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Extra high voltage transmission line operation simulation using the actual corona-loss characteristics

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Abstract: In transmission line equations with distributed parameters, corona power losses are represented as conductivity, i.e. corona losses considered as a function of the line voltage squared. On the other hand, valid corona power losses are 4–8 degree functions from voltage. Therefore, extra high voltage transmission line equations with the distributed parameters have methodical errors. Methodical errors of extra high voltage transmission line operation mode parameters modeling are estimated. The method of modeling extra high voltage transmission line operation mode taking into account actual corona-loss characteristics is offered. The cascade-connected scheme is used for increasing the accuracy of modeling extra high voltage transmission line operation modes in this method. In the offered method, corona power losses consist of two components. The first component is represented as conductivity. The second component is represented in the form of additional loading. Using the proposed method allows incorporation of phasor measurements of electrical parameters into the calculations. The accuracy of modeling using information received from the phasor measurement units is investigated. The software for modeling an extra high voltage transmission line's operation mode is developed on the basis of the proposed method. Results of modeling for a 750 kV extra high voltage transmission line are represented.

Key words: Extra high voltage transmission line, operation, phasor measurement unit, corona losses, actual corona-loss characteristics, reactive effect of corona, chain-connected scheme, equation with distributed parameters, simulation error

1. Introduction

Extra high voltage (EHV) transmission lines (TLs) are one of the main components of a power system. It is well known that, to maintain the normal and secure operation of EHV TLs, the state estimation procedure, which is a very useful tool for system operators and control engineers, is also used [1].

Earlier state estimation was based on measurements from supervisory control and data acquisition systems (SCADAs). The information from a SCADA system is characterized by incompleteness and low accuracy. Therefore, state estimation based on information received from a SCADA system contains errors.

The phasor measurement unit (PMU) is a digital device for measuring synchronized voltage and current phasors. The PMU provides voltage measurement in nodes and current measurements in branches, and also angle φ_{ui} between the node's voltage and currents in branches. PMU data are time-tagged with precision better than 1 ms and magnitude accuracy better than 0.1% [2,3]. PMU-based phasor measurements of electrical parameters allow more exact modeling of TL operation mode. Thus, it increases accuracy of problem decision

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at state estimation, steady-state operation mode, optimization, and reliability of power supply system regimes' management.

One of the phenomena connected with EHV TLs is the corona. Corona loss is the main type of power loss in transmission lines, especially in EHV overhead lines. The physical phenomenon of a corona is very complex. A corona is too complicated to be exactly described by mathematical equations [4–8].

Unlike resistive loss, the percentage of power loss due to coronas is a function of the voltage. Corona losses are also highly dependent on weather conditions and temperature. During bad weather, corona loss can exceed heating loss. Analysis of coronas is important for power system protection. This is due to the fact that the corona is the cause of power loss on TLs, audible noise, and electromagnetic interference in communication and navigation systems [5,7,9].

The current EHV TL regime is determined by nodal voltages and power flows in line. In a π-equivalent model the total shunt capacitance of the line is divided into two equal parts, one at each end of the line.

In telegraph equations for long lines the corona losses are represented as a shunt. In this case a long line is divided into sections with lengths of 100–150 km and shorter, which are then each modeled as π-elements, connected together [8,10].

In [11] methods and expressions for calculation of corona losses in overhead lines were presented. Accordingly, shunt conductance is usually neglected in overhead lines, but it is not negligible in corona phenomena. In this reference corona power losses were calculated by using power losses specific to the corona.

In [12] corona losses were calculated by approximation of specific power losses due to coronas for different weather conditions, which decrease the accuracy of EHV TL operation mode modeling. Note that using the specific corona losses for corona loss calculation leads to inaccuracy of calculations.

The authors of [13] dealt with the software for technical loss calculation of TLs. The inputs of software are line parameters and measured data from the control system of the Czech transmission system operator. Outputs are heating losses, corona losses, and leakage losses for each transmission line. Corona loss calculation is based on the modified Peterson's relation. The use of this expression leads to errors in calculating corona losses.

