

Research on Dynamic Thevenin Equivalence Method Based on Deviation Correction

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Abstract As one of the core algorithms for safety and stability evaluation of the power grid, the method has been used by many scholars to analyze and control the stability of power grid. A method based on deviation correction is studied to track Thevenin equivalent parameters. This is an iterative algorithm based on the correction of the amount of deviation. The direction of the correction is determined based on the real-time data, and the parameters of the real-time estimation are obtained by iterative correction of the Thevenin equivalent parameter. It is possible to accurately track the Thevenin equivalent parameters when the system is disturbed to achieve an accurate analysis of the voltage stability.

Keywords: dynamic Thevenin equivalent, deviation correction, least squares method, complete differential

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1. Introduction

With the increasing demand for electricity, power grid technology is also developing rapidly. However, accompanied by great benefits to society, electricity also brings some problems and challenges. Each parts of the internal structure of the power system is more complex and affects each other. When one of the links is disturbed, or even destroyed, it may bring a chain reaction. What's worse, it may cause some economic losses [1]. To avoid the occurrence of these accidents, to ensure the reliability of the power system to run, the power system analysis and safety and stability control are proposed to be more demanding than ever.

In recent years, the voltage stability analysis method based on Thevenin equivalent is one of the hotspots in related fields. Most of the traditional Thevenin equivalence models assume that in a data window, the Thevenin equivalent internal potential and internal impedance remain unchanged [2]. In the traditional Thevenin equivalence model, the Thevenin equivalence is not accurate when the system is disturbed [3]. So, it is necessary to estimate the system impedance, though which is not stable [4]. A method was studied to estimate the maximum allowable load and voltage stability margin of a power system. However, there will be parameter drift problem in practice [5]. What's more, the traditional Thevenin equivalent methods require several operating data, which is one of the limitations of the traditional Thevenin equivalence [6,7,8]. The Thevenin equivalence method was studied to solve the problem, which is based on phase angle deviation correction without considering the real-time changes in the system impedance [9]. Based on the complete differential

dynamic Thevenin equivalent method, the Thevenin equivalent parameters can only be accurately tracked when there are slight perturbations in the system [10]. This situation is equally problematic by using the local PMU to measure the on-line tracking of the Thevenin equivalence parameters on the node [11]. With the continuous development of the scale of the grid, its universality and its accuracy cannot meet the requirements at the same time [12,13,14].

This paper analyzes the dynamic Thevenin equivalence method based on deviation correction. And it is compared with the traditional method based on the least square method and the method based on the complete-differential dynamic Thevenin equivalence method, which verifies that the method can be accurate to trace the Thevenin equivalent parameters when the system is disturbed.

2. Dynamic Thevenin Equivalence Method Based on Deviation Correction

2.1. Principle

The study of the Thevenin equivalence method of power systems is usually for a node. The circuit diagram is shown as follows.

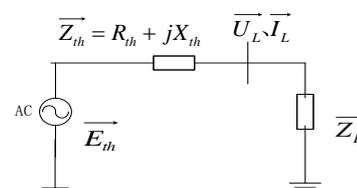


Figure 1. The Thevenin equivalent circuit

In Figure 1, $\overline{E_{th}}$ means the Thevenin equivalent potential and $\overline{Z_{th}}$ means the Thevenin equivalent impedance. $\overline{U_L}$, $\overline{I_L}$ and $\overline{Z_L}$ represent the load node voltage, current and impedance respectively.

The relationship between the electrical quantities in Figure 1 can be described as equation (1).

$$\overline{E_{th}} = \overline{U_L} + \overline{Z_{th}} \times \overline{I_L} \quad (1)$$

If the internal impedance and internal potential of the equivalent system are constant, $\overline{E_{th}}$ and $\overline{Z_{th}}$ can be obtained using two sets of $\overline{U_L}$, $\overline{I_L}$. However, it is not always reasonable to assume the internal potential of the system impedance constant, especially when there is a large disturbance in the system. Therefore, this paper studies the dynamic Thevenin equivalent method based on deviation correction. The following figure shows the deviation of the dynamic correction based on Thevenin vector diagram, where the reference direction is the node injection current vector.

