Security loop closing technology for active distribution network based on synchronous phasor measurement

To cite this article: Wang Cunping et al 2019 J. Phys.: Conf. Ser. 1176 062024

View the article online for updates and enhancements.
Security loop closing technology for active distribution network based on synchronous phasor measurement

Cunping Wang1*, Xijuan Yu1, Hongtao Li1, Hongquan Ji1, Lin Cheng2
1State Grid Beijing Electric Power Research Institute, Beijing, China
2Department of Electrical Engineering, Tsinghua University, Beijing, China

*Corresponding author e-mail: wangcunping163@163.com

Abstract. Aiming at the problem of short-term voltage interruption caused by the switching operation in distribution network, this paper studied the security loop closing technology for active distribution network based on synchronous information measurement. Firstly, the synchronous phasor information on both sides of the loop closing point was measured by the integrated distribution terminal unit (IDU), and the Thevenin equivalent parameter identification method based on the phasor measurement was proposed, improving the network equivalent accuracy. Secondly, the closing loop current calculation method based on identification parameters was proposed, which can effectively estimate the closing loop steady-state current and impulse current. Finally, an actual grid example was given to demonstrate the effectiveness of the proposed method.

1. Introduction
In normal operation of power grid, power supply switching operation is often required to achieve load transfer. At present, the switching operation mainly adopts the mode of "opening first and closing later". The advantage of this mode is that it is easy to operate and does not cause impulse current of closing loop. The disadvantage is that it will cause short-term power failure. Short-term blackouts will seriously affect the supply quality for sensitive loads and cause great economic loss [1, 2]. Therefore, the switching mode of "opening first and closing later" is not suitable for active distribution network with high power supply quality requirements [3].

Aiming at the above problem caused by the current substation switching operation, this paper proposes the security loop closing technology for active distribution network based on synchronous information measurement. The integrated distribution terminal units (IDU) are installed to realize synchronous phasor information collection. The software of the calculation and control of the closing loop current is developed in the control center. The closing loop steady-state current and instantaneous impulse current are calculated by equivalent circuit. If the closing loop current exceeds the limit, the voltage on both sides of the loop closing point are controlled by reactive power and voltage coordinated control to restrain the closing loop current, so as to realize the switching operation of "closing first and opening later" under the normal operation of the power grid.

The application of this operation will further improve the reliability of urban power supply.

2. IDU configuration method
Accurate estimation of closing loop current is the prerequisite for security loop closing.
In this paper, IDU devices are installed upstream of the loop closing point. The synchronous phasor information of voltage and current on both sides of the closing point is measured by IDU, so as to calculate the closing loop current accurately.

The IDU can be installed at the low voltage side of 110kV substation or at both sides of the closing point of the 10kV feeder terminal. The configuration method is shown in Figure 1.

![Schematic diagram of IDU configuration method](image)

Figure 1. Schematic diagram of IDU configuration method.

3. Thevenin equivalent parameters identification method based on synchronous phasor measurement

3.1. The existing Thevenin equivalent method
The principle of Thevenin equivalence in power system is to equate the external power grid to voltage source and series impedance. As shown in Figure 2, $\hat{E}$ and $Z$ represents the equivalent electromotive force and equivalent impedance of the external power grid respectively, $\hat{U}$ and $\hat{I}$ represent the voltage and current phasor of the detection point. They satisfy the following formula:

$$\hat{E} = \hat{I}Z + \hat{U}$$  \hspace{1cm} (1)

![Thevenin equivalent circuit](image)

Figure 2. Thevenin equivalent circuit.

The calculation of Thevenin equivalent parameters is generally based on the following power flow equations.
Based on the above equations, the measured value $U_t$ and $U_{t+1}$ before and after disturbance are substituted into Equation (2) to get the equivalent electromotive force and equivalent impedance. In this method, the phase change of the voltage is ignored, which will cause error [4].

3.2. Thevenin parameter equivalent method based on synchronous phasor measurement

3.2.1. IDU installed at low voltage side of 110kV substation.

Substituting the voltage phasor $\hat{U} = U_r + jU_i$ and current phasor $\hat{I} = I_r + jI_i$ of the detection point into Equation (1), we can get:

$$E_r + jE_i = (I_r + jI_i) \cdot (R + jX) + (U_r + jU_i)$$

(3)

Separating the real part and imaginary part of Equation (3):

$$\begin{align*}
E_r &= RI_r - XI_i + U_r \\
E_i &= RI_i + XI_r + U_i
\end{align*}$$

(4)

Disturbation is applied to the load power P/Q, assuming that the external network state remains unchanged during the disturbance. Measuring the voltage and current phasors at the load side before (t time) and after (t+1) disturbance, and substitute them into Equation (4), we can get:

$$\begin{align*}
E_r &= RI_{r(t)} - XI_{i(t)} + U_{r(t)} \\
E_i &= RI_{i(t)} - XI_{r(t)} + U_{i(t)} \\
E_r &= RI_{r(t+1)} - XI_{i(t+1)} + U_{r(t+1)} \\
E_i &= RI_{i(t+1)} - XI_{r(t+1)} + U_{i(t+1)}
\end{align*}$$

(5)

Solving Equation (5), the values of $E_r$, $E_i$, $R$ and $X$ can be obtained.

