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Electromagnetic Environment of Transmission Line Based on Full Parameter Online Estimation

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Abstract
The parameters of transmission lines have an influence on the electromagnetic environment surrounding the line. This paper proposes a method based on phasor measurement unit (PMU) and supervisory control and data acquisition (SCADA) to achieve online estimation of transmission line full parameters, such as resistance, reactance and susceptance. The proposed full parameter estimation method is compared with the traditional method of estimating resistance independently based on SCADA system. Then, the electromagnetic environment is analyzed based on the different parameter estimation methods. The example results illustrate that online estimation of transmission line full parameters is more accurate in the analysis of electromagnetic environment, which further confirms its necessity and significance in engineering application.

Keywords
Current Capacity, Electromagnetic Environment, Line Parameter, Power Grid, Transmission Line

1. Introduction

With the development of society, the scale expanding of power grid becomes the general trend [1]. The transmission lines are getting closer to public living areas, resulting in many electromagnetic environmental problems [2]. At the same time, public awareness of environmental protection is increasing, and complaints caused by electromagnetic environment often occur, leading to local power grid construction lagging behind the demand for electricity [3]. It not only affects the residential electricity, but also restricts the development of local economy.

The electromagnetic environment of alternating current transmission lines includes power frequency electric field, power frequency magnetic field, radio interference and audible noise [4]. Power frequency magnetic field has become one of the key issues of current research because of its highest public concern and numerous disputes [5,6]. The system power flow includes the line current and the line voltage [7]. The variation of current will impact the magnetic field of transmission lines, and the variation of voltage will impact the electric field [8]. The accurate calculation of current and voltage is beneficial to the exploration of electromagnetic fields [9]. A lot of literatures analyze the electromagnetic environment of high-voltage transmission lines based on the theoretical parameter values [10,11]. In the actual operation

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of the line, there is a certain gap between the theoretical value and the actual value of the parameters such as the resistance and the reactance, which will affect the system power flow, such as the voltages and currents of all transmission lines [12].

The actual parameters deviate from the design values due to the long-term operation of the lines [13,14]. Online tracking and prediction of transmission line resistance can be achieved by phasor measurement unit (PMU) [15]. PMU is characterized by the short sampling period, the measurable voltage and the current phase, which can quickly evaluate the performance of power system and achieve rapid response under the unexpected circumstance [16]. However, it is impractical to configure PMU on all the transmission lines [17]; hence, supervisory control and data acquisition (SCADA) systems are applied to track transmission line resistance [18]. SCADA system can provide abundant real-time measurements of the voltage, the current, the active power and the reactive power. Online estimation of transmission line parameters can be achieved. Although the author [18] achieves the tracking and prediction of transmission line resistance, the theoretical value of other parameters is still adopted. To some extent, it affects the accuracy of online tracking results so that the electromagnetic environment surrounding the line can't be calculated accurately. During the long-time operation, the parameters may change because of the aging of conductors or the influence of climate, geography and environment [19,20].

In this paper, considering the above problems, the method of online estimation of transmission line parameters, and the analysis method of parameters impacting the electromagnetic environment are presented. The rest of this paper is organized as follows. Section 2 introduces the online estimation of transmission line parameters based on PMU and SCADA system, and the calculation of electromagnetic environment. The online estimation results of parameters on the proposed method are presented in Section 3. The method of full-parameter online estimation is compared with the traditional method of estimating resistance independently. Based on the online estimation results, the electromagnetic environment of the IEEE 5-bus system under three cases are also analyzed and compared in Section 3. Conclusions are given finally in Section 4.

2. Method and Model

2.1 Online Estimation of Transmission Line Parameters Based on PMU

Online tracking of the full parameters, such as the resistance, reactance and admittance can be achieved by PMU system. The model of Π-type equivalent line is shown in Fig. 1. P_s and Q_s are the active power and reactive power at the sending end. P_r and Q_r are the active power and reactive power at the receiving end. R_l and X_l is the resistance and the reactance of the transmission line. I_s is the injection current and U_s is the bus voltage at the sending end. I_r is the injection current and U_r is the bus voltage at the receiving end. $\dot{I}$ is the current carrying of transmission line. B_s and B_r are the susceptance at the sending end and receiving end respectively.