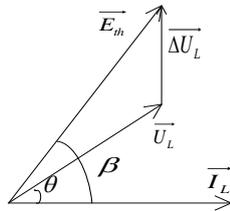


Figure 2. Thevenin vector map

According to Figure 2, (1) can be rewritten into algebraic form such as:

$$\begin{cases} E_{th} \cos \beta = R_{th} I_L + V_L \cos \theta \\ E_{th} \sin \beta = X_{th} I_L + V_L \sin \theta \end{cases} \quad (2)$$

Where E_{th} , β_{th} , R_{th} and X_{th} are unknown. Four variables are defined as follows.

$$|\overline{\Delta Z}| = A \angle \phi \quad (3)$$

$$\phi = \left| \tan^{-1} \left(\frac{{}^*X_{th}^i - X_{th}^{i-1}}{{}^*R_{th}^i - R_{th}^{i-1}} \right) \right| \quad (4)$$

$$B = \left| {}^*Z_{th}^i \right| - \left| Z_{th}^{i-1} \right| \quad (5)$$

$$\overline{E_{th}^i} = \overline{E_{th}^{i-1}} + \overline{\Delta E} \quad (6)$$

${}^*R_{th}^i$ and ${}^*X_{th}^i$ are defined to represent predictions of current resistance and inductance, which are respectively calculated by U_L^i, I_L^i and $E_{th}^{i-1}, \beta_{th}^{i-1}$ with (2). And the deviation amount $\overline{\Delta E}$ between E_{th}^i and the previous estimated value E_{th}^{i-1} is calculated by the deviation amount B between the predicted resistance value ${}^*Z_{th}^i$ and the previous estimated value Z_{th}^{i-1} and the change tendency of the load impedance. Specifically, $\overline{\Delta E}$ is equal

to zero when the load impedance is constant. If the load impedance increases and B is over zero, or the load impedance decreases, and B is below zero, the deviation amount $\overline{\Delta E}$ is assigned by the opposite of $\varepsilon \angle \phi$.

Otherwise, $\overline{\Delta E}$ and $\varepsilon \angle \phi$ are equal. The purpose of the above work is to get E_{th}^i and β_{th}^i . Then calculate the estimated values of R_{th}^i and X_{th}^i through (2).

In addition, ε should be chosen between 0.005% ~ 0.05%. Because the choice of too large ε will make a great fluctuation in the equivalent data, if too small cannot meet the Thevenin equivalent requirements in the fastness [15].

To avoid parameter drift, a representative set of $\overline{U_L}$ and $\overline{I_L}$ is chosen, which is obtained by (7).

$$\tan \beta_{th} = \frac{R_{th} I_L + U_L \cos \theta_L}{X_{th} I_L + U_L \sin \theta_L} \quad (7)$$

Normally, R_{th} is much larger than X_{th} , $|Z_L| > |Z_{th}|$. Therefore, if R_{th}^0 is far less than X_{th}^0 , it is considered that the choice of E_{th}^0 and β_{th}^0 meet the requirements of continuing the experiment. Otherwise need to reselect the initial value until it is reliable.

2.2. Influence of Load Variation on Tracking Accuracy

This paper is based on the system side potential by $\pm 2\%$ random fluctuations to analyze the load changes on the tracking accuracy, according to the load changes as follows: $\pm 1\%$, $\pm 3\%$, $\pm 5\%$, $\pm 8\%$, $\pm 10\%$, $\pm 20\%$. The average error of Z_{th} is written as $\overline{\Delta Z}$, and the average error of E_{th} is written as $\overline{\Delta E}$. Similarly, the maximum error of Z_{th} is written as ΔZ_{max} , and the average error of E_{th} is written as ΔE_{max} . ΔZ_L means load impedance fluctuation.

Table 1. Error Comparison of Load Impedance Fluctuation

$\Delta Z_L / \%$	$\overline{\Delta Z} / \%$	$\Delta Z_{max} / \%$	$\overline{\Delta E} / \%$	$\Delta E_{max} / \%$
± 1	0.0161	18.0731	0.0077	0.0177
± 3	0.0451	20.3807	0.0022	0.0132
± 5	0.0792	19.2088	0.0004	0.0151
± 8	0.1281	18.7193	0.0168	0.0352
± 10	0.1617	21.1506	0.0167	0.0349
± 20	0.1861	22.1430	0.0281	0.0610

Table 1 shows the error comparison between load impedance fluctuation and tracking accuracy. It can be found that with the increase of the load impedance, the error of the equivalent impedance gradually increases, and the equivalent potential is the same. But the variation of the equivalent impedance is more obvious than equivalent potential. In addition, ΔZ_{max} and ΔE_{max} are not directly related to load impedance fluctuations. The maximum error is greater than the corresponding average error. Compared ΔZ_{max} and ΔE_{max} , the former is much larger,

but they are all within reasonable limits. Dynamic equivalent method based on the deviation correction can exactly track the Thevenin equivalent parameter under the condition that the load impedance is disturbed.

