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INCREASING THE ACCURACY OF THE POWER LINES MODELING BASED ON PMU

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Abstract. The article discusses the modeling of power lines based on PMU data to assess the state of overhead lines. Current approaches to solving the problem are analyzed. The advantages and disadvantages of these approaches are presented. It has been established that when modeling power lines are traditionally represented in the form of a π- circuits scheme, which leads to methodological modeling errors. To reduce the methodological error of modeling, overhead lines (OHLs) can be presented in the form of equations with distributed parameters, which allows for maximum accuracy. However, distributed line equations contain hyperbolic functions and reduce performance in real-time simulations. Based on this, it is noted that the selection of an adequate mathematical model of overhead lines with the appropriate accuracy of synchronized vector measurements in real time when assessing the state of power lines is an important stage of modeling. The article discusses overhead line models using equations with distributed parameters, a π-circuits, an equivalent π- circuits and chain π-circuits depending on the number of links. The results of calculating the mode based on the modeling accuracy using the example of a 500 kV overhead line are presented, as well as the results of comparing various equivalent circuits. It is shown that when modeling overhead line modes based on the results of PMU measurements, representing power lines as chain circuits with links 50 km or less in length is appropriate, since it makes it possible to obtain a model accuracy that is adequate to the PMU measurements. Methodological errors in modeling ultra-high voltage transmission lines using the equations of long lines have been studied. The obtained results can be used for monitoring, analysis and operational management of the electric power system

Keywords: *Overhead line, overhead line equations, simplified models, synchronized vector measurements.*

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1. Introduction

The reliability of the functioning of the electric power system (EPS) depends on the successful solution of the tasks of planning and managing the modes of power systems, which also include calculations of electrical modes. All these tasks are solved based on the application of mathematical models of power systems.

The parameters of the electrical mode in the models of power systems according to tele-mechanical information are calculated by state estimation (SE) of power

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systems, the mathematical basis of which is the least squares method (Balametov *et al*., 2019).

After the SE, the calculation of the steady state mode of the EPS is performed and the results obtained are used for monitoring, analysis and operational control of the EPS.

By means of the global positioning system - GPS, it is possible to measure the voltage angle and synchronize the measurement angles. PMU is much faster than traditional methods and improves the reliability and robustness of the state estimation (Figure 1).

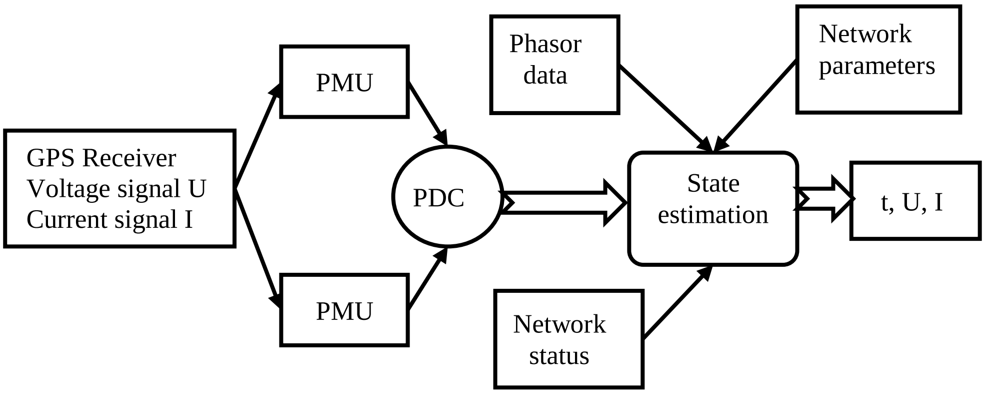

Figure 1. Measurement and identification of the overhead line mode

The control of modern and large and complex EPS requires the implementation of real-time SE of power systems. Supervisory Control and Data Acquisition (SCADA) complexes receive and process tele-information once per second. This information is without synchronization of measurements according to astronomical time. With the creation of satellite communication systems, new measuring equipment appeared – PMU (Zhao *et al*., 2015; Milojevic *et al*., 2018).

