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A Decision-Making Method for the Loop Closing Operation in 10kV Distribution Network

Nan Feng[1], Ziqiang Zhou[2, *], Yuyao Feng[1] and Qiang Guo[1]

[1]Electric Power Science Research Institute of Shanghai Municipal Electric Power Company, Hongkou District, Shanghai 200427, China
[2]Department of Electrical Engineering, Shanghai Jiao Tong University, Minhang District, Shanghai 200240, China

*Corresponding author's e-mail address: z-q_zhou@sjtu.edu.cn

Abstract. Loop closing current may affect the security of power system during loop closing operation. In this study, practical criterion of secure loop closing operation is derived by analysing the relationship between current protection and loop closing current. On the basis of the practical criterion, a decision-making method for loop closing operation in 10kV distribution network considering the probability distribution of electric load is proposed. Based on probabilistic load flow theory, the cumulative distribution characteristic of loop closing current can be obtained by cumulant method. Finally, make a decision on loop closing operation according to the over-limit probability of loop closing current. In addition, a method for calculating cumulants of input variables based on historical load data is proposed, which overcomes the shortcomings of traditional numerical methods. The simulation results of a practical study case verify the effectiveness and practicability of the proposed method.

1. Introduction

Nowadays, distribution networks are usually designed with closed-loop structure and operated with open-loop structure in China [1]. The loop closing operation can transfer electric load and reduce power outage time in case of equipment maintenances or emergencies. However, large transient surge current may occur in the circuit at the moment of loop closing operation because of the voltage difference between two sides of the loop switch, which may cause the action of current protections. Besides, there may be large steady-state current in the loop network after the transient period, which can lead to equipment overload and result in failure of loop closing operation. To avoid large-scale blackout of power grids, operators need to judge whether the loop closing operation is secure or not previously, and then make a decision.

In the actual management of distribution networks, operators generally make loop closing decisions based on experience, lack of corresponding theoretical support, and it is difficult to ensure the security. In [2], the calculation formula of steady-state loop closing current is derived based on the superposition theorem. In [3], a decision scheme of loop closing operation in medium-voltage distribution network is proposed according to the calculation of loop closing current, in which closing operation can be decided by comparing the loop closing current at the head of feeder with protection setting value. However, it is generally difficult to obtain real-time load data of all load nodes due to the limitation of measurement devices. Therefore, the application of the above-mentioned research is limited. To solve the problem, the RMS range of loop closing current can be calculated by concentrating total loads on the head and the end of corresponding feeder, and then make the decision whether to execute loop closing operation or not [4]. However, the decision is conservative due to the fact that the distribution of the load is not taken into consideration.

In this study, a decision-making method for the loop closing operation in 10kV distribution network considering the probability distribution of electric load is proposed, taking the influence of loads on the security of loop closing operation into account, which also has certain engineering applicability.

2. Practical criterion of loop closing operation

Let $\dot{I}$ and $\dot{I}'$ donate steady-state current at the head of feeder before and after loop closing operation, $\dot{I}_c$ donate the steady-state loop current caused by loop closing operation. According to the superposition theorem, the steady-state loop closing current at the head of feeder can be expressed as the sum of loop current and the feeder current before loop closing operation [5],

$$I' = \left|\dot{I} + \dot{I}_c\right| \le I + I_c \tag{1}$$

Where I, I', and I_c donate the RMS of $\dot{I}$, $\dot{I}'$, and $\dot{I}_c$ respectively.

According to the analysis of transient process of loop closing operation [5], the maximum RMS of surge current at the head of feeder is

$$I_h \le I + kI_c \tag{2}$$

where k is impact coefficient and is usually taken as 1.51 to 1.62 in practice.

Rigorous criteria of loop closing operation can be expressed as: electrical equipment will not overload in steady-state process and current protection will not act in transient process.

Assume $t_{\text{set, II}}$ is the setting value of delay time of the II-section current protection, T_a is the decay time constant of transient surge current, generally $t_{\text{set, II}} > 0.2\ s$ and $T_a < t_{\text{set, II}}$. Therefore, the transient process ends within the period of II-section current protection and the transient surge current only affects the I-section current protection.