2.3. Influence of Potential Change on Tracking Accuracy

The load is set to $\pm 5\%$ random fluctuations to analyze the impact of potential changes on the tracking accuracy, in which the change of potential is respectively selected to be $\pm 0.1\%$, $\pm 0.3\%$, $\pm 0.5\%$, $\pm 0.8\%$, $\pm 1\%$, $\pm 2\%$ and $\pm 3\%$ for simulation comparison. ΔE_{th} means potential fluctuation of system.

Table 2 shows the error comparison of tracking with different potential fluctuation. As the potential fluctuation increases, $\overline{\Delta Z}$ and $\overline{\Delta E}$ trend to decrease first and then increase, and ΔZ_{max} is much larger than ΔE_{max} . In short, under the condition of different potential fluctuations, the equivalent method based on the deviation correction can all trace the Thevenin equivalent potential accurately. The maximum error increases rapidly for the Thevenin equivalent impedance when the disturbance is large, but the average error can still be controlled within 0.5%, which means that the equivalent method can also be perfectly good to follow the Thevenin equivalent impedance.

Table 2. Error Comparison of Potential Fluctuation

$\Delta E_{th}/\%$	$\overline{\Delta Z}/\%$	$\Delta Z_{max}/\%$	$\overline{\Delta E}/\%$	$\Delta E_{max}/\%$
± 0.1	0.4977	2.4492	0.0766	0.1443
± 0.3	0.2692	5.6956	0.0292	0.0506
± 0.5	0.1782	10.0435	0.0152	0.0297
± 0.8	0.1364	14.7727	0.0178	0.0263
± 1	0.0758	18.4572	0.0149	0.0274
± 2	0.0792	19.2088	0.0004	0.0151
± 3	0.3529	66.9825	0.0069	0.0124

3. Contrast Research

3.1. Comparison with the Thevenin Equivalent Method Based on Least Square Method

The traditional Thevenin equivalent method mainly obtains the Thevenin equivalent of the system by calculating the power flow equations at two or more operating points. A representative method is the Thevenin equivalent method based on the least square method.

The experimental results of the Thevenin equivalent parameter error based on the least squares method with different potential fluctuations are compared with the Thevenin equivalent method based on the deviation correction. The method of this paper is recorded as method one, and the Thevenin equivalent method based on least square method is marked as method two. Figure 3 shows a scatter plot of the estimated random fluctuations for E_{th} at $\pm 0.1\%$, $\pm 0.5\%$, $\pm 1\%$ and $\pm 3\%$, respectively.