Traditionally, EHV PTLs are presented in the form of a π-circuit, the results of which have methodological modeling errors. As shown in abstract, representation of the OHL in the form of equations with distributed parameters makes it possible to obtain the highest accuracy. Acquisition (SCADA) complexes receive and process tele-information once per second.

Initial information from SCADA system and from Phasor Measurement Units (PMU) obtained in the form of telemetry and tele-signals. Telemetry includes information about the mode parameters.

Unlike SCADA, which does not measure the phase angle, PMU measurements are $Y = [f_i, U_i, I_{ij}, \delta_i, \varphi_{ij}]$.

Measuring systems with PMU devices allows obtaining a more realistic state of the power system (Phadke & Thorp, 2008; Balametov *et al*., 2017).

The purpose of the article is to analyze the errors of different models of overhead lines for the possibility of compared to a standard set of TIs received from a SCADA system, PMUs installed in nodes can provide accurate measurement of the magnitude and phase of the voltage at that node, as well as the magnitude and phase of the currents in the branches adjacent to that node. The joint use of SCADA and PMU measurements leads to the need to develop existing RSRES methods based on the integration of SCADA and PMU data.

Estimating the state evaluation of PTLs by using PMU-measurements. There is some interest in the idea of this approach based on data received only from PMU. RURES program is feasible if the number of PMUs is sufficient to ensure observability.

The WAMS system (in Russia - SMPR) is a complex of PMU devices distributed across power system facilities (substations, large nodes) and connected by Internet - data transmission channels with information collection points - Phasor Data Concentrator (PDC) (level "SO-RDU" or "SO-ODU"), - in turn, transmitting it to the data control center ("SO-CDU"). The most important of the WAMS platform applications is EPS monitoring, which opens new possibilities for managing EPSs, in those areas that operate under different SCADA/EMS systems within interacting EPSs. With the help of SMART-WAMS (the Russian analogue of PMU), accurate synchronous registration of phases and amplitudes of currents and voltages in the EPS is performed with a period of 20 μs, assigning a time stamp to each measurement with a resolution of 1 μs. Table 1 compares the measurement accuracies obtained from PMUs from different manufacturers (Phadke, 2018; Balametov *et al*., 2019).

Table 1. Measurement accuracy of PMU devices

Measured value	SMART-WAMS	BEN6000 (Belgium)	SEL421 (USA)	RES521 (Sweden)	Arbiter (USA)
U, %	±0,3	±0,1	±0,1	±0,1	±0,02
Phase angle δ, °	±0,1	±0,1	±0,2	±0,1	±0,3
I_{ij}, %	±0,3	±0,2	±0,2	±0,1	±0,03
Angle φ_{ij} between I_{ij} and V_i	±0,1°	±0,1°	±0,2°	±0,1°	±0,1°
Frequency, Hz	±0,001	±0,002	±0,01	±0,002	±0,005
Error t SIHX GPS	20 μs	50 μs	5 μs	5 μs	1 μs

The purpose of the article is to analyze the errors of various overhead line (OL) models to be able to select an adequate model for mode estimation based on synchronized vector measurements.

Dispatch control centers received information about the mode of the electric power system from the SCADA system and from PMU devices in the form of telemetry and tele-signals. Tele-measurements include information about the mode parameters.

Traditionally, ultra-high voltage transmission lines (EHV power lines) are presented in the form of a π-circuit, the results of which have methodological modeling errors. Representation of the VL in the form of equations with distributed parameters makes it possible to obtain the highest accuracy. These equations contain hyperbolic functions: on-line simulation reduces performance.

Representation of the VL in the form of equations with distributed parameters makes it possible to obtain the highest accuracy. These equations contain hyperbolic functions: on-line simulation reduces performance (Haiyan, 2022; Karn *et al*., 2018).

