Analysis and evaluation of power system voltage stability considering pumped storage power station

Yue Yu¹, Long Jin¹*, Yanjun Li¹, Longhao Liu¹, and Guangye Liu²

¹State Key Laboratory of Power Grid Safety and Energy Conservation (China Electric Power Research Institute), Beijing, China
²College of Electrical and Information Engineering, Hunan University, Hunan Province, China

*Corresponding author: jinlong@epri.sgcc.com.cn

Abstract. Aiming at the influence of the connection of pumped storage power station to power grid on voltage stability, the impedance modulus margin defined by non-linear equivalent analysis method is used as the evaluation index of system voltage stability, and a method for evaluating power system voltage stability considering pumped storage power station is proposed. Considering the peak-cutting function of pumped storage power station, the calculation method of general impedance modulus margin of load nodes is derived. The general impedance modulus margin of load nodes is calculated by changing the output and access position of pumped storage power station, and its influence on the voltage stability of power system is analyzed. Coordinating the access position and output of pumped storage power station to improve the voltage stability of the system. Finally, through the simulation calculation on the standard node system, the feasibility of the project is verified.

1. Introduction

With the rapid economic growth, wide application of distributed generation, and gradual increase of large-capacity inter-regional networking projects, pumped storage power stations which can better cope with large-scale load changes will have a more rapid development. In the next few years, the State Grid Corporation will start the construction of pumped storage power station in an all-round way. The connection of pumped storage power plants will have a great impact on the voltage stability, power quality and power supply reliability of power grid [1, 2]. Pumped storage power station is to solve the contradiction between supply and demand between peak and trough of power grid [3, 4, 5]. It is a way of indirect storage of electric energy. It uses excess electricity in the second half of the night to drive pumps, pumping water from the lower reservoir to the upper reservoir for storage, and then releasing the water into the lower reservoir during the next day or in the first half of the night to generate electricity. In the whole operation process, although part of the energy will be lost during the conversion, the use of pumped storage power stations is still cheaper and more effective than the construction of additional coal-fired power generation equipment to meet peak power consumption and the situation of pressure and shutdown at low valleys. Besides, Pumped Storage Power Station can also take on dynamic functions such as frequency modulation, phase modulation and accident reserve. Therefore, pumped storage power station is not only the power point, but also the power user, and becomes an important tool for the operation and management of the
power grid, and is the pillar to ensure the safety, economy and stable production of the power grid[6, 7]. In this paper, the influence on the voltage stability of peak-cutting function of pumped storage power station is analyzed.

The influence of pumped storage power station connected to the power grid on the voltage stability of the system can be analyzed from the following two aspects. On the one hand, it can be simply taken as a "negative" load superimposed on a load node to reduce the system load, or seen as a PQ node for system stability analysis [8]; On the other hand, the connection of pumped storage power stations to the power grid will lead to changes in the dynamic equivalent parameters of the system, which will affect the static voltage stability of the power system. Therefore, under the new power network architecture, the voltage stability index can be deduced, and the voltage stability analysis method of power system considering pumped storage power station is proposed.

In this paper, the load node impedance margin index is used to evaluate the voltage stability of the system[9]. Then the index is further extended to the voltage stability analysis for power system considering pumped storage power station. The general impedance modulus margin of load nodes in power system considering pumped storage power station is derived. Furthermore, the influence of output and access position of pumped storage power station on system voltage stability is calculated and analyzed. The simulation using standard node system proves the effectiveness and practicability of this method, and provides a strong theoretical basis for its safe and reliable operation in the future.

2. Node voltage stability assessment method

2.1. Impedance module margin index

Based on the maximum transmission power theorem of simple AC system[5]: the system can be equivalent to the integrated dynamic equivalent circuit shown in Figure 1 through seeing from any load node of the system. When the equivalent impedance mode of the system is equal to the equivalent impedance mode of the load, the system can obtain the maximum transmission power. Thus, impedance modulus margin plays an important role in monitoring and analyzing the maximum transmission power of the system.

![Figure 1. System integrated equivalent circuit diagram.](image)

The equivalent potential of Thevenin can be calculated by analyzing the circuit in Fig. 1:

\[ E_{\text{TH}} = \hat{U}_i + Z_{\text{TH}}(\hat{S}_i)/\hat{U}_i \]  

According to the circuit shown in Fig. 1, the voltage stability index of each load node of the system can be analyzed, and the voltage stability index has a one-to-one correspondence with the specific node of the system.