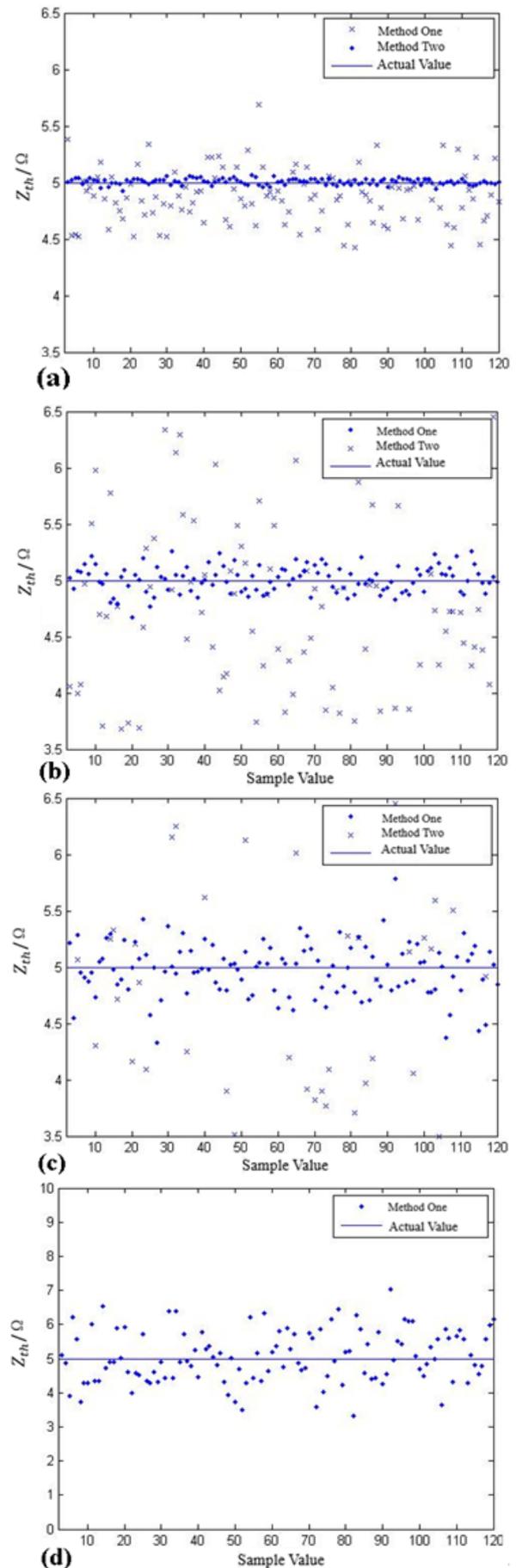


Figure 3. Thevenin Equivalent Impedance Scatter plot for E_{th} when varying to some extent:(a) E_{th} fluctuates at $\pm 0.1\%$, (b) E_{th} fluctuates at $\pm 0.5\%$, (c) E_{th} fluctuates at $\pm 1\%$, and (d) E_{th} fluctuates at $\pm 5\%$

It can be found that the first method is more accurate than the second method. When E_{th} fluctuates by $\pm 0.1\%$, both methods can track the equivalent impedance, but the first method is better than the second method. When E_{th} fluctuates by $\pm 0.5\%$ and $\pm 1\%$, the first method is still around the actual value, but the second method has obvious deviation in the equivalent impedance estimation. Although the estimation of method one shows a large error when E_{th} fluctuates randomly by $\pm 3\%$, the average value can still track the Thevenin equivalent impedance, as the second method has failed. Overall, the average and the maximum error of the two methods all tend to increase with the random fluctuation of E_{th} , but the error of method one increases much faster than that of method two, which indicates that in the presence of a system disturbance, compared to second method, the method one can more quickly and accurately track the Thevenin equivalent parameters, while the second method is easy to fail in the case of large disturbance.

3.2. Comparison with the Thevenin Equivalent Method Based on Complete Differential

The Thevenin equivalent method based on complete differential is to calculate the Thevenin equivalent parameters by the electrical quantity of the load bus. The specific process is to find the Thevenin parameters E_{th} and Z_{th} for the load flow equation. And then set up into equations to solve them [16,17].

R_0 and X_0 are chosen to be 3Ω and 4Ω as the initial values. The Thevenin equivalent method based on the total differential is hereinafter referred to method three.

Figure 4 shows a Thevenin equivalent impedance scatter plot of the estimated random fluctuations for E_{th} at $\pm 0.1\%$, $\pm 0.5\%$, $\pm 1\%$ and $\pm 3\%$, respectively. It can be found that the equivalent of method one is estimated more accurately than method three. When E_{th} fluctuates $\pm 0.1\%$ and $\pm 0.5\%$, both methods can track the equivalent impedance. When fluctuated by $\pm 1\%$ and $\pm 3\%$, the estimation of method one is still near the actual value. However, There have been some deviations in the estimation of the equivalent impedance.

Figure 5 shows the detailed calculation of Thevenin equivalent potential. Although both methods can track the Thevenin equivalent potential, method one is more accurate, and approximately equal to the actual value.