2. Research objects and methods

2.1. Devices for obtaining information about the technological process PMU (phasor measurement unit)

PMU - devices for synchronized measurements of vector quantities. Devices for synchronized measurements of vector quantities. PMUs are recording a sinusoid of voltage and current in the network with a real phase shift between them. The shift between the 50 Hz sinusoid and the mains voltage sinusoid determines the voltage phase $\boldsymbol{\delta}$. Recording accuracy: frequency, 0.001 Hz, voltage angle, (°) 0.1, effective voltage value % 0.3-0.5; effective current value, % 0.3-0.5; active and reactive power, % 0.3-0.5; discreteness of ADC, frequency 6400-12800 Hz; time (GPS), 20 µs.

The SCADA functions are as follows: collection, transmission and processing of information about the technological process in the control center and the transfer of control actions from the center to the process equipment.

In Azerbaijan Scientific Research Institute of Energy calculation of steady-state regime (CSSR), methods for solving have been developed that correspond to PMU data (Ortiz *et al.,* 2021; Zhao *et al*., 2015).

The use of measurements of complex electrical quantities coming from the PMU makes it possible to significantly improve the results of solving the CSSR problem - to remove the problems associated with low redundancy and measurement accuracy and to significantly increase the efficiency of solving the CSSR problem.

In connection with the using of a modern universal measuring complex (UMC), an operational information complex (OIC) and devices for measuring and recording regime parameters based on a personal computer (PC) in the EPS, much attention has recently been paid to determining the total active power losses in OHL according to measuring of active power at the ends of the line and the separation of corona power losses from them.

To create a method for calculating corona losses, in Azerbaijan Scientific Research and Design-Survey Institute of Energy (an automated continuous recording system has been developed based on time-synchronized measurements of PC_1 and PC_2, regime parameters of power losses at the ends of OHL and meteorological parameters (temperature, pressure, humidity, wind speed, amount of precipitation, fog density, volume of deposits on the wire, line current, solar radiation), by means of which continuous measurements are carried out in the operating 500 kV OHL (Kononov *et al*, 2021; Balametov *et al*., 2020).

Selection of an adequate mathematical model of overhead lines for the analysis of steady-state modes in real time when estimating the state

The total error in OS in terms of the parameter Δ_U can be approximately represented as the sum of the components (Balametov *et al.,* 2017).

$$\Delta_U = \Delta_{mod} + \Delta_{meas} \tag{1}$$

where Δmod is the deviation caused by the inadequacy of the mathematical model of the overhead line used to calculate the optimal values; Δ_{meas} is a component caused by measurement inaccuracy about the current state of the mode.

The required accuracy of Δ_{mod} can be determined from (2) by requiring $\Delta_{mod}$to be a statistically insignificant factor among all factors.

Passing to the norms in (2), we have

$$\|\Delta_U\| \leq \|\Delta_{mod}\| + \|\Delta_{meas}\| \tag{2}$$

Hence, provided that the norm $\|\Delta_{mod}\|$ must be a certain specified fraction of the norm ΔU, i.e. $\|\Delta_{mod}\| = \varepsilon\|\Delta U\|$, it turns out:

$$\|\Delta_{mod}\| \leq \frac{\varepsilon}{1-\varepsilon}(\|\Delta_{meas}\|) \tag{3}$$

From this norm, using the optimal model of overhead lines, you can go to the requirements for the accuracy of the controlled mode parameters, for which $\|\Delta_{meas}\|$ determines the required accuracy of the mathematical model when estimating the state. For example, with a measurement error of 0.2%, the methodological error of the mathematical model in accordance with (3) should be less than 0.05%.

2.2. Methods for improving of the accuracy of simulation the mode of EHV PTLs

Methodological errors, depending on the model used and the modeling method, can have values comparable to the errors in measuring the mode parameters (Balametov *et al.*, 2017). In this regard, the requirements for permissible methodological errors in modeling the OHL mode become relevant.

The EHV PTL traditionally is presented in the π-circuit form (Venikov *et al.*, 1972; Pegoraro *et al.*, 2023). Representation of the OHL by the equations with distributed parameters allows for obtaining the highest accuracy. However, line equations with distributed parameters that contain hyperbolic functions and simulation in computer with limited capabilities leads to difficulties and reduce of the operation speed.

Known methods of mode simulation are based on the model of OHL with the π-shaped scheme of the sections (Dotta *et al.*, 2013). Usually, each section of a power transmission line (PTL) has its own meteorological data: altitude, weather, air temperature, solar radiation, precipitation intensity, cloudiness.