Ignoring the difference of the susceptance between the sending and receiving end, such as $B_s = B_r = B_l$. According to two-port circuit theory of Π-type equivalent circuit, Eq. (1) is established.

$$\begin{aligned} \dot{I}_s &= (\dot{U}_s - \dot{U}_r)/(R_l + jX_l) + \dot{U}_s(jB_l) \\ \dot{I}_r &= (\dot{U}_s - \dot{U}_r)/(R_l + jX_l) - \dot{U}_r(jB_l) \end{aligned} \tag{1}$$

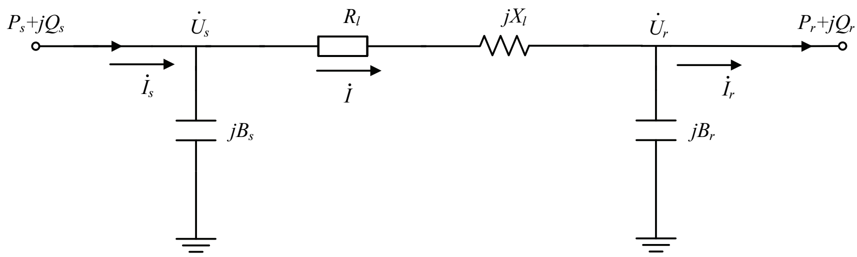


Fig. 1. The Π-type equivalent line.

Matrix form of Eq. (1) is shown in Eq. (2).

$$\mathrm{I} = \mathrm{UY} \tag{2}$$

$$\mathrm{I} = \begin{bmatrix} \dot{I}_s \\ \dot{I}_r \end{bmatrix} \quad \mathrm{U} = \begin{bmatrix} \dot{U}_s - \dot{U}_r & \dot{U}_s \\ \dot{U}_s - \dot{U}_r & -\dot{U}_r \end{bmatrix} \quad \mathrm{Y} = \begin{bmatrix} 1/(R_l + jX_l) \\ jB_l \end{bmatrix} \tag{3}$$

When the measured data m ($m > 2$), there are overdetermined equations. E_M is set as the error phasor, Eq. (4) is established.

$$\mathrm{E}_M = \mathrm{I}_M - \mathrm{U}_M \mathrm{Y}_M \tag{4}$$

where

$$\mathrm{E_M} = [\mathrm{e_1} \quad \mathrm{e_2} \quad \cdots \quad \mathrm{e_m}]^\mathrm{T} \tag{5}$$

$$\mathrm{I_M} = [\mathrm{I_1^T} \quad \mathrm{I_2^T} \quad \cdots \quad \mathrm{I_m^T}]^\mathrm{T} \tag{6}$$

$$\mathrm{U_M} = [\mathrm{U_1^T} \quad \mathrm{U_2^T} \quad \cdots \quad \mathrm{U_m^T}]^\mathrm{T} \tag{7}$$

$$\mathrm{Y}_M = \mathrm{Y} \tag{8}$$

The square sum of the error component is set as J, which is used as the performance index.

$$\min \mathrm{J} = \sum_{\mathrm{i=1}}^{\mathrm{m}} \mathrm{e_i^2} = \mathrm{E_M^T E_M} = (\mathrm{I_M} - \mathrm{U_M Y_M})^\mathrm{T} (\mathrm{I_M} - \mathrm{U_M Y_M}) \tag{9}$$

When the minimum value of J is taken as a necessary condition, Eq. (10) is obtained.

$$\left. \frac{\partial \mathrm{J}}{\partial \mathrm{Y}_M} \right|_{\mathrm{Y}_M = \hat{\mathrm{Y}}_M} = -2\mathrm{U}_M^T \mathrm{I}_M + 2\mathrm{U}_M^T \mathrm{U}_M \hat{\mathrm{Y}}_M \tag{10}$$

Therefore,

$$\hat{\mathrm{Y}}_M = (\mathrm{U}_M^T \mathrm{U}_M)^{-1} \mathrm{U}_M^T \mathrm{I}_M \tag{11}$$

Online estimation of Π-type equivalent line can be achieved by Eq. (11). The R_l, X_l, B_s and B_r included in the extended state variables of the transmission lines can be obtained based on PMU. Due to the high cost of PMU devices and the richness of SCADA data in power system, SCADA systems are put into use.