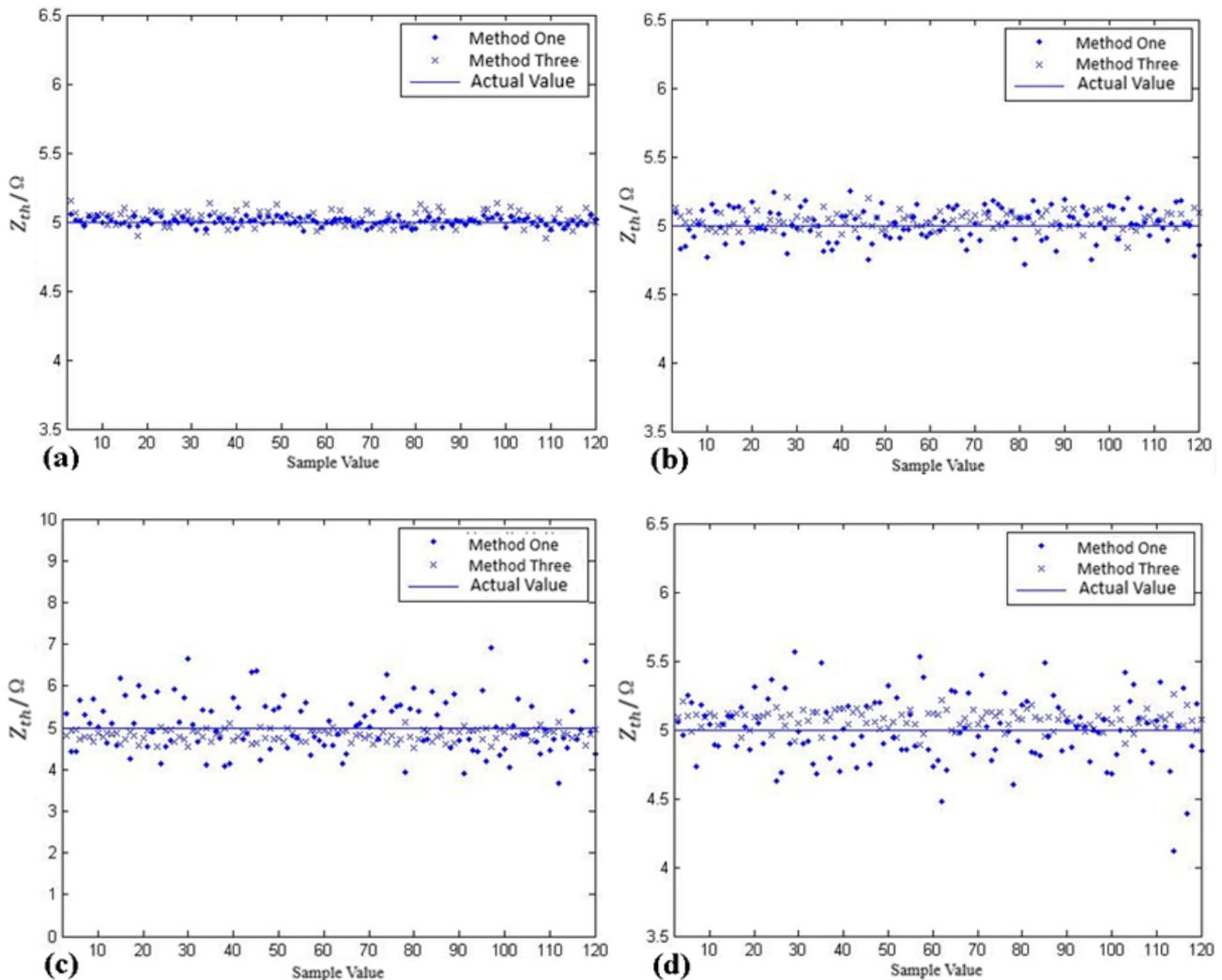


Figure 4. Thevenin Equivalent Impedance Scatter plot for E_{th} when varying to some extent:(a) E_{th} fluctuates at $\pm 0.1\%$, (b) E_{th} fluctuates at $\pm 0.5\%$, (c) E_{th} fluctuates at $\pm 1\%$, and (d) E_{th} fluctuates at $\pm 5\%$