When using of the π-shaped scheme, the scope of problem increases due to the formation of a model from several links. However, this allows for using known software.

In this paper, to solve the problem of determining the electrical parameters of PTLs, different equations of OHL are considered:

1. Use of long line equations with hyperbolic functions.
2. Simplified π-circuit with lumped parameters.
3. Equivalent π-circuit with lumped parameters for considering the influence of distribution, including the calculation of correction factors.
4. Representation of OHL by chain circuits (2 or more sections) with lumped parameters of shorter length.

Representation of a line with distributed parameters. In long-distance lines and ultra-high voltage lines, it becomes necessary to consider the wave nature of energy propagation. In this case, the analysis of the operating modes of the power line is based on the representation of the line by the equations with distributed parameters.

The long line equations for steady-state conditions have the form (Phadke & Thorp, 2008; Venikov *et al.*, 1972):

$$\dot{U}_1 = \dot{U}_2\, ch\dot{\gamma}_0 l + \sqrt{3} \times \dot{I}_2 \dot{Z}_B sh\dot{\gamma}_0 l$$
$$\dot{I}_1 = \dot{I}_2\, ch\dot{\gamma}_0 l + \frac{\dot{U}_2}{\sqrt{3} \times \dot{Z_B}} sh \tag{4}$$

where U_1, U_2 are line voltages of nodes 1 and 2; currents I_1, I_2 respectively, flowing from node 1 to the line and from node 2 to the line; Z_w is wave impedance of line, $\gamma_0 = \beta_0 + y\alpha_0$- wave propagation coefficient per unit length.

Wave impedance of line (1) is a function of line parameters:

$$\dot{Z}_w = \sqrt{\frac{\dot{Z}_0}{\dot{Y}_0}}\ , \tag{5}$$

where $Z_0 = r_0 + jx_0$ is the line resistivity, $Y_0 = \mathrm{g}_0 + jb_0$ is the line conductivity.

$$\dot{\gamma}_0 = \sqrt{\dot{Z}_0 \dot{Y}_0}\,. \tag{6}$$

Here α_0 characterizes of the voltage vector's rotation during the propagation of the voltage wave and is called the phase change coefficient, β_0 characterizes the wave attenuation when it propagates along the line, φ_z is an angle of the line wave propagation coefficient.

$$\dot{\gamma}_0 = \dot{\gamma}_0 \times l\ . \tag{7}$$

Line wave propagation coefficient. Here $\alpha_0\ell$ characterizes (4) the change in the wave phase and is called the wavelength of the line: $\lambda = \alpha_0 \times l$.

Modeling of OHL by an equivalent quadrupole. Long line equations allow for obtaining all relationships for the analysis of PTL modes. In some cases, it is convenient to represent PTLs in the form of a four-terminal network (quadrupole), in the form of π-shaped equivalent circuit.

Modeling of OHL by an equivalent π-shaped equivalent circuit. To consider the distribution of parameters in circuits with lumped equivalent parameters, correction factors are introduced (Venikov *et al.*, 1972; Idelchik *et al*., 1977).

In this case, it is quite reasonable to calculate the OHL mode according to equivalent circuits with lumped parameters, as for equivalent circuits with uniformly distributed parameters along the length of the line. The introduction of correction factors into the calculation makes it possible to estimate the degree of deviation of the apparent line parameters from their actual values, due to the influence of the physics of wave processes in it.

For a symmetric π-shaped equivalent circuit, the PTL has the following relationships (Zhao *et al*., 2015; Bommidi & Lakshmi, 2022):

$$Z_\pi = \underline{B} = Z_B sh(\gamma_0 l) = \underline{Z_0} l \frac{sh(\underline{\gamma_0} l)}{\underline{\gamma_0} l}\ ,$$
$$\underline{Y_\pi} = 2(\frac{\underline{A} - 1)}{\underline{B}} = \frac{2(ch(\underline{\gamma_0} l - 1)}{\underline{Z} sh\left(\underline{\gamma_0} l\right)}\ . \tag{8}$$

where the correction factors can be represented as the Kennelly coefficients $\underline{K}_Z$ and $\underline{K}_Y$ numerically equal to:

$$\underline{K_Z} = \frac{sh(\underline{\gamma_0} l)}{\underline{\gamma_0} l}; \quad \underline{K_Y} = \frac{th\left(\frac{\gamma_0 l}{2}\right)}{\frac{\gamma_0 l}{2}}. \tag{9}$$

Equivalent circuits (5, 6) make it possible to reveal only the relationships between the mode parameters of the line at the it's end.