After obtaining the equivalent parameters of the high-voltage system at both sides of the closing loop, the equivalent circuit is shown as Figure 3. Then the closing loop current can be calculated by the power flow calculation of the power network equivalent model.

![Figure 3. The equivalent circuit. (IDU installed at low voltage side of 110kV substation)](image)

3.2.2. IDU installed at the 10kV feeder terminals.

Due to the downstream load of IDU is too small, it is difficult to identify the parameters of the two sides by exerting P/Q disturbance. Here we return to the definition of Thevenin equivalence, that is, determining the equivalent parameters by the method of loop closing test.

At $t_1$ time, $\hat{U}_{t,1}$ and $\hat{U}_{t,2}$, the voltage phasors of the two ends are measured respectively by IDU, calculating the equivalent electromotive force of the closing point:

$$\hat{E}_{t1} = \hat{U}_{t,1} - \hat{U}_{t,2}$$

(6)

After a short moment ($t_2$ time), a loop closing test is carried out. The current phasors of $\hat{I}_{t,2}$ and $\hat{I}_{t,2}$ are measured by the two IDUs, so the closing loop current is about:
2,2,2,2(\bar{t}) = \bar{i} + \bar{i}_2\left(\bar{t}_2\right) / 2 \tag{7}

Then the equivalent impedance of the ring point can be obtained.

\[ Z = R + jX = \bar{E}_{\bar{i}} / \bar{i}_2 \tag{8} \]

The equivalent circuit is obtained as Figure 4.

**Figure 4.** The equivalent circuit. (IDU installed at the 10kV feeder terminals)

### 4. Closing loop current calculation based on the equivalent circuit

#### 4.1. Steady state closing loop current calculation

Before loop closing, it is first necessary to confirm that the steady state closing loop current does not exceed the breaking current of the load circuit breaker. When IDUs are installed at the low voltage side of 110 kV substations, the calculation method is as follows:

First, get the equivalent circuit of IDU upstream power grid. Then, a steady-state power flow model is established based on the real-time loads and line impedances obtained from measurement or state estimation [5]. Finally, power flow calculation is used to obtain the steady current flowing through the switches after closing the loop.

**Figure 5.** Circuit model of loop steady current calculation.

#### 4.2. Closing loop transient impulse current calculation

Before loop closing, it is also necessary to confirm that the transient impulse current does not exceed the protection setting value of the breaker at the first end of the feeder. The equivalent calculation model of the impulse current is composed of equivalent electromotive force and equivalent impedance [6].

Suppose the equivalent electromotive force is \( \bar{E} = E_m \sin(\omega t + \alpha) \), where \( \alpha \) is the phase angle at the closing time, which is mainly determined by the phase angle of the voltage at both sides of the closing point. The non-homogeneous differential equation of the equivalent circuit is:

\[ E_m \sin(\omega t + \alpha) = Ri + L \frac{di}{dt} \tag{9} \]

The time domain expressions for the closing loop current can be obtained:

\[ i(t) = I_m \sin(\omega t + \alpha - \varphi) - I_m \sin(\alpha - \varphi) e^{-\frac{t}{\tau}} \tag{10} \]

And the maximum value of the transient impulse current is:
2 \left[1 + \exp(0.01 / T_a) \right]}

(11)

Where,$I_c = U_{eq} / Z_{eq}$, $T_a = X / \omega R$.

For networks with equivalent parameters at both ends, the equivalent impedance and equivalent voltage can be approximated as follows.

$$
\begin{align*}
U_{eq} &= \sqrt{(E_1 - E_2)^2 + (E_1 - E_2)^2} \\
Z_{eq} &= \sqrt{(R_1 + R_2)^2 + (X_1 + X_2)^2}
\end{align*}
$$

(12)

If the closing loop current exceeds the limit, the adjustable equipment in the active distribution network should be adjusted if necessary to suppress the closing current.

5. Example verification of security loop closing

5.1. Example illustration

Take an actual distribution network in Beijing as an example, as shown in Figure 6. Two power sources come from two 220 kV substation respectively, after two stage transformer voltage reduction, supplying power to two 10 kV systems A and B. Systems A and B each has a feeder terminal connected by a loop switch. The parameters of the example system are annotated in the diagram.

Figure 6. Schematic diagram of actual example.