In this way, define the following indicator:

\[ \mu = \frac{|Z_{\text{ad}}| - |Z_{\text{max}}|}{|Z_{\text{ad}}|} \]  

The impedance modulus margin index can well reflect the distance between the current operating point of the system and the limit power transmission point of the system. The voltage stability of system nodes can be calculated effectively. The value range of is 0-1, and the smaller, the worse the voltage stability of the system nodes. When the value of reaches the minimum value, the system voltage is at the critical point. So impedance margin is an intuitive expression of node voltage stability.
According to the magnitude of impedance modulus margin, the voltage stability of system nodes can be sorted. The weak nodes are those with smaller impedance modulus margin.

2.2. Method for calculating dynamic equivalent parameters of power system

In the form of rectangular coordinates, a power flow equation with \( n \) nodes can be expressed as:

\[
W = F(U, U_{n})
\]

Where: \( U_{n} \) is the voltage of the balancing node; \( W = [P_1, Q_1, \ldots, P_{(n-1)}, Q_{(n-1)}]^{T} \); \( U = [e_1, f_1, \ldots, e_{n-1}, f_{n-1}]^{T} \).

Node injection power is:

\[
\lambda \text{ is the control parameter of power change.}
\]

After modifying and expanding the parameters involved in equation (3), and derivative of \( \lambda \) on both left and right sides:

\[
\frac{dW}{d\lambda} = J \frac{dU}{d\lambda}
\]

Where: \( J \) is the Jacobian matrix after iteration convergence of power flow calculation, equation (5) can be transformed to the form:

\[
\frac{dU}{d\lambda} = J^{-1} \frac{dW}{d\lambda}
\]

The augmented Jacobian matrix obtained by power flow calculation method can be used to solve the equation (6) quickly.

Current of PQ Node:

\[
\hat{I}_i = \hat{S}_i / \hat{U}_i
\]

Where: \( \hat{S}_i \) is complex power of load node, derivative of \( \lambda \) on both left and right sides:

\[
\frac{d\hat{I}_i}{d\lambda} = (d\hat{S}_i / d\lambda - \hat{I}_i \alpha) / \hat{U}_i
\]

The integrated dynamic equivalent impedance of the system is obtained from formula (6) and (8):

\[
Z_{\text{eqv}} = \frac{dU_i}{dI_i} / \lambda
\]

The static equivalent impedance mode of the load:

\[
|Z_{\text{eq}}| = \frac{U_i}{I_i}
\]

3. Voltage stability analysis of power system with pumped storage power station

3.1. Integrated dynamic equivalent model of power system

The peak-cutting function of pumped storage power station is conducive to the improvement of system voltage stability. However, most papers do not essentially analyze the mechanism of voltage stability improvement. Therefore, this paper analyses how peak shaving of pumped storage power station can improve the voltage stability of power system.

Seen from any load node of the system, the system can be equivalent to the dynamic equivalence diagram shown in Figure 2. The equivalent model of pumped storage power station is formed in the dotted line, and finally the dynamic equivalence diagram of power system taking into account pumped storage power station is formed.
3.2. Calculation of voltage stability index of power system with pumped storage power station

The influence of pumped storage power station connected to the power grid on the voltage stability of the system can be analyzed from the following two aspects. On the one hand, pumped storage power station can be simply equivalent to a “negative” load superimposed on a load node to reduce the system load, or equivalent to a constant power load of the PQ node for system stability analysis; On the other hand, the connection of pumped storage power plants to the power grid will lead to changes in the dynamic equivalent parameters of the system, which will affect the static voltage stability of the power system:

(1) If the output of pumped storage power station is \( S_D \), and the power absorbed by the load from the power system is \( S_I \). Then the power absorbed by the load from the system changes to \( S_I - S_D \) considering pumped storage power station. So, it is advantageous to the improvement of voltage stability of state grid.