Modeling of overhead lines by an equivalent U-shaped equivalent circuit.

Method of correction factors. With an increase in the actual length of the line, its apparent electrical parameters will differ significantly from their actual values. To consider the distribution of parameters in circuits with lumped substitution parameters, correction factors are introduced (Haiyan *et al.,* 2022; Karn *et al*., 2018).

In practical calculations for lines with a length of 200 km, the correction factors are usually 1÷2%. For longer lines, correction factors must be considered.

As is known, the apparent parameters of the line equivalent circuit will differ from their actual values. The degree of difference between the apparent parameters and the real ones is determined using the Kennel coefficients.

To accurately estimate the actual values of currents and voltage levels in the line, it is necessary to take into account the physics of wave processes in the parameters of the equivalent circuits of the equivalent two-port line by introducing special correction factors. In this case, it is perfectly reasonable to calculate the long-distance power transmission mode using equivalent circuits with lumped parameters, as for equivalent circuits with uniformly distributed parameters along the length of the line. The introduction of correction factors into the calculation makes it possible to estimate the degree of deviation of the apparent line parameters from their actual values, due to the influence of the physics of wave processes in it.

3. Results and its discussion

3.1. Modeling of OHL by a chain equivalent circuit

The division of the line into sections 100 km long is considered practically acceptable in order not to consider the distributed nature of the parameters (Kononov *et al.*, 2021; Suleimanov & Katsadze, 2008). The representation of a line which has the distributed parameters in the form of chain schemes with lumped parameters (Figure 2) makes it possible to simulate the wave nature of energy transfer along extended lines.

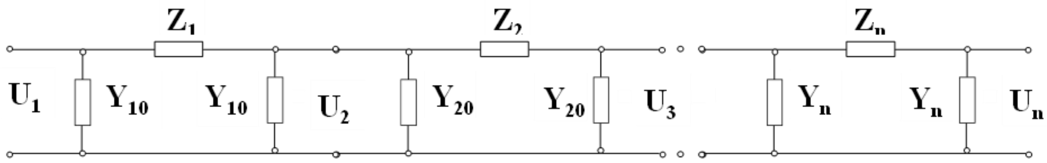

Figure 2. A chain equivalent circuit for a long transmission line

Comparison of calculation methods on the example of 500 kV OHL. Calculation results on the example of 500 kV PTL with wires 3*AC330/43, 350 km long, load at the end of transmission 900 MW, voltage at the beginning U1=520 kV, end U2=500 kV and specific corona power losses 4 kW/km. The results of calculating the correction factors for the equivalent π-circuit are shown in Table 2.

Calculations of steady-state modes for 2-node initial and equivalent π circuits for different values of transmitted active power at P_2=900 MW, U1=520 kV, U2=500 kV have been carried out. Specific corona losses are assumed to be 4 kW/km. The calculation results are shown in Table 2.

Table 2. Calculated values of the correction factors for the equivalent π-circuit

Parameters of initial π-circuit			
R_{pi}, Ohm	Xpi, Ohm	Bpi, Sм	Gpi, Sм
10.15	104.65	$1309 \cdot 10^{-6}$	$5.6 \cdot 10^{-6}$
Parameters of equivalent π-circuit			
102.301	$1321 \cdot 10^{-6}$	$7.22 \cdot 10^{-6}$	
Deviations of parameters of equivalent scheme, %			
4.618	2.245	-1.143	-22.441

In the mathematical model of the OHL, the decrease in active resistance is compensated by an increase in the transverse conductivity g_k and an increase in active power losses in it. The corona power and energy losses are considered not by introducing conductivity into the line equivalent circuit, but by other methods.

