ABSTRACT

With the large-scale renewable energy incorporation, the system operation fluctuation and randomness are increasing, and the real-time requirement of the static voltage security analysis of power system is more urgent. In order to meet the requirements of real-time, fast Thevenin equivalent parameter is used as the static voltage safety analysis index. The fast N-1 scanning of the static voltage security is achieved by studying the analytic relationship between line outage and Thevenin equivalent parameters, and then instable points of the voltage are found to ensure the system at safe operation level. The advantage of this method is that it can calculate the Thevenin equivalent parameter after disconnection, only using the voltage, phase angle, active power and reactive power of the system before line outage. The validity and correctness of this method are verified by simulation results.

Keywords: Analysis of static voltage safety, Thevenin equivalent, fast line outage analysis.

INTRODUCTION

With wind power and other large-scale the renewable energy integration making the system more volatile and unstable, the rapid voltage security assessment of power system is very important. Due to the large number of expected accidents, real-time online analysis requires to achieve voltage security judgments in a short period of time[1]. At present, the common safety requirements are subject to the N-1 security criterion.

In the disconnection calculation, the ability to quickly get the N-1 power flow is an important criterion for determining the merits of a method, that is, the speed is often the first [2]-[6]. Whether it can meet both accuracy and speed requirements is an important indication to make proper evaluation of a static voltage safety analysis method [7]. The fast algorithm for power network outage-simulation is the base of static security assessment [8], [9]. In the power network outage-simulation calculation, the relatively mature methods include: DC method, compensation method, distribution coefficient method and so on. The methods of static voltage security include continuous power flow method, improved continuation power flow method and singular value decomposition method. Continuous power flow method introduces the additional parameters to the traditional power flow equations, forms the parameter power flow equations, overcomes the
and cannot converge outside the collapse point. The disadvantage is that the calculation is large. The singular value decomposition method is used to decompose the Jacobi matrix singular value of power flow equation, and the problem of studying the static safety for the given system is transformed to the study of the sure Jacobin matrix and singular degree of the Jacobin matrix.

Analysis of Thevenin equivalent static voltage security become a research direction of power system voltage security for its method concept it’s both clear concept and simple principle. The method proposed in [10] is applicable for both normal connection state and disconnection state, and does not require two or more nodes power flow, only needs to provide the normal load voltage and voltage sensitivity of the connection state, which can calculate N-1 state power flow results very quickly. There are many methods for the calculation of power system N-1 state static voltage stability limit point. [11]-[12] obtain static voltage stability limit based on power flow equations. [13] considers the dynamic characteristics of generators and loads to calculate the stability limit point. [14] considers the fluctuation of wind power to judge the static voltage safety.

The Thevenin equivalent simplifies the power system into a two-node simple network. Due to the simplicity and effectiveness of the Thevenin equivalent model, the static voltage safety analysis based on the Thevenin equivalent has become a hotspot [15]. In this paper, fast and reliable Thevenin equivalent parameters are used as static voltage safety analysis indicators.

By studying the analytic relationship between branch outage and Thevenin equivalent parameters, the static voltage N-1 check is analyzed quickly and voltage stability weak nodes are found rapidly, which provides the basis for the preventive control of the power system, and has practical significance for avoiding voltage collapse. The primary objective of the system voltage safety analysis is to improve the safety in power system.

The traditional method using the disconnection power flow for N-1 static voltage analysis is difficult to meet the speed requirements of large modern power system. Fast analysis method of static voltage security based on Thevenin equivalent proposed in this paper greatly improve the computing speed and meet the real-time requirement of modern power system within the requirements of calculation accuracy.

The remainder of the paper is organized as follows: Section II introduces the static voltage safety study based on the Thevenin equivalent and propose the static voltage safety index in order to find the static voltage safety weak point. Section III deduces the fast Thevenin equivalent parameter calculation after disconnection. Section IV presents a case study. In Section V, the main results are summarized and the key conclusions are recapped.

**ANALYSIS OF THE STATIC VOLTAGE SECURITY BASED ON THEVENIN EQUIVALENT**

**The Basic Principle of Thevenin Equivalent**

The Thevenin equivalence is the equivalent network observed by the target node to the ground port. For any moment, Thevenin equivalent transfer a complex system into two nodes simple system from the perspective of a load node.

At any time, any complex power system can be regarded as an equivalent network in which the equivalent electromotive force $E_{thi}$ feeds power to node i through an equivalent impedance $Z_{thi}$, as shown in Figure 1 (taking load 1 for example).