Assume $I_{\text{set,I}}$ donates the setting value of I-section current protection, $I_{\max}$ donates the maximum current capacity of the feeder. According to the rigorous criteria, the loop closing operation is secure when a combination of the following two conditions is true:

$$I + I_c < I_{\max} \tag{3}$$

$$I + kI_c < I_{\text{set,I}} \tag{4}$$

In practice, $I_{\text{set, I}} > kI_{\max}$ generally. If (3) is true, then

$$I + kI_c < k(I + I_c) < kI_{\max} < I_{\text{set,I}} \tag{5}$$

Therefore, (4) is true accordingly.

Above all, a practical criterion can be expressed as: the RMS of the steady-state loop closing current shall not exceed the maximum current capacity of the feeder, just as condition (3). The specific calculation method of steady-state loop closing current will be studied below.

3. Calculation of steady-state loop closing current

3.1. Maximum RMS of steady-state loop closing current

In practice, it is difficult to obtain the real-time load data of each load node on the feeder before loop closing operation due to the limitation of actual measurement system. Therefore, it is also difficult to calculate the voltage difference between two sides of loop switch $\Delta\dot{V}$ and the accurate value of $\dot{I}_c$ by determinate load flow calculation.

The real-time data of voltage, current, and power factor at the head of two feeders on both sides of the loop switch can be obtained from the SCADA system, then the total active load and reactive load of each feeder can be calculated. The amplitude range of $\Delta\dot{V}$ can be obtained through the following two determinate load flow calculations:

1) Concentrate total load on the left side of loop switch at the head of feeder, and total load on the right side is concentrated at the end of feeder;

2) Concentrate total load on the left side of loop switch at the end of feeder, and total load on the right side is concentrated at the head of feeder;

Then calculate the RMS range of $\dot{I}_c$ according to amplitude range of $\Delta\dot{V}$, and the maximum RMS of the steady-state loop closing current at the head of feeders can also be obtained by equation (1).

In the above calculation, actual load distribution is neglected and only the most unfavourable situation for the security of loop closing operation is considered, therefore the result is conservative. In the following, the cumulant method is used to calculate the probability distribution of the steady-state loop closing current based on the probabilistic load flow theory, considering the probability distribution of electric load.

3.2. Calculation of loop closing current based on probabilistic load flow

3.2.1. Cumulants calculation of input variables. In traditional way, the cumulants of input variables can be calculated through numerical method, which has fast calculation speed and high precision when input variables obey normal distribution [6]. However, many variables are not normal distributed or the distribution function is unknown in practice, which makes traditional method lack practicality. Nowadays, electricity company has mastered a large number of users power-expenditure information, which makes it possible to calculate cumulants of input variables based on historical load data.

Select the ratio of active and reactive load at each load node to the active and reactive power at the head of the feeder as input variables. The calculation method of cumulants of these input variables is as follows.

Let input variable k_P donate the ratio of active load at a load node to the active power at the head of feeder. Firstly, construct a sample set S based on the 96-point load data for the whole year of the load node. Then divide S into several subsets according to season and time period. Finally, calculate cumulants of k_P for each season and time period through analysis of each subset.

If a subset of the sample set S is $\{k_{P1}, k_{P2}, k_{P3}, \cdots, k_{PN}\}$, then the v th moment of the distribution of input variable k_P is

$$\alpha_v = \frac{1}{N}\sum_{i=1}^{N} k_{Pi}^v, \quad v = 1,2,3,\cdots \tag{6}$$

Correspondingly, the v th cumulant of k_P (γ_v) can be obtained from the relationship between moments and cumulants [6].

3.2.2. Probability distribution of loop closing current. Let $\boldsymbol{K}$ donate the input variable of probabilistic load flow, which indicates the ratio of active and reactive load at each load node to the active and reactive power at the head of the feeder. If $\boldsymbol{W}$ is injection power at each node, then $\boldsymbol{W} = \boldsymbol{AK}$, where $\boldsymbol{A}$ is a diagonal matrix composed of active and reactive power at the head of two feeders.

Let $\boldsymbol{X} = [\theta_1, V_1, \theta_2, V_2, \cdots, \theta_n, V_n]^{\mathrm{T}}$ donates the state variable of loop closing system, the power flow equation can be expressed as:

$$\boldsymbol{W} = \boldsymbol{f}(\boldsymbol{X}) \tag{7}$$

If I_1 and I_2 donate initial currents at the head of two feeders before loop closing operation. According to (1), maximum RMS of steady-state loop closing current at the head of feeders can be expressed as