2.2 Online Estimation of Transmission Line Parameters Based on PMU

In practice, the active power (P_s, P_r), the reactive power (Q_s, Q_r), the current value (I_s, I_r) and the voltage (U_s, U_r) can be obtained by SCADA. The phase angle of reference node is set as phase angle $\dot{I}$ and $\dot{I} = I\angle 0^{\circ}$, the estimated state variables can be expressed as Eq. (12).

$$\mathbf{x} = [U_s \quad U_r \quad \theta_s \quad \theta_r \quad I \quad R_l \quad X_l \quad B_l]^T \tag{12}$$

where θ_s and θ_r are the voltage phase angles at both ends of the transmission lines. According to the principle of electric engineering, Eq. (13) is established [14].

$$\begin{aligned}
&I_s^2 = I^2 + B_l^2 U_s^2 - 2IB_l U_s \sin\theta_s \\
&I_r^2 = I^2 + B_l^2 U_r^2 + 2IB_l U_r \sin\theta_r \\
&0 = U_s^2 + U_r^2 - 2U_s U_r \cos(\theta_s - \theta_r) - (R_l^2 + X_l^2) I^2 \\
&0 = \frac{P_r^2 + (Q_r - B_l U_r^2)^2}{U_r^2} - \frac{P_s^2 + (Q_s - B_l U_s^2)^2}{U_s^2} \\
&\frac{P_s^2 + (Q_s - B_l U_s^2)^2}{U_s^2} = I^2 \\
&P_{loss} = I^2 R_l \\
&Q_{loss} = I^2 X_l - B_l (U_s^2 + U_r^2)
\end{aligned} \tag{13}$$

where P_{loss} is the active power loss of the transmission line, and $P_{loss} = P_s - P_r$; Q_{loss} is the reactive power loss, and $Q_{loss} = Q_s - Q_r$. From a mathematical point of view, Eq. (14) is shown as the measurement equation based on the least square estimation of a time section.

$$\mathbf{z} = \mathbf{h(x)} + \mathbf{v} \tag{14}$$

where $\mathbf{z}$ is the measurement vector, $\mathbf{h}(\cdot)$ is the measurement function vector, $\mathbf{v}$ is the disturbance vector of the random measurement error. According to each measurement data based on SCADA, such as P_s, P_r, Q_s, Q_r, I_s, I_r, U_s, U_r. Measurement vector based on the least square estimation of a time section is shown in Eq. (15), and the measurement function vector is shown in Eq. (16).

$$\mathbf{z} = [U_s \quad U_r \quad I_s^2 \quad I_r^2 \quad 0 \quad P_s^2 \quad P_r^2 \quad P_{loss} \quad Q_{loss}]^{\mathrm{T}} \tag{15}$$

$$\mathbf{h(x)} = \begin{bmatrix} U_s \\ U_r \\ I^2 + B_l^2 U_s^2 - 2IB_l U_s \sin\theta_s \\ I^2 + B_l^2 U_r^2 + 2IB_l U_r \sin\theta_r \\ U_s^2 + U_r^2 - 2U_s U_r \cos(\theta_s - \theta_r) - (R_l^2 + X_l^2) I^2 \\ I^2 U_r^2 \text{-} (Q_r - B_l U_r^2)^2 \\ I^2 U_s^2 \text{-} (Q_s - B_l U_s^2)^2 \\ I^2 R_l \\ I^2 X_l - B_l (U_s^2 + U_r^2) \end{bmatrix} \tag{16}$$

According to Eq. (14), the modified equation of least square estimation is shown in Eq. (17) and its iterative equation is shown in Eq. (18).

$$\Delta\hat{\mathbf{x}}^{(k)} = \left[\mathbf{H}^{\mathrm{T}}\left(\hat{\mathbf{x}}^{(k)}\right)\mathbf{R}^{-1}\mathbf{H}\left(\hat{\mathbf{x}}^{(k)}\right)\right]^{-1}\mathbf{H}^{\mathrm{T}}\left(\hat{\mathbf{x}}^{(k)}\right)\mathbf{R}^{-1}\left[\mathbf{z}-\mathbf{h}\left(\hat{\mathbf{x}}^{(k)}\right)\right] \tag{17}$$

$$\hat{\mathbf{x}}^{(k+1)} = \hat{\mathbf{x}}^{(k)} + \Delta\hat{\mathbf{x}}^{(k)} \tag{18}$$

