The Modification of Line Parameters in Distribution Network Considering the Electro-thermal Coordination

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Abstract. Compared with the transmission network, the distribution network resistance parameters cannot be ignored. The resistance is closely related to the temperature, and the influence of temperature should be considered in the process of parameter estimation. In this paper, the line resistance is corrected in real time by combining the line temperature, resistance and power flow closely through the heat balance equation. Based on the theory of electro-thermal coordination, a method of temperature resistance correction for distribution network is proposed. This method integrates the heat balance equation and the least square method of state estimation, and proposes an extended Jacobian matrix circuit parameter correction algorithm considering the state vector. Then, this paper derives the deviation of the SCADA measurements, PMU measurements and the line temperature in detail. And the Jacobian matrix is extended to make the line temperature and node state can be calculated at the same time, which effectively corrects the overall line resistance of the distribution network. Finally, based on PSCAD / EMTDC IEEE 33 node distribution network model, this paper obtains the simulation data considering load fluctuation and measurement error and analysis the consistency deviation, which verifies the effectiveness and convergence of the algorithm. The results show that the algorithm significantly reduces the estimation error.

1. Introduction
The progress of condition monitoring and data analysis technology greatly promotes the improvement of power system automation level and plays an increasingly important role in the safe and economic operation of power grid. Accurate grid parameters and network topology are the prerequisite for reliable operation of advanced applications such as state estimation. The improvement of SCADA and the application of PMU in the distribution network make it possible to modify the line parameters based on the measurement data, which provides a way to improve the line parameter management level [1-3]. Especially, the parameter identification method using PMU synchronous phasor at both ends of the line has the advantages of strong adaptive ability, high identification accuracy and small calculation. Compared with the transmission network, the R/X ratio of the distribution network is large. The resistance is closely related to the temperature, while the line temperature is related to the current carrying capacity, environmental temperature and other conditions. In the current research, the parameters of transmission lines are often regarded as constant values, it results the errors in grid parameters.
Electric -thermal coordination (ETC) is a method that uses electricity to coordinate the line temperature. It can reduce the temperature related errors in power flow calculation, state estimation and correlation analysis. Its basic principle is to establish the analytical relationship among the temperature, line current and environmental weather conditions of the transmission line through the heat balance equation (HBE). The HBE method is used to calculate the temperature of transmission line, and the resistance of transmission line is modified to improve the accuracy of power flow calculation and state estimation. The research of ETC in power system analysis mainly focuses on the following aspects:

1. In the field of state estimation, reference [4] proposes a tracking estimation of transmission line temperature based on PMU measurement. Using the monotonic relationship between line temperature and resistance, the continuous estimation of line temperature is realized through the estimation of line resistance. However, most of the existing literature deal with the estimation of line temperature and state separately, which leads to a large error in the estimation results [5].

2. Line parameters correction of distribution network. The ratio of R/X is large in distribution network, so it is more significant to transplant ETC into distribution network to improve the accuracy of power flow calculation. Shu Jun et al [6] introduced ETC into power flow calculation of distribution network for the first time, proposed an extended push back method, and studied the influence of external environmental factors and load levels on power flow distribution.

On the basis of the above research, this paper proposes a modified model of distribution network line parameters, which takes the line temperature into account, in the traditional weighted least square state estimation model. The heat balance equation of the line is taken as pseudo quantity measurement, and the line temperature is introduced into the state quantity. The change of the augmented ratio matrix H after the temperature state quantity increasing is analysed. The proposed algorithm can improve the accuracy of state estimation of the whole network while modifying the parameters of distribution network. Finally, the IEEE 33 node distribution network model based on PSCAD is used to obtain the simulation data considering load fluctuation and measurement error.

2. State estimation of Power Grid Considering electric heat correlation

2.1. Heat balance principle of overhead lines
It is assumed that the overhead transmission line in the distribution network is an ideal conductor with uniform material. According to IEEE-738 standard, when the heat exchange process of the transmission line reaches dynamic balance, the line temperature will be constant, and the heat balance equation can be expressed as follows:

\[ f[T(t)] = I^2R[T(t)] + q_s(t) - q_c[T(t)] - q_r[T(t)] = 0 \]  

where T is the temperature of transmission line(°C); R(T) is the AC resistance value of transmission line per unit length (Ω); I is the current value of transmission line (A); q_s, q_c and q_r are the solar radiation heat absorption of transmission line per unit length quantity (W/m), convective heat transfer (W/m) and radiation heat dissipation (W/m).