$$I_{1t} = I_1 + I_c = g_1(\boldsymbol{X}) \tag{8}$$

$$I_{2t} = I_2 + I_c = g_2(\boldsymbol{X}) \tag{9}$$

Let $\boldsymbol{Z} = [I_{1t}, I_{2t}]^{\mathrm{T}}$ donate loop closing current variable, the loop closing current equation can be expressed as the following matrix form:

$$\boldsymbol{Z} = \boldsymbol{g}(\boldsymbol{X}) \tag{10}$$

Random variable $\boldsymbol{K}$ can be expressed as $\boldsymbol{K} = \boldsymbol{K}_0 + \Delta\boldsymbol{K}$, where $\boldsymbol{K}_0$ is the expected value of $\boldsymbol{K}$ and $\Delta\boldsymbol{K}$ is stochastic disturbance. Similarly, $\boldsymbol{W} = \boldsymbol{W}_0 + \Delta\boldsymbol{W}$ where $\boldsymbol{W}_0 = \boldsymbol{A}\cdot\boldsymbol{K}_0$, $\Delta\boldsymbol{W} = \boldsymbol{A}\cdot\Delta\boldsymbol{K}$.

State variable can X be expressed as $\boldsymbol{X} = \boldsymbol{X}_0 + \Delta\boldsymbol{X}$, and the power flow equation (7) can be expanded through Taylor series ignoring high order terms.

$$\boldsymbol{W}_0 + \Delta\boldsymbol{W} = \boldsymbol{f}(\boldsymbol{X}_0 + \Delta\boldsymbol{X}) = \boldsymbol{f}(\boldsymbol{X}_0) + \boldsymbol{J}_0\cdot\Delta\boldsymbol{X} \tag{11}$$

In (11), $\boldsymbol{W}_0 = \boldsymbol{f}(\boldsymbol{X}_0)$, $\Delta\boldsymbol{W} = \boldsymbol{J}_0\cdot\Delta\boldsymbol{X}$ where $\boldsymbol{J}_0$ is the Jacobian matrix.

Similarly, loop closing current variable can be expressed as $\boldsymbol{Z} = \boldsymbol{Z}_0 + \Delta\boldsymbol{Z}$, and the loop closing current equation (10) can be expanded as

$$\boldsymbol{Z}_0 + \Delta\boldsymbol{Z} = \boldsymbol{g}(\boldsymbol{X}_0 + \Delta\boldsymbol{X}) = \boldsymbol{g}(\boldsymbol{X}_0) + \boldsymbol{G}_0\cdot\Delta\boldsymbol{X} \tag{12}$$

In (12), $\boldsymbol{Z}_0 = \boldsymbol{g}(\boldsymbol{X}_0)$, $\Delta\boldsymbol{Z} = \boldsymbol{G}_0\cdot\Delta\boldsymbol{X}$ where $\boldsymbol{G}_0 = \left.\dfrac{\partial\boldsymbol{g}(\boldsymbol{X})}{\partial\boldsymbol{X}}\right|_{\boldsymbol{X}=\boldsymbol{X}_0}$.

According to (11) and (12), $\Delta\boldsymbol{Z}$ and $\Delta\boldsymbol{K}$ obey the following linear relationship.

$$\Delta\boldsymbol{Z} = \boldsymbol{G}_0\cdot\boldsymbol{S}_0\cdot\boldsymbol{A}\cdot\Delta\boldsymbol{K} = \boldsymbol{T}_0\cdot\Delta\boldsymbol{K} \tag{13}$$

In (13), $\boldsymbol{S}_0 = \boldsymbol{J}_0^{-1}$ is sensitivity matrix, $\boldsymbol{T}_0 = \boldsymbol{G}_0\cdot\boldsymbol{S}_0\cdot\boldsymbol{A}$ is transformation matrix.

According to the property of cumulant [6], the v th cumulant of loop closing current ($\Delta\boldsymbol{Z}^{(v)}$) can be obtained by linear combination of the v th cumulant of input variable ($\Delta\boldsymbol{K}^{(v)}$).

$$\Delta\boldsymbol{Z}^{(v)} = \boldsymbol{T}_0^{(v)}\cdot\Delta\boldsymbol{K}^{(v)} \tag{14}$$

where $\boldsymbol{T}_0^{(v)}$ is coefficient matrix composed of v th power of each element in $\boldsymbol{T}_0$.