Mode calculations were carried out for 350 km OHL, presented according to a chain scheme with 1÷7 sections with an active power setting of 900 MW at the end of transmission (Table 3). To determine the voltage error, the calculations of modes were carried out with the setting of active power of 900 MW and reactive power at the output of the power transmission line -7.03 MVAr, presented according to a chain scheme with 1÷7 sections (Table 4).

Table 3. Calculation results of the steady-state modes of OHL

№	Parameters	By equations with distributed parameters	According to the VL equations with lumped parameters			
			the π-circuit		the equivalent π-circuit	
			values	error %	values	error %
1	Degree δ2, degree	-21.125	-21.657	2.521	-21.123	-0.011
2	Total losses, MW	34.277	35.53	3.656	34.28	0.009
3	Load losses, MW	32.82	34.072	3.815	32.399	-1.283
4	Corona losses, MW	1.457	1.4571	0.007	1.8786	0.007
5	Reactive losses, MWAR	338.4	351.29	3.809	342.37	-2.636
6	Charging power, MWAR	340.57	-340.6	0.009	-344.50	1.154

Thus, by the representation by chain circuits, depending on the number of sections, the accuracy and reliability of EHV OHL modeling is achieved.

The comparison results for the π-circuit and the equivalent π-circuit with correction factors show that the simulation accuracy when using the equivalent circuit is close to the results obtained from the long line equations. Thus, the equivalent representation of the OHL using the Kenelly correction factors leads to an increase in the accuracy of the simulation.

Table 4. The results of calculating the OHL mode of 350 km presented according to the chain scheme

Chain plots		Simulation results			Simulation errors		
		U1	δ2	ΔPn	ΔU1	Δδ2	ΔPn
Number	Length, km	in a.u.	deg	MW	%	%	%
1	350	0.994	-21.758	34.30	-0.574	-2.958	4.430
2	175	0.998	-21.275	33.17	-0.128	-0.672	0.989
3	116.666	0.999	-21.189	32.97	-0.050	-0.264	0.387
4	87.5	0.99977	-21.159	32.90	-0.023	-0.122	0.180
5	70	0.99989	-21.145	32.87	-0.011	-0.057	0.085
6	58.333	0.99996	-21.138	32.85	-0.004	-0.021	0.033
7	50	1.00000	-21.133	32.84	0	-9.5E-05	0

The conducted studies allow for choosing models for calculating of the EHV PTLs corresponding to the initial data accuracy of the initial data by choosing the length and number of links of cascade π-equivalent circuits.

The errors in modeling the parameters of the PTL mode are comparable to the accuracy of modern measuring instruments (PMUs).

An analysis of the results of calculating the mode of the EHV PTL using the π-circuit shows that the model errors can reach 0.2% or more.

To improve the accuracy of modeling the modes of the EHV PTL, it is recommended to represent the π-equivalent circuit with links about 50 km long.

The advantage of using the technique of cascaded π-shaped circuits for modeling the mode of the EHV PTL is the absence of trigonometric and hyperbolic functions in the calculations.

Comparative analysis of the accuracy of calculating the mode parameters from the length of the chain sections of the power line (Figure 3 and Figure 4).

3.2. Areas of application of calculation methods

In the operational modeling of the regime, when an accelerated solution is required, it is recommended to use method 1 (use of long line equations with hyperbolic functions). To obtain high accuracy, it is necessary to represent the OHL with many sections (Balametov *et al.*, 2020; 2015). To obtain high accuracy results, it is recommended to use method 3 (equivalent π-circuit with lumped parameters for considering the influence of distribution, including the calculation of correction factors). This requires a small number of sections (2-3) and the computational complexity is high and requires more computing resources. The accuracy of obtaining a solution by method 2 (simplified π-circuit with lumped parameters) is two times higher than by the first method and a relatively small number of sections (5-10) is required. At present, the representation of the line by chain sections with a length of 50 km or less can be considered acceptable. This ensures the accuracy of modeling the EPS mode with the accuracy of obtaining information from the HVTS.