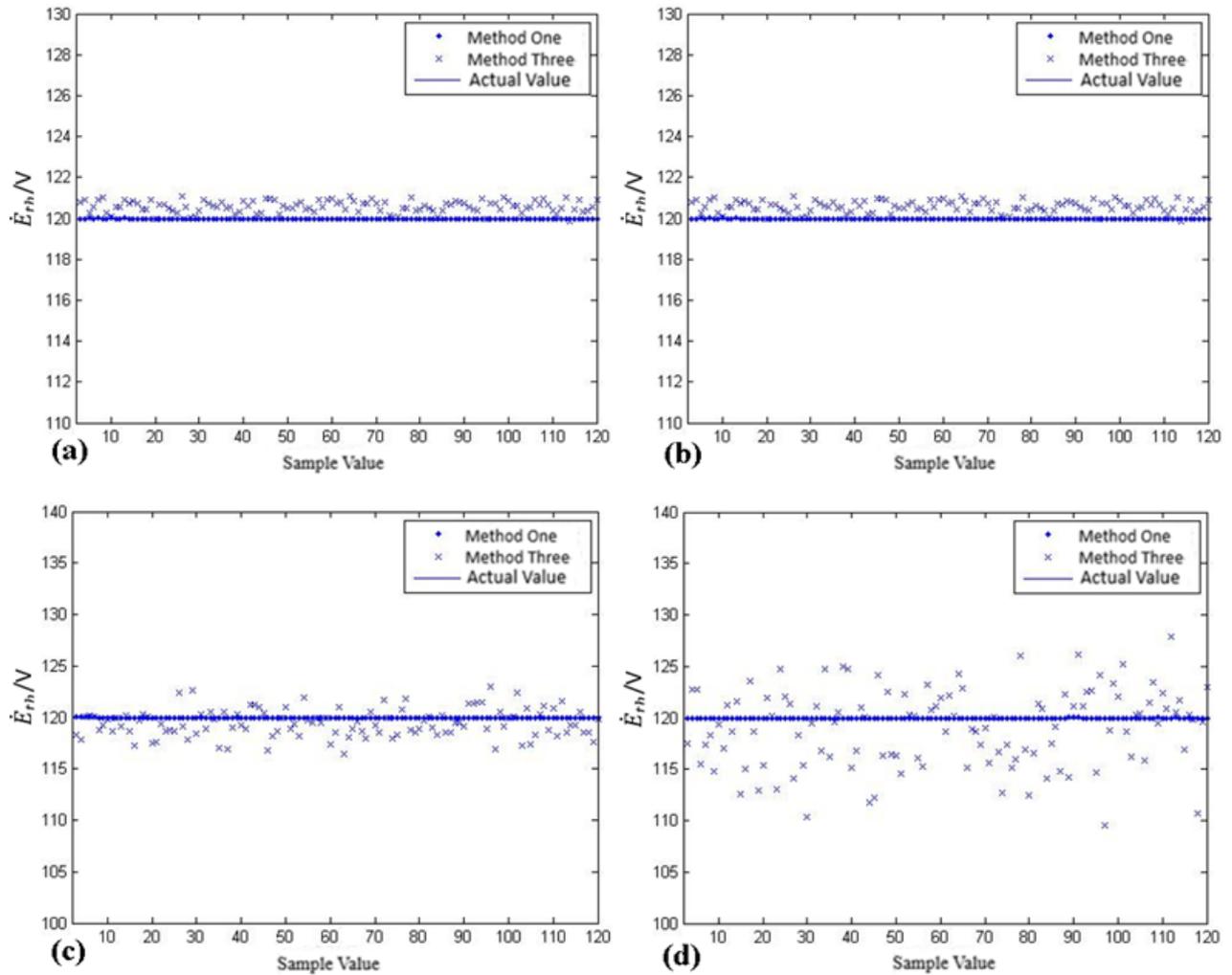


Figure 5. Thevenin Equivalent Potential Scatter plot for E_{th} when varying to some extent:(a) E_{th} fluctuates at $\pm 0.1\%$, (b) E_{th} fluctuates at $\pm 0.5\%$, (c) E_{th} fluctuates at $\pm 1\%$, and (d) E_{th} fluctuates at $\pm 5\%$

Therefore, method one and method three each have their own advantages. In the estimation of equivalent impedance, the average value of the former is more accurate, and the latter is more concentrated. The former is more accurate and focused on the estimation of the equivalent potential.

4. Dynamic System Adaptability

Three-machine ten-bus system is used to carry out simulation experiments, the system model shown in Figure 6. The algorithm adaptive to the system load change and system disturbance is verified by the increase of induction motor load and the short circuit of three-phase grounding, respectively.