The superscript (k) represents the k-th iteration. The corresponding Jacobi matrix is shown in Eq. (19).

$$\mathbf{H}\left(\hat{\mathbf{x}}^{(k)}\right) = \left.\frac{\partial\mathbf{z}}{\partial\mathbf{x}}\right|_{\mathbf{x}=\hat{\mathbf{x}}^{(k)}} \tag{19}$$

According to Eq. (14) and Eq. (18), online estimation of the parameters such as R_l, X_l and B_l included in the extended state variables of transmission lines can be obtained, which is known as online estimation of full parameters based on SCADA. Therefore, online estimation of the resistance, reactance and susceptance can be achieved. Due to the universality and the richness of SCADA data in power system, full parameter estimation based on SCADA system can be obtained without extra hardware facilities and provide a reliable basis for power grid analysis.

2.3 Calculation of Electromagnetic Environment

The electromagnetic environment of alternating current transmission lines includes power frequency electric field, power frequency magnetic field, radio interference and audible noise, of which power frequency magnetic field is the main research direction. The calculation of electric field intensity at point is shown in Eqs. (20) and (21).

$$[Q_c]=[C]^{-1}[U] \tag{20}$$

$$\begin{aligned} E_x &= \frac{1}{2\pi\varepsilon}\sum_{k=1}^{n} Q_{ck}\left(\frac{x-x_k}{d_k^2}-\frac{x-x_k}{d_k'^2}\right) \\ E_y &= \frac{1}{2\pi\varepsilon}\sum_{k=1}^{n} Q_{ck}\left(\frac{y-y_k}{d_k^2}-\frac{y-y_k}{d_k'^2}\right) \end{aligned} \tag{21}$$

where $[Q_c]$, $[C]$ and $[U]$ are the charge, potential coefficient matrix and voltage matrix, respectively. E_x and E_y are the abscissa and ordinate components of electric field intensity, respectively. ε is the air dielectric constant. n is the sum of the number of lines and mirror lines. k is the line number; x_k and y_k are the abscissa and ordinate of the line k. The distance from the point $A(x,y)$ to the line k and its mirror line are demoted by d_k and d_k', respectively. The potential coefficients are calculated by Eq. (22).

$$\begin{aligned} C_{m,m} &= \frac{1}{2\pi\varepsilon}\ln\frac{2H}{R} \\ C_{m,n} &= \frac{1}{2\pi\varepsilon}\ln\frac{D_{m,n}'}{D_{m,n}} \\ C_{m,n} &= C_{n,m} \end{aligned} \tag{22}$$

where R is the line radius. $D_{m,n}$ and $D^{'}_{m,n}$ are the distance from the line m to the line n and its mirror line, respectively. H is the vertical distance from the line to ground. According to $E = \sqrt{E_x^2 + E_y^2}$, electric field intensity can be obtained. It can be seen that the variation of the line voltage will directly affect the power frequency electric field.

According to the ampere circuit theorem, the magnetic field intensity at point $A(x, y)$ can be calculated by Eq. (23):

$$
\begin{aligned}
M_x &= \sum_{k=1}^{n} \frac{\mu I_k}{2\pi} \left(\frac{x_k - x}{d_k^2}\right) \\
M_y &= \sum_{k=1}^{n} \frac{\mu I_k}{2\pi} \left(\frac{y_k - y}{d_k^2}\right)
\end{aligned}
\tag{23}
$$

where M_x and M_y are the abscissa and ordinate components of magnetic field intensity, respectively. μ is the magnetic permeability. I_k is the current of the line k. According to $M = \sqrt{M_x^2 + M_y^2}$, magnetic field intensity can be calculated. The power frequency magnetic field will be directly affected by the variation of the line current.