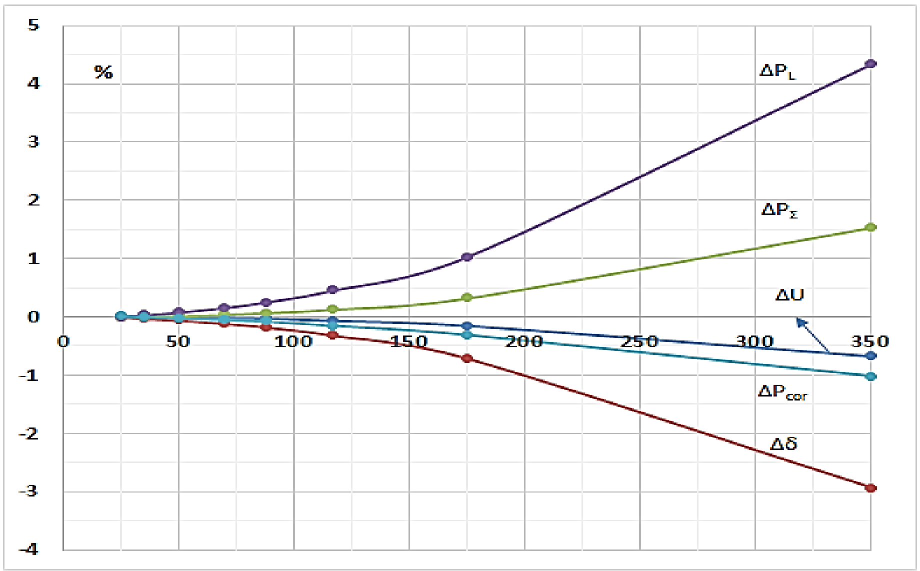

Figure 3. Dependences of the error in calculating the mode parameters on the length of the chain sections of the power line

The results of modeling the power losses to the corona in steady-state modes of a 500 kV 350 km power transmission line presented by chain circuits up to 35 sections at g_0=4.085568*10^{-7}, U_1=1.0424 in p. u. (521.2164 kV), according to the program for calculating the Newton method are shown in Table 5.

When modeling based on PMU measurements, it is more accurate to represent overhead lines as chain circuits with a length of 70 km or less, which makes it possible to obtain an accuracy of the model that is adequate to PMU measurements.

The results of comparing the π circuit and the equivalent π circuit show that the simulation accuracy when using the equivalent π circuit is close to the results obtained by the long line equations.

Table 5. Results of simulation of power losses to the corona under weather conditions on the path of the corresponding rime

№	Quantity plots Number	Number knots	Length plots, km	Power losses to the crown, MW
1	1	2	350	38.84
2	2	3	175	38.00
3	3	4	116.666	37.75
4	4	5	87.5	37.63
5	5	6	70	37.56
6	7	8	50	37.47
7	10	11	35	37.41
8	14	15	25	37.36
9	25	26	14	37.32
10	35	36	10	37.30
11	70	71	5	37.18

Thus, the equivalent representation of the VL, using the Kenelly correction factors, leads to an increase in the accuracy of the simulation. The relationship between the voltage modeling error and the length of sections of chain π circuits in % is shown in Figure 4.