(2) Considering the influence of grid connection of pumped storage power station on network parameters of power system. Seeing from the load node to the system, the integrated dynamic equivalent circuit of the system considering the pumped storage power station is shown in Figure 2, then the equivalent potential of the system equivalent circuit:

\[
E_{\text{eq}} = \frac{Z_{\text{eq}}}{Z_{\text{eq}} + Z_{\text{they}}} (E_{\text{they}} + jZ_{\text{they}}) \tag{11}
\]

Equivalent impedance of power system:

\[
Z_{\text{they}} = \frac{Z_{\text{eq}} Z_{\text{they}}}{Z_{\text{eq}} + Z_{\text{they}}} \tag{12}
\]

So the general impedance Modulus Margin with pumped storage power station:

\[
\mu = \left| \frac{Z_{\text{eq}}}{Z_{\text{eq}} + Z_{\text{they}}} \right| \left| \frac{Z_{\text{they}}}{Z_{\text{eq}} + Z_{\text{they}}} \right| \tag{13}
\]

After the pumped storage power station is connected to the grid, the integrated dynamic equivalent impedance of the system is the parallel of the parameters introduced by the pumped storage power station and the integrated dynamic equivalent parameters of the original system. After parallel connection, the integrated equivalent impedance of the system decreases, while the static equivalent impedance of the load increases, and the voltage stability of the system increases.

4. Simulation calculation and analysis

Pumped storage power station is connected to the standard node test system through transformers and lines, as shown in Figure 3. And the MATLAB program is written for simulating.

![Figure 3. Pumped Storage Power Station access basic system diagram.](image-url)
The impedance margin of load nodes is calculated when the output and grid-connected position of pumped storage power station are different, which is based on the evaluation method of power system voltage stability with pumped storage power station.

4.1. IEEE14 node testing system

The system adopts the load growth strategy of synchronous power disturbance. Under the initial load state, the impedance margin index of each load node in IEEE14-bus system is calculated. The calculation results are shown in Fig. 4.

![Figure 4. Pumped Storage Power Station access basic system diagram.](image)

The simulation results show that the impedance modulus margin of No. 14 load node is the smallest and the stability is the worst, the impedance modulus margin of No. 5 load node is the largest and the stability is the best. It is obvious that the 5th load node is the nearest to the power supply, so the voltage stability level is higher; the 14th load node is the farthest from the power supply, and the corresponding voltage stability is also poor. Therefore, the theoretical calculation results based on the proposed method are consistent with the actual situation, impedance modulus margin can effectively evaluate the voltage stability of power system.

Continuous increase of system load for simulation analysis: Node 14 will first occur voltage collapse, the voltage collapse point of the whole network also starts from Node 14. Near the limit power point, the impedance modulus margin of all load nodes is close to zero. The larger the load power of the system, the smaller the corresponding impedance margin, and the weaker the stability level of the system. The impedance margin index can well reflect the stability of the system voltage.

(1) The influence of pumped storage power station on system voltage stability is calculated and analyzed by changing the output of pumped storage power station. Because the load of IEEE 14-bus system is lighter, the load power factor is chosen as $\lambda = 1.5$. Pumped storage power station is connected to the 13th node of IEEE14 node system with medium stability. Adjusting the output of pumped storage power station according to the load condition of the system node, and the general impedance modulus margins of the system load nodes are calculated respectively as shown in Table 1.

### Table 1. General Impedance Modulus Margin with Different Output of Pumped Storage Power Station

| Node | 0MW   | 2MW   | 3MW   | 5MW   |
|------|-------|-------|-------|-------|
| 4    | 0.6695| 0.6771| 0.6806| 0.6876|
| 5    | 0.6930| 0.7006| 0.7040| 0.7110|
| 9    | 0.5885| 0.5981| 0.6025| 0.6114|
| 10   | 0.5815| 0.5913| 0.5958| 0.6050|
| 11   | 0.5911| 0.6014| 0.6062| 0.6158|
| 12   | 0.5886| 0.6003| 0.6057| 0.6167|
| 13   | 0.5810| 0.5936| 0.5995| 0.6113|
| 14   | 0.5572| 0.5683| 0.5734| 0.5837|
Continuously increasing the output of pumped storage power station, and calculating the general impedance modulus margin growth value of load node for each additional 1 MW output of pumped storage unit, the results are shown in Fig. 5.

![Figure 5](image)

**Figure 5.** Increasing value of impedance modulus margin/MW.

Table 1 shows that the overall load level of the IEEE14 bus system is relatively light, and the system can achieve a better voltage stability level with less output of the pumped storage power station. The bigger the output of pumped storage power station is, the bigger the impedance margin of load node is, that is, the better the voltage stability of the system is. Moreover, the closer to the access point of the pumped storage power station, the more obvious improvement of voltage stability.