3. Case Study

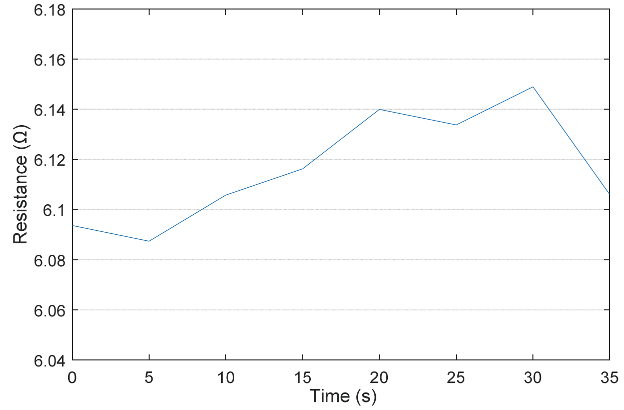
3.1 Analysis of 500kV Transmission Line Parameters Based on PMU

In this paper, a case study of a 500kV transmission line equipped with PMU is conducted. The PMU sampling width is 35s and the PMU sampling interval is 5s. The theoretical value of parameters is R = 6.0951 Ω , X = 57.4038 Ω , B_l = 0.000478S. According to the Π-type equivalent line based on PMU, online estimation of R, X and B_l at sampling interval points can be calculated and the results are shown in Table 1 and Fig. 2.

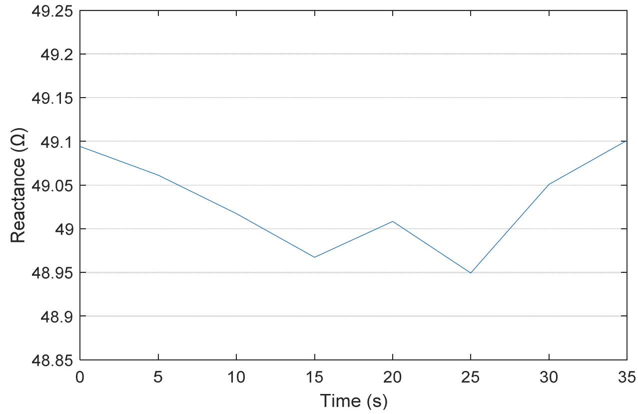
According to the estimation results of transmission line parameters in Table 1 and Fig. 2, there is a gap between the actual value and the theoretical value. During the actual operation of power grid, it may lead to the inaccurate state estimation. This further verifies the necessity and the importance of online estimation of transmission line parameters.

Table 1. Online estimation results of line parameters based on PMU

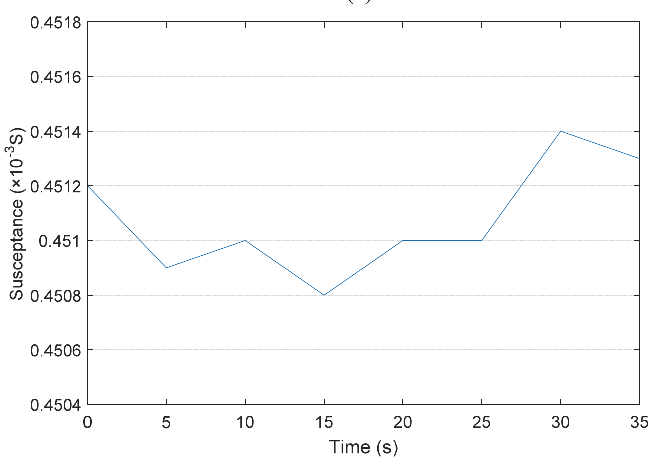
Time (s)	Resistance (Ω)	Reactance (Ω)	Susceptance ($\times 10^{-3}$S)
0	6.0937	49.0941	0.4512
5	6.0874	49.0613	0.4509
10	6.1058	49.0173	0.4510
15	6.1163	48.9674	0.4508
20	6.1400	49.0084	0.4510
25	6.1338	48.9493	0.4510
30	6.1490	49.0507	0.4514
35	6.1061	49.1011	0.4513



(a)



(b)



(c)

Fig. 2. Online estimation results of line parameters based on PMU: (a) resistance, (b) reactance, and (c) susceptance.

3.2 220 kV Transmission Line Parameters Based on SCADA

A case study of a 220kV transmission line named Yuxin Line from Gangyu Station to Xingang Station in Yantai is conducted. The parameter information of the transmission line is shown in Table 2. The theoretical value of parameters is R = 3.95 Ω, X = 20.8 Ω, B_l = 68.325 μS, which is set as the base case. The test time is from 21:00 to 22:00. The sampling interval is 5 minutes and there are 12 groups of samples.

