A SCADA/PMU hybrid measurement state estimation method considering load uncertainty

Tianen Huang¹, Hao Sun²,³, Zhenjie Wu¹, Xingchen Zong², Yuxiao Li², Yuantao Wang¹, Jian Tang¹, Xiang Li¹, Yajun Mo¹, Chengda Li¹ and Shuangdie Xu¹

¹State Grid Hangzhou Power Supply Company, Hangzhou 311599, China
²Zhejiang University
³E-mail: 22110118@zju.edu.cn

Abstract. This paper proposes a power system state estimation method combining the Monte Carlo method and the SCADA/PMU hybrid measurement state estimation algorithm. Quantify the impact of load uncertainty on the state estimation results to reduce the influence of power system measurement error. The results show that the method takes into account the uncertainty of load measurement and the influence of flexible load, and accurately estimate the operating state of the power system.

1. Introduction
To achieve the goal of reducing fossil energy consumption, carbon emissions and environmental pollution, it is necessary to increase the penetration rate of renewable energy in the power system [1]. Relying on traditional power generation resources to stabilize the fluctuation of renewable energy is becoming more and more difficult [2]. Therefore, it is necessary to promote load side resources to participate in power grid regulation. However, with the continuous advancement of new energy grid connection, it brings challenges to the accuracy of power system measurement [3]. At present, the power system still has the problem of insufficient load-side power measurement data [4], and load power measurement has certain uncertainty. When flexible load participates in power grid operation, it also has the problems of low power acquisition accuracy and poor real-time performance [5]. The above factors will increase the error of the power system measurement data, thus affect the accuracy of the power system state estimation results.

With the further development of power system state estimation, the traditional power system state estimation based on SCADA system cannot meet the actual needs of power system operation [6]. With the gradual improvement of the WAMS system, the hybrid of SCADA and PMU measurement has become a development trend of power system state estimation [7-9].

The traditional state estimation method does not consider the influence of load uncertainty, the output results of state estimation is certain [10]. In this paper, a SCADA / PMU hybrid measurement state estimation method considering flexible load participating in power grid operation is proposed. Considering the uncertainty of unknown load, Monte Carlo method is introduced to randomly sample the measurement results of uncertain load. The sampling results are substituted into the operation to obtain the cumulative probability distribution of the state estimation results and thus to quantifying the uncertainty of the state estimation results caused by the load uncertainty. The results of the case study
show that the state estimation results are closer to the true value than the measured value, thereby reducing the influence of the measurement error on the system operating state estimation.

2. Model building

2.1. Monte Carlo method
Considering that the Monte Carlo method is simple and fast when dealing with the load uncertainty problem, and has strong adaptability [11], this paper introduces the Monte Carlo method to deal with the uncertainty of the load. According to the distribution characteristics of uncertain load, the most likely value of uncertain load is selected as the benchmark. Assuming that the uncertain load conforms to the normal distribution, the uncertain load is randomly sampled to generate a group of random variables of uncertain load, it is used as the measured value of uncertain load to participate in power flow calculation.

2.2. SCADA and PMU hybrid measurement state estimation model

2.2.1. PMU node voltage measurement. The PMU node voltage measurement correction equation used in this article is as follows:

\[
\begin{align*}
\Delta U_{\text{pmu}} &= \Delta U \\
\Delta \theta_{\text{pmu}} &= \Delta \theta
\end{align*}
\]

(1)

\[
H_U = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}
\]

(2)

In the above formula, \(\Delta \theta\) and \(\Delta U\) are node voltage phase angle correction and node voltage amplitude correction respectively. \(\Delta U_{\text{pmu}}\) is the residual phasor of PMU voltage magnitude, and \(\Delta \theta_{\text{pmu}}\) is the residual phasor of PMU voltage phase angle. The Jacobi matrix for node voltage measurement is as follows:

\[
\frac{\partial \Delta I_r}{\partial \theta} \quad \frac{\partial \Delta I_i}{\partial \theta} \quad \frac{\partial \Delta I_r}{\partial U} \quad \frac{\partial \Delta I_i}{\partial U}
\]

\[
\begin{bmatrix} \Delta I_r \\ \Delta I_i \end{bmatrix} = \begin{bmatrix} \frac{\partial \Delta I_r}{\partial \theta} & \frac{\partial \Delta I_r}{\partial U} \\ \frac{\partial \Delta I_i}{\partial \theta} & \frac{\partial \Delta I_i}{\partial U} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta U \end{bmatrix}
\]

(3)

\(\Delta r\) and \(\Delta i\) are the residual vector of the real part of the PMU branch current and the residual vector of the imaginary part of the PMU branch current, respectively. The specific elements of Jacobi matrix for branch current measurement are as follows:
The mathematical model of SCADA/PMU hybrid measurement state estimation.

