrence of voltage collapse.^[3]

According to the different state of the system, maintain the reactive power's supply and demand balanced in each region.

1) The generator capacity under the condition of phase lag and phase advance

In the planning phase of the construction of the power plant, the design should be considered to improve the excitation current capacity of the generator, reducing the rated power factor so that the generator can provide required reactive power when the system is in abnormal state. Of course, with the decrease of the generator rated power factor, weight and price will rise. The economic benefits should be considered and surveyed with the factors above and increased charges for parallel capacitors.

2) Sufficient phase modulation equipment

The phase modulation equipment is needed not only in the normal operating system but also an abnormal on. In order to maintain the balance of needs and supply of reactive power in each regional system, phase modulation equipment is also needed with suitable distributions.

Improve the characteristics of voltage and reactive power of transmission system

1) By using multi-loop transmission lines and ring network system

By using multi-loop transmission line or ring network system, we can reduce the reactance (increase the receiving-end short-circuit capacity) or reduce the trend, and improve the receiving-end characteristics of voltage and trend.^[4]

2) By using high voltage

The percentage impedance of the transmission line is inversely proportional to the square of the voltage. Therefore, if high voltage is used, the percentage impedance can be reduced and the same effect as 1 can be achieved.

4.3 Operation measures for the prevention of voltage collapse

1) Monitor with running target values

This is achieved by comparing and monitoring the operating target voltage (reference voltage) determined from the main points in the system with the actual voltage information obtained online^[6]. If there're areas that cannot maintain the reference value, we can ensure the system voltage to run on the reference value by taking actions like switching loads and systems, equipping or disconnecting phase modulation equipment and so on.

2) Monitor the system according to the simulation of hypothetical failure

Based on the online information of the system, the simulation is carried out for the hypothetical power supply disconnection and the line fault. When the voltage anomaly is the same as the hypothetical fault, the same precautionary measures as above can be adopted.

Conclusion

Power system stability failure is often the combinations of one another among power angle stability problem, the frequency stability problem and the voltage stability problem. Therefore, the voltage model used in studying voltage stability are quite different from the analyzing method. Combining various voltage stability analysis, studying the quantitative indicators of various voltage stability, and truly understanding the differences and connections between power angle stability and

voltage stability, learning from those mature experience and theories from the power angle stability analysis and using them to analyze the voltage stability issue, all have great significance in the stability analysis of eclectic system.

References

- [1] M.O.Faruque, Zhang Yuyan,V.Dinavahi. Detailed modeling of CIGRE HVDC benchmark system using pscad/emtDCand psb/simulink[J].Power Delivery, IEEE Transactions on, 2006.21(1):378-387.
- [2] Lv Jinzhuang, Li Licheng.Study on the key equipment's insulation level of $\pm 800\text{kV}$ HUVDC power transmission project, July 2007.
- [3] WANG Dongju, ZHOU Hao, DENG Xu. Switching overvoltage characteristics of $\pm 1100\text{-kV}$ HUVDC converter station[J]. IEEE Transactions on Power Delivery,2015.30(3):1205-1212.
- [4] Sun Shouguang.Receiving-end grid:The core of programming,construction and operation in power system[J].China Electric Power,2003(7):34-37.
- [5] IEEE/CIGRE Joint Task Force on Stability Terms andDefinitions.Definition and classification of power system stability[J].IEEE Trans on Power Systems,2004,19(2):1387-1401.
- [6] Tang Y, Ma S Y,Zhong W Z.Mechanism research of short-term large-disturbance voltage stability[C].2006 International Conference on Power System Technology,Chongqing,China,2006.