4.1. Algorithm Adaptability of System Load Variation

At 15s, the induced motor load at node N10 is increased by 5% and the Thevenin equivalent of the system is analyzed from N9. The node voltage U_L , phase angle θ_L , active power P_L and reactive power Q_L of the load at the node are simulated. Choose 10s ~ 20s node data for equivalent calculation.

It can be seen from the Figure 7 that Thevenin equivalent method based on the deviation correction can trace the equivalent parameter value more quickly and accurately although the fluctuation is relatively large. The Thevenin equivalent method based on the total differential has little fluctuation when the load fluctuates, which means that it is not sensitive to changes in load impedance. It is also proved that the former is faster and more accurate than the latter in load impedance fluctuation, but it has a larger floating, that means, it is more sensitive to load changes.

Thus, in practical application, for the load-side disturbance, we can choose appropriate method to estimate Thevenin equivalent parameters according to the actual requirements.

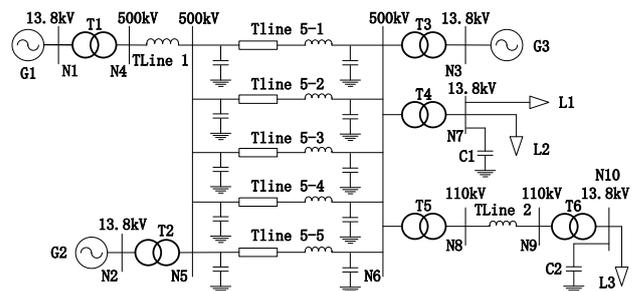


Figure 6. Three-machine ten-bus system model

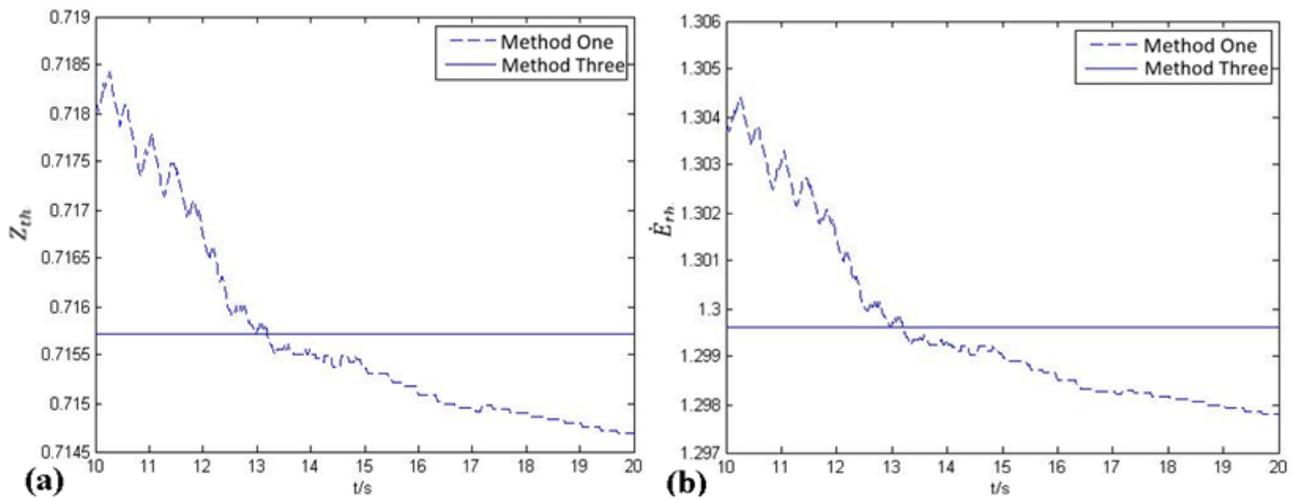


Figure 7. Thevenin formula estimates the scatter plot when load fluctuation: (a) Thevenin equivalent impedance comparison chart of the two methods, (b) Thevenin equivalent potential comparison chart for two methods

4.2. Algorithm Adaptability of Large Disturbance

Similarly, using Figure 6 as a model, three-phase grounding short circuit occurs in lines N5 ~ N6 near 20% of node N6 at 15s, and the fault is cleared after 0.04s. Choose 10s ~ 20s node data for equivalent calculation.