2.2.3. The mathematical model of SCADA/PMU hybrid measurement state estimation. The Jacobi matrix $H_j$ for branch current measurement is as:

$$H_j = \begin{bmatrix} M_j & N_j \\ K_j & L_j \end{bmatrix}$$

Here $M_j$, $N_j$, $K_j$, $L_j$ are the specific elements of the Jacobi matrix for PMU branch current measurement.

Combining the PMU node voltage measurement equation and the branch current measurement correction equation, the mathematical model of the state estimation of the SCADA/PMU hybrid measurement is as follows:

$$\Delta Z = \Delta P \Delta Q \Delta U_n \Delta \theta_{pmu} \Delta U_{pmu} \Delta I = \begin{bmatrix} M & K & 0 & 0 & M_j & N_j \\ N & L & I & 0 & N_j & L_j \end{bmatrix}^T \begin{bmatrix} \Delta \theta \\ \Delta U \end{bmatrix}$$

$\Delta Z$ is the complete residual vector of the mixed measurement. Hybrid measurement Jacobi matrix $H_M$:

$$H_M = \begin{bmatrix} H \\ H_U \\ H_I \end{bmatrix}$$

The mixed data variance matrix $R_h$ is as follows:

$$R_h = \begin{bmatrix} R & 0 & 0 \\ 0 & R_U & 0 \\ 0 & 0 & R_I \end{bmatrix}$$

The iterative correction formula is as follows:

$$\Delta x = \begin{bmatrix} \Delta \theta \\ \Delta U \end{bmatrix} = \left[H_M^T R_h^{-1} H_M \right]^{-1} H_M^T R_h^{-1} \Delta Z$$
\( R \) is the variance matrix of traditional measurement, \( R_I \) is the variance matrix of PMU branch current measurement, \( R_U \) is the variance matrix of PMU node voltage measurement.

3. Algorithm flow

Calculation process of the state estimation is shown in Figure 1. First, the value of flexible load and the benchmark of uncertain load is set in the beginning, and the value of uncertain load is assumed to conform to normal distribution. Next the possible value \( S_i, i \in \{1,1000\} \) of 1000 uncertain loads is selected from the distribution to participate in the power flow calculation based on the Monte Carlo method. The power flow calculation results are taken as the actual value of the electric network, and it is superimposed with the set normal deviation to simulate the measured value of power system state estimation. Then the calculation of mixed measurement state estimation is carried out.

![Figure 1. Calculation process of the state estimation.](image)

The measurement value of the power system state estimation is input, the initial value of the node voltage magnitude and phase angle are respectively defined as 1 and 0. The number of iterations is set as \( k = 0 \), and the PMU branch current measurement is convert into rectangular coordinates form, then generate the traditional measurement Jacobi matrix \( H \), calculate \( h(x^k) \), and get the residual \( \Delta Z^k = Z - h(x^k) \). Substitute (5) to calculate the Jacobi matrix \( H_I \) of the branch current measurement, the accurate current is calculated by (3). Obtain the PMU node voltage measurement residual and the PMU branch current measurement residual, finally the mixed data Jacobi matrix and the residual phasor of the SCADA/PMU mixed measurement is formed. The variance matrix of mixed measurements \( R_m \) is substituted into the iterative correction (10) to calculate \( \Delta x^k \), and judge whether the maximum value of the state variable correction amount \( \Delta x^k \) is less than the requirement of the convergence criterion. If the criterion requirement is not met, the iteration index is updated as \( k = k + 1 \). The state variable at this time is output when the requirement of the convergence criterion is met. Finally, 1000 sets of state estimation results is output.
4. Example analysis

Taking the power transmission network in a certain area as an example, the calculation of the SCADA/PMU hybrid measurement state estimation considering the flexible load and load uncertainty is carried out. Figure 2 shows the structure of the electric network. L7 is the flexible load, and L9 is the uncertain load. The PMU node number set in this simulation is 5, the PMU voltage measurement data is the voltage amplitude and phase angle of the No. 5 node. The PMU branch current measurement data is the branch current of the branch 5-6.