The equivalent load impedance can be obtained in the current state, but not be considered as the constant impedance model. When the system power flow changes, the equivalent load impedance $Z_{Li}$ changes. The equivalent system is shown in Figure 2. The equivalent impedance formula is
The $E_{thi}$ can be calculated according to the definition of the Thevenin equivalent electromotive force, that is, the open circuit voltage of the node, and equivalent impedance $Z_{thi}$ is obtained according to equation (2).

\[
egin{align*}
E_{thi} &= U_i - jQ_i \\
I_i &= \left( \frac{S_i}{U_i} \right)^* = \frac{P_i - jQ_i}{U_i}
\end{align*}
\]

where $S_i$ represents the complex power of node $i$, and the superscript * denotes conjugate.

Figure 1. Schematic Diagram of System before and after Thevenin Equivalent.

Figure 2. Schematic Diagram of System after Load Equivalent to Impedance.

**Static Voltage Safety Index**

In the DC network, the maximum transmission power of the network to any load node appears if the Thevenin equivalent resistance is equal to the load resistance of the node. According to the principle of DC to AC expansion, the system is in the critical stability state if system Thevenin equivalent impedance is equal to the load impedance, so we define the system Thevenin equivalent impedance value as the critical impedance value of the load.
impedance. The impedance modulo $Z_L$ of the load node is compared with its critical value $Z_{th}$ to determine the voltage safety.

- When $Z_L > Z_{th}$, the system is stable.
- When $Z_L = Z_{th}$, the system is in the critical state.
- When $Z_L < Z_{th}$, the system is unstable.

It is important to measure the voltage safety margin in the static voltage safety analysis. The impedance modulus margin can accurately describe the distance between the current operating state and the critical state. The deviation from critical impedance $\Delta Z$ is taken as the voltage stability index, which are defined by:

$$\Delta Z = \frac{(Z_L - Z_{th})}{Z_L}$$ (3)

Using the above indicators to determine the degree of static security, the greater the impedance margin $\Delta Z$ is, the more stable the system is.

**FAST ALGORITHM OF BRANCH OUTAGES**

The sensitivity method of disconnection analysis considers the disconnection of the line as a disturbance under normal conditions. The formulations of expanded Taylor series for power flow equations are established to form the sensitivity matrix with which the branch break is simulated by the increment of bus injection power.

The power equations are:

$$P_i = V_i \sum_{j \in i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})$$

$$Q_i = V_i \sum_{j \in i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})$$ (4)

Where $P_i$ and $Q_i$ represent the given active and reactive power flow; $j \in i$ represents the node $j$ which is adjacent to node $i$, including $j=i$; $G_{ij}$ and $B_{ij}$ are the mutual conductance and mutual acceptance between node $i$ and node $j$ respectively; $V_i$ and $V_j$ are the voltage of node $i$ and node $j$ respectively; $\theta_{ij}$ is the voltage phase difference between node $i$ and node $j$.

Equation (4) can be summed up as:

$$W_0 = f(X_0, Y_0)$$ (5)

$W_0$ is active and reactive power injection power vector under normal circumstances. $X_0$ is the state vector composed of node voltages and phase angles under normal conditions. $Y_0$ is the network parameter under normal circumstances.

If the injection power of the system is perturbed by $\Delta W$, or the network parameter is perturbed by $\Delta Y$, the state variable will change. If the change is $\Delta X$, the following equation can be obtained:

$$W_0 + \Delta W = f(X_0 + \Delta X, Y_0 + \Delta Y)$$ (6)

(7) is derived from formula (2) by expanding the Taylor series and leaving out the higher term of $\Delta X$. 

102
\[ \Delta X = \left[ f_x'(X_0, Y_0) + f_y'(X_0, Y_0) \Delta Y \right]^{-1} \times \left[ \Delta W - f'_x(X_0, Y_0) \Delta Y \right] \] (7)

Without considering the power perturbation (\(\Delta W = 0\)), equation (7) can be changed to:

\[ \Delta X = \left[ f_x'(X_0, Y_0) + f_y'(X_0, Y_0) \Delta Y \right]^{-1} \left[ -f'_x(X_0, Y_0) \Delta Y \right] \] (8)

So, (8) can be summarized as (9)

\[ \Delta X = S_0 \Delta W_y \] (9)

\(\Delta W_y\) can be regarded as the disturbance of bus injection power caused by disconnection. Therefore, the method can be considered that the power system has a small disturbance when the line is broken, with network parameters unchanged but bus injection powers changed. In order to check the operating state of the various disconnection, the increment of the state variable can be calculated directly by equation (10) as long as the corresponding bus injected power increment \(\Delta W_y\) can be found.