2.2. Mixed Measurement and State Vector
In this section, symmetrical lumped parameter line model has been selected. The circuit model is shown in the figure. Wherein, \( U_{12} \) is the voltage phasor at both ends of the line to be identified, \( I_{12} \) is the current phasor at both ends, \( P_{12} \) is the active power at both ends and the reactive power at both ends.
In this paper, by modifying the influence of line temperature on line resistance, the measurement and state vectors of the model are extended, in which the measurement vectors are:

\[ \mathbf{z}_{\text{aug}} = [\mathbf{z}_{\text{SCADA}} \mathbf{z}_{\text{PMU}} \mathbf{z}_{\text{wea}}]^T \]

(2)

\[ \mathbf{z}_{\text{ele}} = \left[ U_1 P_1 Q_1 P_{12} Q_{12} U_1 \theta_1 I_x I_y \right]^T \]

(3)

\[ \mathbf{z}_{\text{wea}} = [Q_{\text{solar}} \vartheta V_w T_e \phi]^T \]

(4)

The measurement equation is:

\[ \mathbf{h}_{\text{aug}} = [\mathbf{h}_{\text{SCADA}} \mathbf{h}_{\text{PMU}} \mathbf{h}_{\text{HBE}}]^T \]

(5)

The state quantity is:

\[ \mathbf{x}_{\text{aug}} = [U \theta T_{v,e}]^T \]

(6)

In the formula, \( \mathbf{z}_{\text{SCADA}}, \mathbf{z}_{\text{PMU}}, \mathbf{h}_{\text{SCADA}}, \mathbf{h}_{\text{PMU}} \) respectively represent the measurement of SCADA and PMU and the corresponding measurement equation; \( U_i \) and \( \theta_i \) are the amplitude and phase angle of the phasor \( U_i \); \( Q_{\text{solar}}, \vartheta, V_w, \mathbf{h}_{\text{HBE}} \) is the steady-state heat balance equation of the line.

2.3. The mixed measurement equation

After considering the electric heat correlation, the line admittance becomes the function of the line temperature, as follows:

\[ G_{12}(T) = -g_{12}(T) = -\frac{R_{11}(T)}{R_{11}(T)^2 + X_{12}^2} \]

(7)

\[ B_{12}(T) = -b_{12}(T) = \frac{X_{12}}{R_{12}(T)^2 + X_{12}^2} \]

(8)

At this time, the non-linear model measured by SCADA and PMU is as follows:

\[
\begin{align*}
I_{11} &= U_1 g \cos \theta_1 - U_2 g \cos \theta_2 - U_1 b \sin \theta_1 \\
&\quad + U_2 b \sin \theta_2 + U_1 (g_1 \cos \theta_1 - b_1 \sin \theta_1) \\
I_{12} &= U_1 b \cos \theta_1 - U_2 b \cos \theta_2 + U_1 g \sin \theta_1 \\
&\quad - U_2 g \sin \theta_2 + U_1 (b_1 \cos \theta_1 + g_1 \sin \theta_1) \\
P_1 &= U_1 \sum_{i=1}^{12} U_2 \left[ G_{12}(T) \cos \theta_2 + B_{12}(T) \sin \theta_2 \right] = 0 \\
Q_1 &= U_1 \sum_{i=1}^{12} U_2 \left[ G_{12}(T) \sin \theta_2 - B_{12}(T) \cos \theta_2 \right] = 0 \\
P_{12} &= U_1^2 (g + g_1) - U_1 U_2 g \cos \theta_2 - U_1 U_2 b \sin \theta_2 \\
Q_{12} &= -U_1^2 (b + b_1) - U_1 U_2 g \sin \theta_2 + U_1 U_2 b \cos \theta_2 \\
U_1 &= U_1 \\
\theta_1 &= \theta_1
\end{align*}
\]

(9)
According to IEEE-738 standard and meteorological data, the expression of heat loss is obtained as follows:

\[ h_{\text{HBE}} = I^2 R(T) + q_s - q_c(T) - q_r(T) = 0 \]  

\[ R(T) = R_R [1 + \alpha_l (T - T_d)] \]  

where \( q_s, q_c, \) and \( q_r \) are the solar heat gain, convective heat loss and radiation heat loss rate respectively; \( \alpha_l \) is the temperature coefficient of resistance; \( T_d \) is the reference temperature, and \( R_R \) is the rated resistance under the temperature \( T_d \).