![Diagram of transmission network.](image)

Figure 2. Diagram of transmission network.

Line parameter: \( r_o = 0.0001 \text{p.u./km} \), \( x_o = 0.001 \text{p.u./km} \), \( b_o = 0.00175 \text{p.u./km} \). Parallel capacitor parameter: capacity = 900 MVA, ratio \( k = 1.00 \), \( Z_T = 0.15 \). The network voltage level is 10KV. The initial value of the node parameter is shown in Table 1, where \( P \) is the node injected active power, \( Q \) is the node injected reactive power, \( U \) and \( \theta \) are the node voltage magnitude and phase angle.

Table 1. Initial value of node parameters.

| Node number | Node type   | \( P \) (MW) | \( Q \) (Mvar) | \( U \) (p.u.) | Phase angle |
|-------------|-------------|--------------|---------------|---------------|-------------|
| 1           | PV          | 7.00         | 0.00          | 1.03          | 0.00        |
| 2           | PV          | 7.00         | 0.00          | 1.01          | 0.00        |
| 3           | Balance node| 0.00         | 0.00          | 1.03          | 0.0         |
| 4           | PV          | 7.00         | 0.00          | 1.01          | 0.00        |
| 5           | PQ          | 0.00         | 0.00          | 1.00          | 0.00        |
| 6           | PQ          | 0.00         | 0.00          | 1.00          | 1.00        |
| 7           | PQ          | 9.67         | 1.00          | 1.00          | 0.00        |
| 8           | PQ          | 0.00         | 0.00          | 1.00          | 0.00        |
| 9           | PQ          | 17.67        | 1.00          | 1.00          | 0.00        |
| 10          | PQ          | 0.00         | 0.00          | 1.00          | 0.00        |
| 11          | PQ          | 0.00         | 0.00          | 1.00          | 0.00        |

The active power of the flexible load L7 is adjusted to 10, and the reference value of the active power of the uncertain load L9 is set to 17.67. Using the Monte Carlo method, the uncertain load L9 is assumed to satisfy a normal random distribution with an expectation of 17.67 and a variance of 1. 1000 values are randomly selected from the distribution as the predicted value of the uncertain load to participate in the power flow calculation. The node voltage magnitude and phase angle in power flow calculation are used to superpose a certain normal random deviation as the measured value, then the state estimation calculations are performed. The cumulative distribution curve of the results of the power flow calculation, the initial measurement and the results of the state estimation is drawn.

The cumulative distribution curve of node 9 is shown in Figures 3 and 4. The results show that the node voltage magnitude and phase angle obtained by the mixed state estimation are closer to the actual values compared with the measured initial values of the node voltage magnitude and phase angle. Considering the uncertainty of the load, the hybrid state estimation method in this paper can output the distribution curve of the state estimation results, and realize the quantification of the uncertainty of the state estimation results caused by the load uncertainty.
The active power of the flexible load L7 is adjusted to 9, the state estimation calculations are performed again, the cumulative distribution curve of node 9 is shown in Figures 5 and 6. The results show that, compared with the initial value of the measurement, the results of the mixed state estimation is still close to the actual value. That is, under the influence of flexible load, the method of mixed state estimation considering load uncertainty still has sufficiently high accuracy.
Figure 6. CDF of Node 9 Vm after load L7 adjustment.

5. Conclusions
Considering the influence of flexible load participation in grid operation and load uncertainty on power system state estimation results, this paper proposes a power system state estimation method combining Monte Carlo method and SCADA/PMU hybrid measurement state estimation algorithm.

Compared with the measured value, the result obtained by the state estimation method in this paper is closer to the actual value, which reduces the influence of measurement error. Considering the uncertainty of load, Monte Carlo method is introduced to obtain the cumulative distribution curve of actual value, measured value and state estimation result of nodes. Compared with the single point expectation output by the traditional state estimation method, the state estimation method in this paper can realize the quantitative analysis of the impact of load uncertainty on the state estimation result. Besides, the influence of flexible load on the power system state estimation method is considered in this paper. In the case of flexible load adjustment, it still maintains a sufficiently high accuracy to estimate the operating state of the power system.

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