Fig. 5 shows that the increase value of impedance mode margin/MW of each load node shows a downward trend with the increase of output of pumped storage power station. When the output of pumped storage power station is 5 MW, the impedance margin of 14th node of the system increases from 0.5572 to 0.5837, which is 4.76%.

(2) Keeping the output of grid-connected pumped storage power station unchanged and changing the grid-connected position of pumped storage power station, the general impedance modulus margin of weak node of the system is calculated as Fig. 6.

![Figure 6](image)

**Figure 6.** General impedance margin of weak node.

Analysis of Figure 6 shows that the impedance modulus margin of weak nodes of the system increases greatly when the pumped storage power station with the same output is connected to different nodes of the system. The voltage stability of the system can be improved by connecting the pumped storage power station into the system. The connection location of pumped storage has a great influence on the voltage stability of the system. It is better to improve the voltage stability of the system by connecting pumped storage power station to weak nodes or adjacent nodes.

4.2. **IEEE33 node testing system**
In order to prove the influence of the output and access position of pumped storage units on the voltage stability of load nodes better, the simulation analysis is carried out based on IEEE33 bus system. In the case of load power factor $\lambda = 1.3$, the general impedance modulus margin of the system for relatively weak load nodes is calculated. The results are shown in Table 2.

**Table 2. IEEE33 system general impedance modulus margin of some relatively weak nodes.**

| Node | General impedance modulus margin $\mu$ |
|------|---------------------------------------|
|      | A          | B          | C          | D          |
| 12   | 0.8828     | 0.9011     | 0.9403     | 0.9593     |
| 13   | 0.8793     | 0.8941     | 0.9375     | 0.9625     |
| 14   | 0.8771     | 0.8935     | 0.9368     | 0.9652     |
| 15   | 0.8750     | 0.8932     | 0.9362     | 0.9677     |
| 16   | 0.8718     | 0.8917     | 0.9346     | 0.9741     |
| 17   | 0.8712     | 0.8915     | 0.9342     | 0.9737     |
| 28   | 0.8895     | 0.9200     | 0.9236     | 0.9173     |
| 29   | 0.8840     | 0.9156     | 0.9188     | 0.9121     |
| 30   | 0.8781     | 0.9095     | 0.9128     | 0.9064     |
| 31   | 0.8768     | 0.9081     | 0.9115     | 0.9051     |
| 32   | 0.8764     | 0.9077     | 0.9111     | 0.9047     |

In the table, A indicates a system with no pumped storage power station; B indicates a system with pumped storage power station connecting at No. 14 load node; C indicates a system with pumped storage power station connecting at No. 14 load node, which the output is 1.5 times that of B; D indicates a system with the pumped storage power station connecting at No. 17 load node and its output is the same as that of B.

The analysis of table 2 shows that the impedance modulus margin of weak nodes increase greatly through connecting the pumped storage power station to the system by comparing A with B, C or D, so it is helpful for the improvement of voltage stability of system with pumped storage power station; The connection of pumped storage power station at weak nodes of the system is more conducive to the improvement of voltage stability by Comparing B with D; In a certain range, the greater the output of pumped storage power station, the more obvious improvement of system voltage stability by Comparing B with C. And the simulation results of 33-bus system are consistent with those of the previous 14-bus system.

Therefore, in the practical engineering applications, the impedance modulus margin of load nodes in the system can be calculated first according to the load situation of the network, then the weak nodes in the system can be determined according to the order of the impedance modulus margin value. Finally, the appropriate output and access location of pumped storage power station can be selected based on the proposed analysis method of power system voltage stability with pumped storage power station.

5. Conclusion

(1) The impedance modulus margin defined by the non-linear equivalent analysis method is used as the evaluation index of system voltage stability, and a method for evaluating voltage stability of power system with pumped storage power station is proposed.

(2) The peak-cutting function of pumped storage power station is conducive to the improvement of system voltage stability. The greater the output, the better the voltage stability of the system. And the closer to the access location of the pumped storage power station, the more obvious improvement of the voltage stability for the load nodes.

(3) Accessing pumped storage power stations to relatively weak nodes of the system is more conducive to the improvement of voltage stability. In the practical application of engineering, the node with poor voltage stability can be selected as the access position of pumped storage power station.
6. References

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