Based on the cumulants of loop closing current variable, calculate the cumulative probability distribution of maximum RMS of steady-state loop closing current at the head of feeders through Cornish-Fisher series expansion method. According to the practical criterion in section 2, only the over-limit probability of the maximum steady-state current (I_{1t} , I_{2t}) needs to be paid attention to when making a loop closing decision. Therefore, it is sufficient to calculate the cumulative probability of just a few points through Cornish-Fisher series expansion method, which makes it efficient.

4. Decision-making method for the loop closing operation

The technology roadmap of decision-making method for loop closing operation in 10kV distribution network is shown in Figure 1. The main steps are as follows.

Step I. State estimation of high-voltage distribution network. The 10kV bus node at the head of the feeder is generally selected as reference node while calculating loop closing current. However, the phase angle is still not available due to the limitation of measurement system. Based on the real-time operation data of power system, estimate the state of the high-voltage distribution network through Weighted Least Squares (WLS) method, then the phase angle of the 10kV bus is obtained and some bad measurement data can be corrected.

Step II. Calculate the maximum RMS of steady-state loop closing current. According to section 3.1, calculate the maximum RMS of the steady-state loop closing current at the head of two feeders without considering the load distribution. Then compare the maximum RMS of loop closing current with the maximum current capacity of the feeder to make the first judgement: if the maximum loop closing current does not exceed the capacity of feeder, then decide to allow the loop closing operation. Otherwise, turn to step III to make a further judgment.

Step III. Calculate the probability distribution of loop closing current. According to section 3.2, calculate the cumulative probability distribution of maximum RMS of steady-state loop closing current at the head of two feeders (I_{1t}, I_{2t}). If cumulative distribution function of I_{1t} and I_{2t} are $F_1(x)$ and $F_2(x)$, maximum current capacity of the two feeders are $I_{\max,1}$ and $I_{\max,2}$, then the over-limit probability of I_{1t} and I_{2t} are as follows.

$$P_1 = P(I_{1t} \ge I_{\max,1}) = 1 - F_1(I_{\max,1}) \quad (15)$$

$$P_2 = P(I_{2t} \ge I_{\max,2}) = 1 - F_2(I_{\max,2}) \quad (16)$$

Based on P_1 and P_2, make the second judgement: if both P_1 and P_2 are less than 5%, then decide to allow the loop closing operation. Otherwise, the loop closing operation is not allowed. The whole decision-making process is over.

Above all, the first judgement only need twice determinate load flow calculation which requires quite short time but the result may be conservative. The second judgement need to calculate probabilistic load flow and takes longer time, but result is more accurate. Considering the timeliness and security together, the proposed method can make a quick decision within a large security margin, or sacrifice some timeliness to make a more accurate decision within a small security margin.

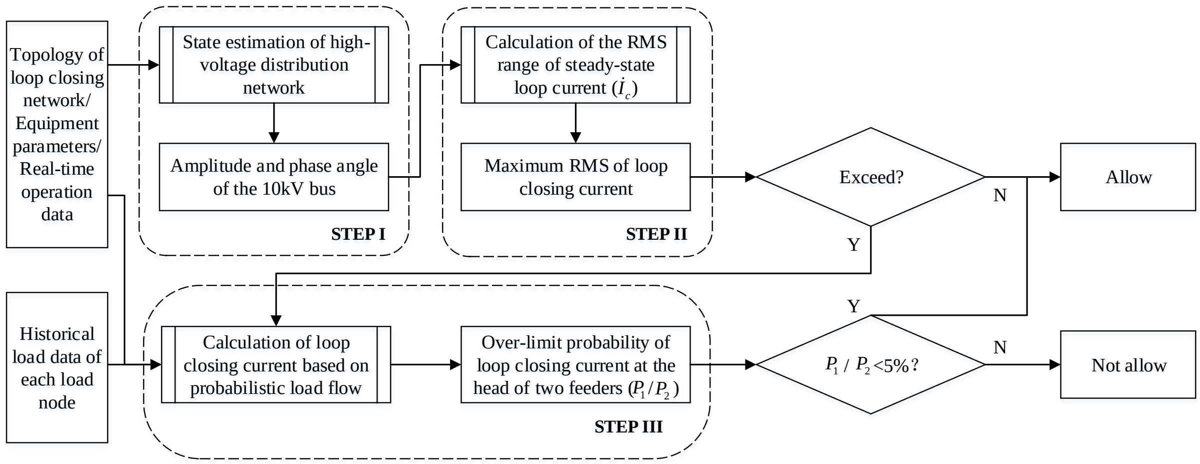


Figure 1. Technology roadmap of decision-making method for loop closing operation.