**2.4. The derivation of the Jacobian matrix based on the least square method**

The circuit temperature and node voltage of this algorithm are calculated at the same time. The state vector is consistent with \( x_{\text{aug}} \) in the previous section. The measurement vector \( z_{\text{aug}} \) is:

\[ z_{\text{aug}} = [u_1, P_1, Q_1, P_{12}, Q_{12}, u_1, I_{k,1}, I_{k,2}, I_{k,3}, \theta_{k,1}, \theta_{k,2}, \theta_{k,3}]^T \]  

Compared with the traditional least square method, the measurement dimension and state vector of the model are increased. However, in addition to the change of matrix dimension, the model is still a set of overdetermined equations, so it can still be solved by the weighted least square method. The measurement equation can be expressed as:

\[ z_{\text{aug}} = h(x_{\text{aug}}) + v_z \]  

where \( v_z \) is the vector of measurement errors.

In order to minimize the residual, the objective function formula correction vector in \( k \)th step is:

\[ J(x_{\text{aug}}) = [z_{\text{aug}} - h(x_{\text{aug}})]^T R^{-1} [z_{\text{aug}} - h(x_{\text{aug}})], \]  

\[ \Delta x_{\text{aug},k} = [H^T(x_{\text{aug},k}) R^{-1}[H(x_{\text{aug},k})]^T]^T \Delta x_{\text{aug},k} \]

\[ x_{\text{aug},k+1} = x_{\text{aug},k} + \Delta x_{\text{aug},k} \]

The extended Jacobian matrix is shown as follows. In order to simplify, block representations of \( H \)-matrix (the expressions of sub matrix \( H_{11}, H_{12}, H_{21}, \) and \( H_{22} \) are the same as those of general state estimation) are

\[ H_{\text{aug}} = \frac{\partial h(x)}{\partial x} = \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \end{bmatrix} = \begin{bmatrix} \partial h_{\text{SCADA}}/\partial U & \partial h_{\text{SCADA}}/\partial \theta & \partial h_{\text{SCADA}}/\partial T \\ \partial h_{\text{PMU}}/\partial U & \partial h_{\text{PMU}}/\partial \theta & \partial h_{\text{PMU}}/\partial T \\ \partial h_{\text{HBE}}/\partial U & \partial h_{\text{HBE}}/\partial \theta & \partial h_{\text{HBE}}/\partial T \end{bmatrix} \]

Take \( H_{23,1} \) as an example, which represents the derivative between the measurement and the corresponding line temperature when PMU is configured on bus 1.

\[ H_{23,1} = \begin{bmatrix} 0 & 0 \\ L & M & M & M & M & L \\ \partial U_1/\partial T_i & \partial \theta_1/\partial T_i & \partial I_{1,f}/\partial T_i & \partial I_{1,r}/\partial T_i \\ L & M & M & M & M & L \\ 0 & 0 \end{bmatrix}^T \]
It should be noted that the partial derivative is not equal to 0 only when the temperature $T_L$ corresponds to the transmission line 12. That is to say, each line has only one element and is not equal to 0. In the submatrix $H_{31}$, at most two elements in each row are not equal to 0, as follows:

$$H_{ij} = \begin{bmatrix} \cdots & \frac{\partial h_{B,E,i}}{\partial U_i} & \cdots & \frac{\partial h_{B,E,j}}{\partial U_j} & \cdots & \cdots \end{bmatrix} \rightarrow \text{line } 1$$

where,

$$\frac{\partial h_{B,E,i}}{\partial U_i} = (G_i^2 + B_i^2) \cdot (2U_i - U_j \cos \theta_j) \cdot R$$

Similarly, the expression of $H_{32}$ can be derived. Finally, the sub matrix $H_{33}$ is a diagonal matrix, because the $HBE$ of transmission line $L$ is only related to the corresponding line temperature $T_i$, namely:

$$H_{33} = \begin{bmatrix} \cdots & 0 & \cdots & 0 \\
0 & \frac{\partial h_{B,E,i}}{\partial T_i} & \cdots & 0 \\
0 & \cdots & \frac{\partial h_{B,E,n}}{\partial T_n} & 0 \\
0 & \cdots & \cdots & \cdots \end{bmatrix}$$

The relevant elements in the augmented Jacobian matrix $H$ have been completely derived. As shown in the figure above, the ETC – WLS state estimation model is very similar to the WLS state estimation model, which only extends the measurement and state vector, and it can correct the parameters of the line in real time during the iteration. Besides, Newton method can still be used to solve the problem.

3. Case study

3.1. The influence of power flow on resistance in distribution network

The IEEE 33 node distribution network system is used to explain the influence of power flow on line resistance. The system network diagram is shown below (all nodes are equipped with SCADA measurement), and all branches are considered electrothermal correlation. The following table shows the calculation results of line current and line resistance of some branches by adopting the Newton-Raphson method and ETC power flow algorithm. It can be seen that after taking ETC into account, the line resistance increases substantially. At the same time, the change of line resistance affects the node voltage and power flow distribution. Compared with the traditional Newton-Raphson method, the node voltage of the system after taking etc into account decreases by 0.1822% on average. Furthermore, when the climate conditions and transmission current are different, the maximum...
The resistance of the line increases by 18.4537% compared with its rated value. The minimum resistance of the line decreases by 9.1%.