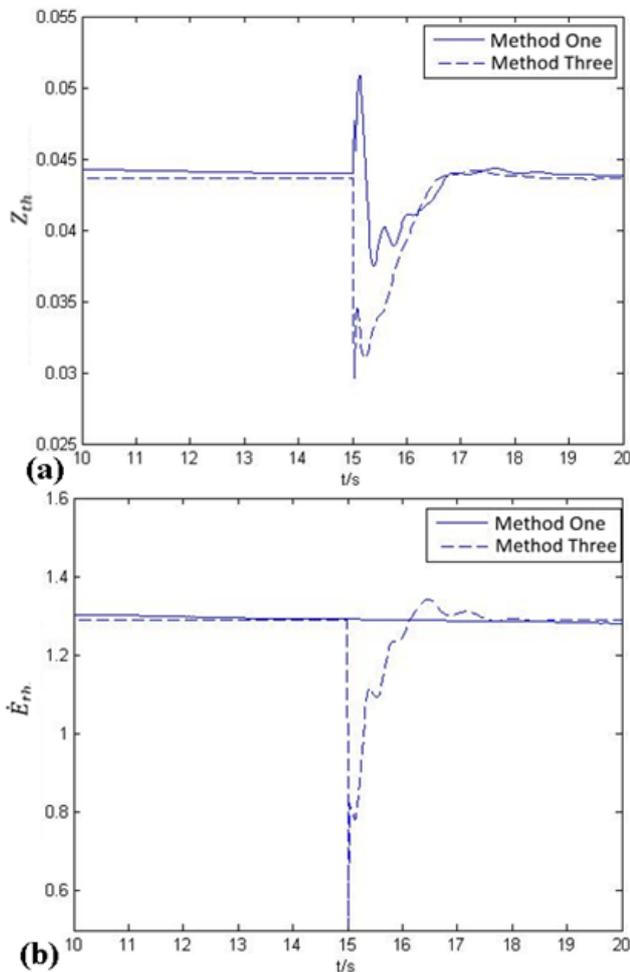


Figure 8. Thevenin formula estimates the scatter plot when system disturbance: (a) Thevenin equivalent impedance comparison chart of the two methods, (b) Thevenin equivalent potential comparison chart for two methods

Figure 8 shows the equivalent impedance and the equivalent potential comparison of method one and method three. When the three-phase grounding short circuit occurs on the system side in 15s, the equivalent parameters can be rapidly and accurately tracked. In comparison, the method one after the fault tracking slightly faster, and the accuracy is slightly higher. It can be seen from Figure 8(a) that the equivalent impedance of Thevenin equivalent impedance of the two methods in the 15s system-side perturbation shows some fluctuations after the system disturbance, and can achieve the system equivalent after the fault removal Impedance re-tracking. From the perspective of equivalent potential in Figure 8(b), method one is not sensitive to short-circuit faults in the system. In comparison, the Thevenin equivalent potential of the second method is greatly disturbed, but the equivalent potential can be rapidly tracked in almost 1 second. At the same time, the average value of the equivalent impedance under the Thevenin equivalent method based on the least square method is 0.0712 and the equivalent potential is 1.6875, that is, it has deviated from the equivalent parameters.

Therefore, in practice, the advantages of the Thevenin equivalent method based on deviation correction can be fully utilized, and the Thevenin equivalent parameters can be accurately estimated when the system is disturbed.

5. Conclusion

In this paper, from the simple Thevenin equivalent model to the actual three-machine ten-bus system model, the simulation analysis of the two models is respectively based on the Thevenin equivalent method based on the deviation correction, the least squares method and the complete differential method. The Thevenin equivalent method based on the deviation correction can accurately track the Thevenin equivalent parameters to meet the accuracy requirements of equivalent values, whether under different load impedance fluctuations or under different potential fluctuations.

On the contrary, compared with the conventional system, the traditional Thevenin equivalent method represented by the Thevenin equivalent method based on

the least squares method cannot track the Thevenin equivalent parameter when the system disturbance is slightly larger, which is decided by the characteristics of the method. Overall, the Thevenin equivalent method based on deviation correction and based on the total differential have their own advantages and disadvantages, and is more suitable for the actual system calculation. Different methods are suitable for different situations.

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