Modified state variable is showed as

\[ X = X_0 + \Delta X \] (10)

In this way, many intermediate processes are omitted, so it has a fast operation speed and is very important for real-time voltage monitoring in power system. This method is simple and improves the efficiency of N-1 calculation, so it is a practical method for analysis of disconnection.

For a given power system, fast outage method based on Thevenin equivalent and static voltage security analysis procedure is shown in Figure 3.

Figure 3. Flowchart of the Proposed Method.
CASE STUDY

IEEE three-machine nine-node is selected based on reference [1]. According to the method proposed in this paper, the Thevenin equivalent parameters after the disconnection are calculated quickly, and the parameters results are compared with that obtained by Newton-Raphson method in order to value the error of this method.

The impedance modulus margins under different break simulations are shown in Table I. Calculation errors of parameters compared with Newton method are shown in Table II.

Table II represents the errors of equivalent parameters obtained by fast analysis method. The maximum relative error of electromotive force is 2.21%, and the maximum relative error of impedance modulus is 7.29%. It shows that the fast disconnection method has the advantages of high accuracy. The impedance modulus margins obtained in Table I is analyzed to determine the static voltage safety and find weak points. When the branch 4-5 is broken, the bus 5 impedance margin is the smallest, which shows bus 5is voltage weak point. When the line 4-6 is broken, the node 6 is a weak voltage node. In the same way, voltage weak points are bus 6, bus 8, bus 8, bus 5 respectively when branch 6-9, branch 8-9, branch 7-8, branch are broken.

<table>
<thead>
<tr>
<th>Table I. Impedance modulus margins.</th>
<th>Impedance modulus margin $\Delta Z(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bus 5</td>
</tr>
<tr>
<td>4-5 breakdown</td>
<td>62.26</td>
</tr>
<tr>
<td>4-6 breakdown</td>
<td>88.17</td>
</tr>
<tr>
<td>6-9 breakdown</td>
<td>87.86</td>
</tr>
<tr>
<td>8-9 breakdown</td>
<td>88.09</td>
</tr>
<tr>
<td>7-8 breakdown</td>
<td>88.53</td>
</tr>
<tr>
<td>5-7 breakdown</td>
<td>81.52</td>
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</table>

<table>
<thead>
<tr>
<th>Table II. Errors of Thevenin Equivalent Parameters.</th>
<th>Relative error of electromotive force (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bus 5</td>
</tr>
<tr>
<td>5-7 breakdown</td>
<td>2.21</td>
</tr>
<tr>
<td>7-8 breakdown</td>
<td>0.29</td>
</tr>
<tr>
<td>8-9 breakdown</td>
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</tr>
<tr>
<td>6-9 breakdown</td>
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</tr>
<tr>
<td>4-6 breakdown</td>
<td>0.31</td>
</tr>
<tr>
<td>4-5 breakdown</td>
<td>2</td>
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</tbody>
</table>

| Impedance relative error(%)                        | Bus 5  | Bus 6  | Bus 8  |
|-----------------------------------------------------|------------------------------------------|
| 5-7 breakdown                                      | 0.46   | 7.29   | 0.66   |
| 7-8 breakdown                                      | 3.97   | 6.37   | 2.15   |
| 8-9 breakdown                                      | 0.77   | 1.34   | 3.75   |
| 6-9 breakdown                                      | 1.61   | 4.36   | 0.78   |
| 4-6 breakdown                                      | 0.44   | 1.58   | 0.45   |
| 4-5 breakdown                                      | 2.94   | 0.35   | 1.44   |

CONCLUSION

Under the condition of wide area measurement, the broken line of the system is regarded as a disturbance of normal operation using the fast disconnection method. By analyzing the Taylor series of the power flow equation and considering the influence of the broken line as the change of bus injection power, the power flow after the break is estimated in order to get the Thevenin equivalent parameters quickly which can be seen as indicators of static security analysis. It can
complete the static voltage safety analysis of power grid rapidly, find out the voltage weak points, and ensure power system at safe operation level.

The case study verifies the validity and correctness of the method. When the branch is broken, the overall system operation indices of N-1 (including active power, reactive power, voltage and phase angle) can be calculated quickly only by using the existing power flow data. Moreover, this method has higher calculation accuracy and lower complexity, greatly improving the speed of static voltage safety analysis, and has a very good online application prospects.

The analysis of the problem is limited by the selection of simulation models, and the future work will compare more models in order to achieve more accurate results.

REFERENCES