5.2. Synchronous measurement and equivalent parameters identification results

5.2.1. IDU installed at low voltage side of 110kV substation.

The equivalent parameters can be identified through the combination of load disturbance and synchronized phasor measurement. Before the disturbance, the measured voltage and current parameters are shown in Table 1.

| System A status | System B status |
|-----------------|-----------------|
| **Voltage**     | **Voltage**     |
| RMS: 9.92 kV, phase: 48.51° | RMS: 9.98 kV, phase: 53.13° |
| **Current**     | **Current**     |
| RMS: 741.16 A, phase: 37.15° | RMS: 737.92 A, phase: 40.98° |

After a short time, disturbance is applied to the load of system A and B, that is, the total load on the non-closing loop feeder is increased by 3MW + 0.5MVar. After the disturbance, the measured voltage and current parameters are shown in Table 2.
Table 2. Measured voltage and current parameters. (After disturbance)

|                      | System A status            | System B status            |
|----------------------|----------------------------|----------------------------|
| **Voltage**          | RMS: 9.76 kV, phase: 47.39°| RMS: 9.65 kV, phase: 51.39°|
| **Current**          | RMS: 889.06 A, phase: 36.33°| RMS: 883.68 A, phase: 40.39°|

Based on the above measurement results, the equivalent parameters of external power grids of system A and B, and the closing loop equivalent circuit are shown in Figure 7.

Figure 7. Equivalent parameters of external power grids and closing loop circuit.

5.2.2. IDU installed at the 10kV feeder terminals

When IDUs are installed at both sides of the closing point, the equivalent parameters can be identified by the loop closing test. The set of events and measured parameters are shown in Table 3.

Table 3. Events and measured parameters.

| Events            | Point a | Point b |
|-------------------|---------|---------|
| **Before switch closed** | Voltage RMS: 9.80 kV, phase: 77.49° | Voltage RMS: 9.75 kV, phase: 81.82° |
| **After switch closed** | Current RMS: 196.83 A, phase: -68.85° | Current RMS: 211.05 A, phase: 107.71° |

Based on the above measured information, the equivalent parameters are obtained. The equivalent electromotive force between the two sides of the closing point is \( \hat{E}_{ab} = \hat{U}_a - \hat{U}_b = 0.07 \angle 171.8° \), the equivalent impedance of the ring point is \( R + jX = \hat{E}_{ab} / (\hat{I}_a - (\hat{I}_a + \hat{I}_b) / 2) = 0.0085 + j0.0175 \).

5.3. Simulation result of closing loop current

Based on the equivalent circuits, the steady state current flowing through the closed switch at the feeder terminal can be calculated to be about 216.6 A.

The simulation waveform is shown in Figure 8. The peak-to-peak value of the closing loop current is 610 A and the RMS is 215.7 A, which is basically consistent with the calculation results.

The results show that the equivalent circuit based on synchronous phasor measurement can well estimate the closing current and provide support for safety loop closing.
6. Conclusion
In this paper, the Thevenin equivalent parameter identification method based on the synchronous phasor measurement is proposed, which overcomes the problem that the traditional Thevenin equivalent method does not consider the voltage phase and improves the estimation accuracy. The closing loop current calculation method based on the equivalent circuit is proposed, which can effectively estimate the steady state current and impulse current. If the closing loop current does not exceed the switch limit, the closing operation will be carried out. Finally, the simulation results using an actual practical grid example show that the proposed methods can well estimate the closing current and provide support for security loop closing. Further application of this method will realize switching operation without short-time voltage interruption, improving power supply reliability.

References
[1] Jian Liu, Quan Sun, Xiaoqing Zhang, Zhihua Zhang, “Analysis on and criteria for loop closing operation for distribution grids,” Automation of Electric Power Systems, Vol. 38, No. 11, pp. 130-135, 2014.
[2] Bai Xiao, Longan Zhao, Yu Zhang, et al., “Analysis and decision of loop closing operation in urban mid-voltage distribution network,” Power System Protection and control, Vol. 42, No. 16, pp. 133-138, 2014.
[3] Chengshan Wang, Chongbo Sun, Peng Li, “Review and perspective on the optimization of active distribution network,” Electric Power Construction, Vol. 36, No. 1, pp. 8-15, 2015.
[4] Rui Zhang, Shuyong Chen, Daowei Liu, et al., “Review of the Thevenin equivalent parameters identification methods,” Power System Technology, Vol. 41, No. 1, pp. 146-156, 2017.
[5] Bin Wang, Huadong Sun, Daonong Zhang, “Review on data sharing and synchronized phasor measurement technique with application in distribution systems,” Proceedings of the CSEE, Vol. 35, No. S, pp. 1-7, 2015.
[6] Guoxiao Gan, Zhuding Wang, Rui Li, Qiliang Wang, “Methods and simplified formulas for calculating surge currents from loop closing in distribution networks,” Automation of Electric Power Systems, Vol. 38, No. 20, pp. 115-120, 2014.