5. Analysis of a study case

5.1. Decision of loop closing operation

Taking a local distribution network in Shanghai Pudong New Area as a study case, the schematic diagram of loop closing operation is shown in Figure 2 where V1~V6 are voltage amplitude measurements of each bus and PQ1~PQ10 are power measurements of each branch in high-voltage distribution network. Load distribution of feeder I and feeder II are shown in Figure 3.

In this study case, the time of loop closing operation is selected at September 20, 2017, 3 pm. According to the method proposed in section 4, make a decision of loop closing operation and the results of each step are as follows.

Step I. State estimation of high-voltage distribution network. Select 220kV bus as reference node. From the SCADA system, the amplitude and phase angle of A-I are 231.08kV and $-9.2°$ respectively. The amplitude and phase angle of B-I are 230.34kV and $-12.2°$. Based on the measurement values of V1~V6 and PQ1~PQ10, the voltages of 10kV buses (C-II and D-II) obtained from state estimation are $\dot{V}_3 = 10.45\angle -14.33°$ and $\dot{V}_6 = 10.22\angle -17.6°$ respectively.

Step II. Calculate the maximum RMS of steady-state loop closing current. Real-time operation data of 10kV distribution network before loop closing operation are as follows: initial currents at the head of two feeders are 116.8A and 71A, power factors are 0.97 and 0.94 respectively. Combining with the state estimation results in step I, calculate the maximum RMS of steady-state loop closing current by concentrating total load on the head and end of two feeders. The results are 395A at feeder I and 269A at feeder II which are both over-limit compared with the maximum current capacity of feeders (385A and 220A). Therefore, it is unreasonable to make a decision on whether or not to allow the loop closing operation in the first judgement.

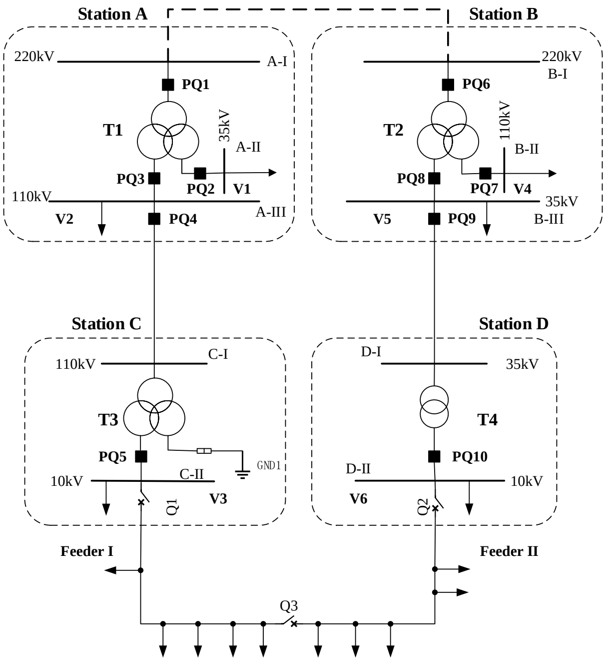


Figure 2. Schematic diagram of loop closing operation.

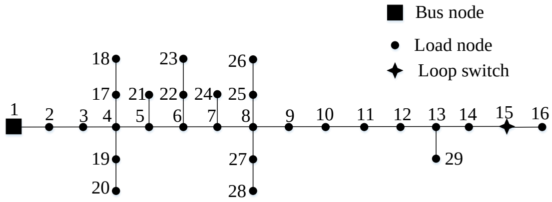


Figure 3(a). Load distribution of feeder I.

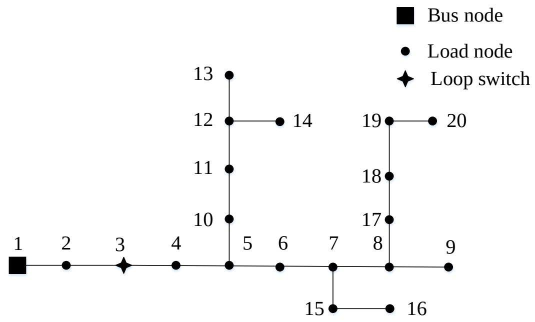
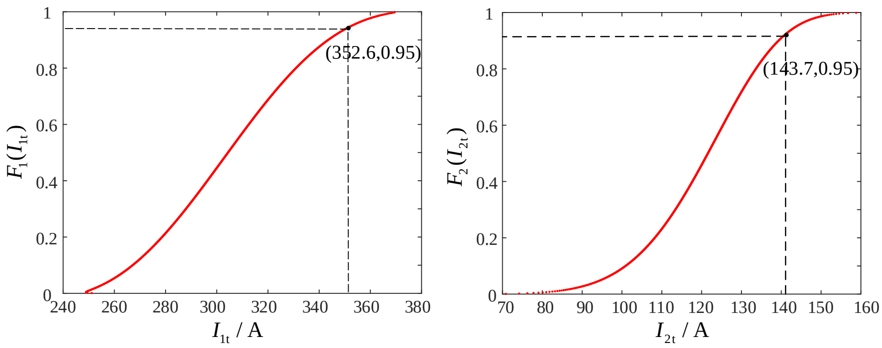