Table 2. The information of line parameters

Line parameters	Information
Line name	Yuxin Line
The first station	Gangyu Station
The last station	Xingang Station
Voltage level (kV)	220
Line type	LGJ-400
Line length (km)	50
Unit resistance (Ω)	0.079
Unit reactance (Ω)	0.416
Unit susceptance (μS)	2.733
Unit specific heat (J/(km·°C))	1127
Safety current (A)	845

Table 3. Comparisons of online estimation results based on SCADA

Sampling point	Full-parameter online estimation			Independent resistance online estimation		
	Resistance (Ω)	Reactance (Ω)	Susceptance (μS)	Resistance (Ω)	Reactance (Ω)	Susceptance (μS)
1	4.3729	19.3273	68.431	4.2890	20.8000	68.325
2	4.2335	18.8677	68.376	4.4395	20.8000	68.325
3	4.4231	19.3496	68.302	4.3859	20.8000	68.325
4	4.3804	18.5730	68.412	4.4086	20.8000	68.325
5	4.2799	19.9671	68.297	4.3275	20.8000	68.325
6	4.4238	18.7734	68.288	4.5064	20.8000	68.325
7	4.2803	18.5423	68.305	4.2076	20.8000	68.325
8	4.2640	17.9758	68.349	4.1098	20.8000	68.325
9	4.3346	17.9857	68.286	4.4683	20.8000	68.325
10	4.3709	19.3020	68.376	4.2279	20.8000	68.325
11	4.4555	19.4563	68.478	4.4203	20.8000	68.325
12	4.3644	19.8603	68.455	4.3068	20.8000	68.325

Firstly, online estimation of full parameters is achieved by the proposed method in this paper. The result of full-parameter estimation is shown in the left part of Table 3, and there are 12 sampling points. The maximum difference between the actual value and the theoretical value of the resistance is 0.5055 Ω at the 11th sampling point, and the maximum difference between the actual value and the theoretical value of the reactance is 2.8242 Ω at the 8th sampling point.

Then, the resistance is estimated independently online while the reactance and the susceptance are set to be the theoretical value. The results of independent resistance estimation based on SCADA are shown in the right part of Table 3. Fig. 3 further describes online estimation results of the resistance under the two methods. It can also be seen from Table 3 and Fig. 3 that the maximum difference of resistance between full-parameter estimation and independent resistance estimation is 0.206 Ω at the 2nd sampling point, which accounts for 4.8% of the total resistance. The difference does exist and it is necessary to be considered. This further illustrates the necessity of the full-parameter online estimation. The full parameter estimation of the resistance will be more appropriate with the actual operation of transmission lines.

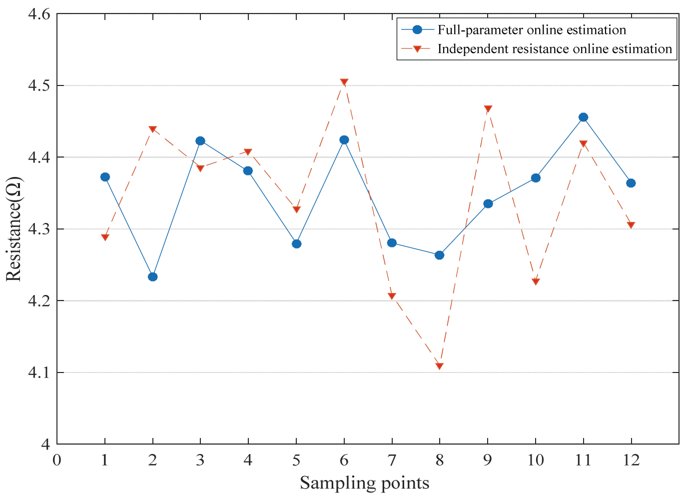


Fig. 3. Online estimation results of the resistance under two methods.

3.3 Analysis of Electromagnetic Environment

A 5-bus power system is taken as the example. The transmission line type is LGJ-400/50, and the voltage level is 220 kV. The conductor diameter is 27.63 mm. The phase sequence is horizontal arrangement, and the spacing is 8 m. The height of the line to ground is 10 m. The lengths of branch 1–2, 2–3, and 1–3 are all 50 km. The electromagnetic environment indicator A is the midpoint of branch 2–3. The network structure is shown in Fig. 4.