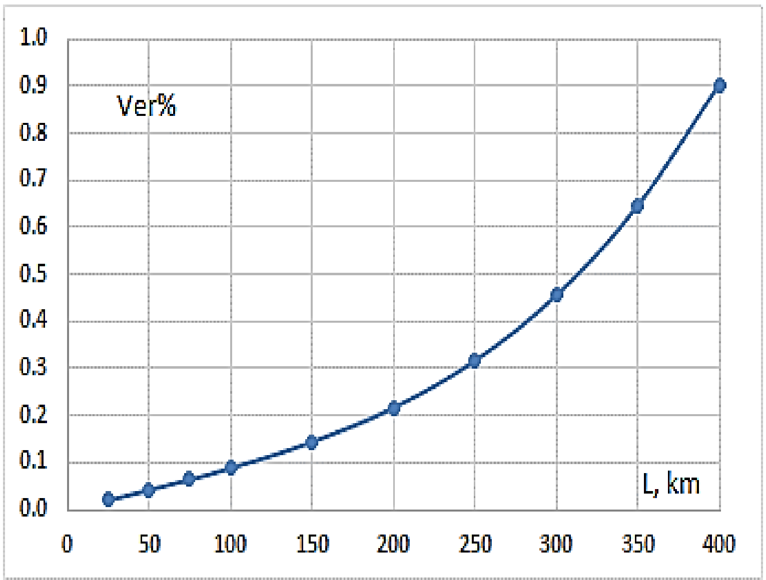

Figure 4. Error of voltage simulation from the length of sections of chain □-circuits

To obtain high accuracy, it is required to represent the OHL with many chain sections 50 km long (4-7 in number) and use the combined equations of the steady state and heat balance for mode modeling (Balametov *et al.*, 2020).

For the simulation of modes by PMU measurements, the representation of the line by chain segments with a length of about 50 km can be considered acceptable.

This ensures that the simulation of the EPS mode corresponds to the accuracy of the information obtained.

Error regarding the results obtained by long line equations in hyperbolic functions δ_2, U_2, ΔP_n, ΔP_k, ΔP_{sum}, Q_{charg} 900 MW, U1=520 kV, U2=500 kV.

Table 6. Results of steady state calculations for 2-node initial and equivalent P-and schemes

№	Mode Options	According to the transmission line equations		
		Long line	Lumped parameters	π-equivalent circuit
1	Voltage, r. u.	1	0.994	1
2	Degree δ2,	-21.125	-21.6576	-21.122
3	Total losses, MW	34.277	35.53	34.28
4	Load losses, MW	32.82	34.072	32.822
5	Corona losses, MW ΔP_k,	1.457	1.4571	1.4571
6	ΔQ,	338.4	351.29	342.37
7	Reactive losses, MWAR	7.23	7	7.23
8	Charging power, MWAR	340.57	340.6	344.5

Calculations of steady state modes for 2-node initial and equivalent P-and circuits for different values of active power of transmitted power at P_2=900 MW, U1=520 kV, U2=500kV are carried out. The calculation results are given in Table 6.

Simulation of the mode of the EHV power transmission line using equations with lumped parameters has unacceptable errors in voltage of more than 0.1%, in angle of more than 2.5% and in power losses of 4% compared to the results of long line equations.

4. Conclusion

It has been established that the errors of the method of modeling the mode of OHL by simplified equations are comparable with the accuracy of measurements obtained using modern intelligent measuring systems. Representation of OHL by 3-5 chains allows obtaining the accuracy corresponding to the PMU accuracy. Devices used to measure of the electrical quantities should have accuracy class not less 0.1% for voltage and 0.2% for active power. To calculation OHL modes with the appropriate accuracy in terms of voltage and power losses the selection of an adequate calculation model depending on the length and mode of power transmission line is required.

The errors of the π-circuit increase with an increase in the length of the OHL and in the transmission of active power. To consider the distribution of parameters in lumped circuits, according to the measurements of the PMU substitution, correction factors are introduced into the equivalent π-circuit. The most accurate for modeling the EHV PTL mode are long line equations with hyperbolic functions. The study of methodical errors of modeling the EHV PTLs according to the long line equations shown, that modeling errors associated with non-considering the real characteristics of corona losses can reach more than 0.1% in voltage, which is unacceptable for state estimation according to PMU data. An analysis of the results of calculating the mode of the EHV PTL using the π-circuit shows that the model errors can reach 0.2% or more.

Modeling of EHV power lines with a π-shaped equivalent circuit, depending on the length and mode of power transmission, leads to a methodological error of 1% for voltage, 3% for loading losses, 10% or more for corona and charging power losses of the line.

In practical calculations for lines longer than 100 km, it is proposed to use an equivalent circuit using Kennel correction factors, when using PMU measurements to assess the state of the OHL mode, it is required to comply with the requirements for voltage modeling accuracy of 0.025%. Representation of power OHLs by chain sections 50 km long makes it possible to obtain sufficient modeling accuracy.

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