Figure 3(b). Load distribution of feeder II.

Step III. Probabilistic load flow computation. Based on historical load data from September 2014 to September 2017, the cumulative distribution curves of steady-state loop closing current are shown in Figure 4.



(a) Loop closing current at feeder I (b) Loop closing current at feeder II

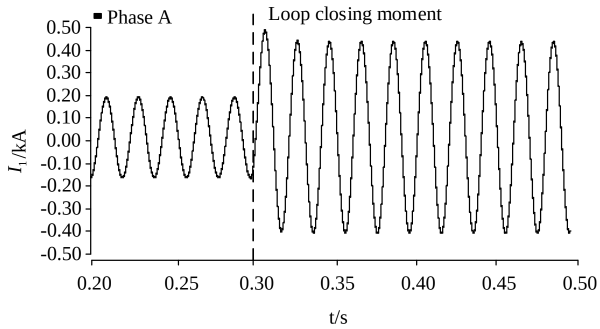
Figure 4. Cumulative distribution curves of steady-state loop closing current.

The maximum current capacities are $I_{\max,1}$=385A for feeder I and $I_{\max,2}$=220A for feeder II. As shown in figure 4, the RMS of loop closing current are 352.6A and 143.7A which are both less than the maximum current capacities if the over-limit probability is set as 5%. Therefore, the final decision is to allow the loop closing operation.

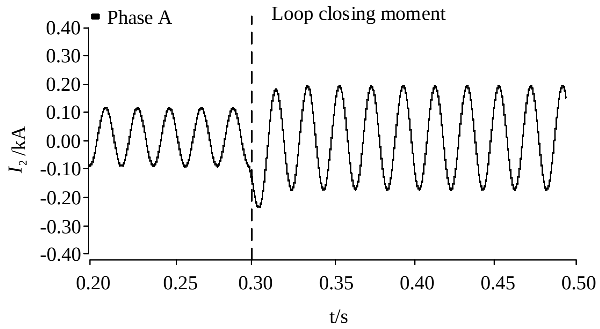
5.2. Simulation and analysis

Firstly, extract 1000 sets of samples from historical load data by Monte Carlo method. Then simulate the loop closing operation in the study case for 1000 times with these samples based on PSCAD/EMTDC simulation platform.

The current curves at the head of two feeders during loop closing operation are shown in Figure 5. As shown in the figure, the transient process of loop closing operation lasts less than a period. The attenuation of transient surge current will end within the period of II-section current protection, just as the analysis in section 2.



(a) Current at the head of feeder I



(b) Current at the head of feeder II

Figure 5. Current curves at the head of two feeders

There are only two times of failure among the 1000 times simulation of loop closing operation. The success rate is 99.8% and it can be considered that loop closing operation is secure which is also consistent with the final decision made in Section 5.1 with the proposed method. The whole decision-making process takes 2.8s which can meet the needs of practical engineering.

6. Conclusion

For the 10kV distribution network, the real-time load data is difficult to obtain and thus the loop closing current cannot be accurately calculated while making a decision whether or not to allow the loop closing operation. To solve the problem, a decision-making method for loop closing operation in 10kV distribution network based on probabilistic load flow theory is proposed. The major findings of the study are as follows.

1) Calculating the cumulants of input variables based on historical load data overcomes the shortcomings of numerical methods, which also makes the calculation simpler and more practical.

2) Compared with the traditional decision-making method which makes only once judgement and only takes maximum RMS of loop closing current as the standard of loop closing operation, twice judgment in this study can take the impact of actual load distribution into account, which is more accordant with the actual situation and also helpful for operators to make decisions on loop closing operation more securely.

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