Table 1. Comparison of voltage & resistance value of N-R method and ETC

| Line Number | Node Voltage N-R (p.u.) | ETC (p.u.) | Rate of change % | Line Resistance N-R (p.u.) | ETC (p.u.) | Rate of change % |
|-------------|-------------------------|------------|------------------|---------------------------|------------|------------------|
| 1-2         | 1.0004/0.9973           | 0.9995/0.9965 | 0.0914/0.0792    | 0.0058                   | 0.0063     | 8.7701           |
| 15-16       | 0.9163/0.9149           | 0.9160/0.9146 | 0.0349/0.0357    | 0.0465                   | 0.0500     | 7.3612           |
| 19-20       | 0.9967/0.9931           | 0.9960/0.9925 | 0.0732/0.0645    | 0.0938                   | 0.1017     | 8.4185           |
| 24-25       | 0.9741/0.9707           | 0.9697/0.9657 | 0.4515/0.5179    | 0.0559                   | 0.0662     | 18.4537          |
| 32-33       | 0.9168/0.9165           | 0.9165/0.9162 | 0.0274/0.0294    | 0.0213                   | 0.0227     | 6.7617           |

To sum up, the line power flow and environmental conditions have a significant impact on the line resistance. In power flow calculation and state estimation, if the influence of temperature on the resistance is not considered, the high-level application error will be larger.

3.2. Correction of line parameters considering electrothermal combination

The above example is used to verify the effectiveness of the proposed parameter correction method and to prove that it can effectively improve the state estimation accuracy. The PMU installation location is shown in the above figure. The electrothermal power flow solution is used as the real value of measurement, power measurement and voltage amplitude measurement add 3% and 2% Gaussian white noise to the real value respectively. Monte Carlo simulation is used to randomly generate 1000 sets of measurement data. Traditional WLS estimation and electrothermal joint estimation models are used to calculate the error distribution, assuming that the environmental parameters remain constant during the study period. RMS is defined as follows:

$$H_{33} = \begin{bmatrix} 0 & \frac{\partial h_{j(R)}}{\partial T_i} & 0 & 0 \\ 0 & L & 0 & 0 \\ 0 & L & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

(20)

Table 2 shows the resistance and temperature estimation results of some circuits. It can be seen that, compared with the rated resistance of the line, the real value of the line resistance increases by more than 6% after considering the electrothermal correlation. It has been verified for many times that the error of all line resistances estimated by traditional WLS in this example is more than 5%, and most of them are more than 7%. The average error of the line temperature obtained by the two-step electrothermal estimation method is 0.20%, which shows that the proposed model can effectively correct the error of resistance parameters and improve the estimation accuracy.

Table 2. Resistance and temperature estimation results of several circuits

| Line | R/p.u. | T°C  | e_{RMS}/% | Line | R/p.u. | T°C  | e_{RMS}/% |
|------|--------|------|-----------|------|--------|------|-----------|
| 1-2  | 0.0060 | 34.67| 0.21      | 19-20| 0.1015 | 35.63| 0.30      |
| 9-10 | 0.0078 | 34.63| 0.20      | 24-25| 0.0670 | 34.97| 0.20      |
| 15-16| 0.0499 | 34.59| 0.23      | 32-33| 0.0008 | 34.58| 0.17      |

Figure 3 shows the probability density diagram of voltage amplitude error of two estimation methods. It can be found that the estimation errors of both methods are normal distribution, but the traditional results on the left are more scattered and larger. After considering the correction of the line...
temperature to the resistance parameters, the error of state estimation decreases obviously, and the average error of amplitude decreases from 0.32% to 0.17%. It is further proved that the proposed model can effectively correct the error of resistance parameters and improve the accuracy of state estimation.

![Figure 3. Voltage amplitude error probability density diagram of WLS & ETC-WLS](image)

4. Conclusion
The line resistance parameters of distribution network are constantly changing under the influence of meteorological parameters (such as air temperature, wind speed, solar radiation intensity, etc.) and line current. It is necessary to use the line temperature to modify the line resistance parameters in real time. Based on the traditional WLS, this paper proposes a new method to modify the line parameters of the distribution network, which takes account of the combination of electric heating and electric heating. It can process the temperature estimation and state estimation together, and use the real-time estimation of the line temperature to modify the resistance parameters, improving the accuracy of the line parameters of the distribution network and the precision of state estimation.

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