Based on the online estimation results of transmission line parameters in Section 3.2, the electromagnetic environment of alternating current transmission lines is obtained. The theoretical value of parameters is set as the base case. The result of full-parameter estimation at the 11th sampling point is set as the case 1, and the result of independent resistance estimation at the 6th sampling point is set as the case 2. The line parameters of three cases are shown in Table 4.

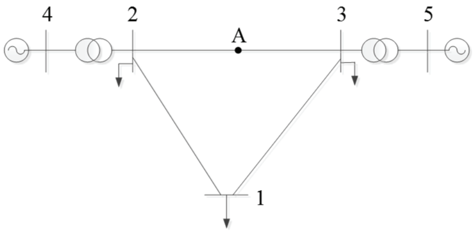


Fig. 4. The network structure diagram.

Table 4. Line parameters of three cases

	Resistance (Ω)	Reactance (Ω)	Susceptance (μS)	Voltage (kV)	Current (A)
Base case	3.9500	20.8000	68.325	228.8	43.94
Case 1	4.4555	19.4563	68.478	228.8	44.58
Case 2	4.5064	20.8000	68.325	228.8	44.55

The results of voltage and current are obtained, and then the electromagnetic environment surrounding the line is analyzed. The voltage magnitudes at point A under the three cases are all 1.04 p.u., so that the electric field intensity of three cases are close. For the currents at point A under the three cases, base case is 43.94 A, case 1 is 44.58 A, and case 2 is 44.55 A. The magnetic field intensity of three cases are different. The height of calculation point to ground is 1.5 m. The horizontal range is between -20 m and +20 m. The magnetic field intensity is calculated every 0.01 m horizontal distance. The distribution curves of the magnetic field intensity distribution at point A is shown in Fig. 5.

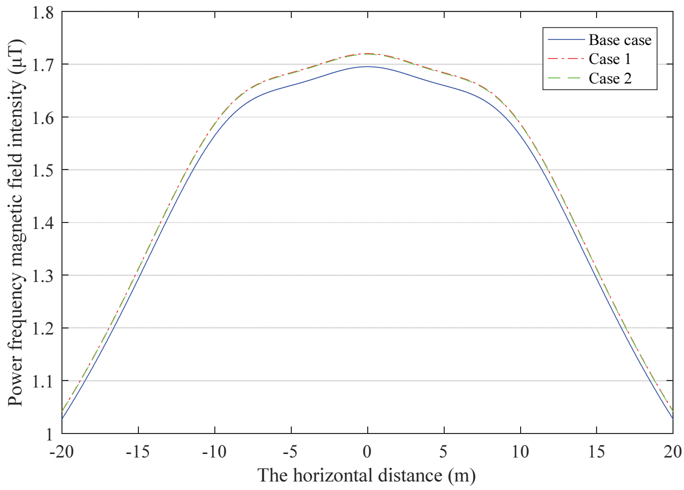


Fig. 5. Power frequency magnetic field intensity at point A.

The curves are distributed unimodally, presenting lateral attenuation trend with horizontal distance increasing. The maximum magnetic intensity M_m occurs at the center of the tower. Overall, for the magnetic field intensity, case 1 and case 2 are both higher than base case. The closer to the tower, the more obvious the phenomenon. The magnetic field intensity at the M_m of three cases are shown in Table 5. Case 1 is 1.7200 μT, which is 1.46% higher than base case. Case 2 is 1.7188 μT, which is 1.39% higher than base case. It can be seen that online estimation of parameters have a great influence on the power frequency magnetic field.

Table 5. The maximum magnetic field intensity of three cases

	M_m (μT)	Difference (%)
Base case	1.6953	0
Case 1	1.7200	1.46
Case 2	1.7188	1.39

4. Conclusion

In this paper, online estimation of transmission line parameters is achieved based on PMU. On the basis of SCADA, the parameters of any transmission line in power grid can be estimated without adding extra hardware by the least square method. The electromagnetic environment surrounding the line is analyzed and compared based on the variation of line voltage and current. The actual results show that line parameters have a great influence on the electromagnetic environment. The higher accuracy of online estimation of transmission line parameters, the higher utilization and reliability of power grid. The proposed method can be adapted to any transmission line.

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