The author of [14] considered the calculation of technical losses of the transmission network system line. Calculations of Joule losses, corona losses, and leakage losses were presented. Developed by the author, software enables evaluation of results in different forms. To calculate the corona losses, the Peterson formula was used. However, this formula was simplified in the software.

In accordance with [13,14] for real calculations taking into account atmospheric influences, the Russian methodology [15,16] is most adequate. A modern digital device measures the active power and voltage with an accuracy of 0.2% and 0.1%, respectively [2,3].

A specialized system of the synchronized measurements of current parameters of TL operation was developed [8]. This system provides online estimation of total losses of active power in TLs on the basis of converters and personal computers.

The actual corona-loss characteristics are 4-8 degree functions from voltage. Presentation of corona losses as a shunt leads to a modeling error. Increased capacitive conductivity in the corona phenomenon is known as the reactive effect of the corona. Neglect of this effect leads to EHV TL operation simulation errors. Corona losses increase by 1–2 orders in bad weather. Therefore, increase of an EHV TL's operation simulation accuracy based on the information from the PMU becomes very important. When the length of the line is more than 300 km, the line is called a long line. Therefore, parameters distributed uniformly throughout the line length must be considered.

2. Long line equations at steady state

Long line equations in steady state can be presented in a more convenient form through hyperbolic functions as shown below [8,10]:

$$\begin{aligned} \dot{U}_1 &= \dot{U}_2 ch\dot{\gamma}_0\ell + \sqrt{3}\cdot \dot{I}_2\dot{Z}_\beta sh\dot{\gamma}_0\ell\,; \\ \dot{I}_1 &= \dot{I}_2 ch\dot{\gamma}_0\ell + \tfrac{\dot{U}_2}{\sqrt{3}\cdot\dot{Z}_\beta} sh\dot{\gamma}_0\ell, \end{aligned} \tag{1}$$

where U_1 and I_1 are sending-end voltage and current and U_2 and I_1 are receiving-end voltage and current, respectively. $Z_0 = r_0 + jx_0$ and $\gamma_0 = \beta_0 + j\alpha_0$ are called the characteristic impedance of the line and propagation constant, respectively.

Shunt conductance $g$is usually neglected in overhead lines, but it is not negligible in corona phenomena. As noted above, in long line equations, losses are presented as specific conductivity. However, the specific corona losses should be presented as a function of the voltage

$$\Delta P_{sc} = \Delta P_{c0}\cdot\left(\frac{U_k}{U_{nom}}\right)^{\rho}, \tag{2}$$

where ΔP_{c0} is specific corona losses in an overhead line corresponding to the nominal line voltage U_{nom}, U_k is actual voltage at the kth node, and ρ is an exponent.

On the other hand, the power loss can be defined as the loss in uniformly distributed conductivity using the formula

$$\Delta P_{c\rho} = 3\cdot g_0\cdot\int_0^L U_\ell^{\rho}\, d\ell, \tag{3}$$

where g_0 is shunt conductance per unit length and L is line length.

The exact dependence of corona losses from the line voltage can be expressed as:

$$\Delta P_c = g_0\cdot L\cdot U_{nom}^2\cdot\left(\frac{U_k}{U_{nom}}\right)^{\rho}. \tag{4}$$

Corona losses in overhead lines, obtained by integrating the voltage of ρth degree along the line, have the following form:

$$\Delta P_{c\rho} = \Delta P_{c0}\cdot\int_0^L \left(\frac{U_\ell}{U_{nom}}\right)^{\rho} d\ell \tag{5}$$

This paper proposes a method of calculating the EHV TL operation mode that takes into account the actual corona-loss characteristics as a function of voltage. The technique is based on equations with distributed parameters. In these equations, the first component of corona losses is accounted as a function of the line voltage squared (i.e. in the form g_0). The second component is modeled as the difference of ρth and squared corona losses. This component is represented as an additional load on the ends of TL segments. Then it is necessary to calculate the reactive effect of the corona and update the conductivity.

Equations of lines with distributed parameters use the exact values of active and reactive conductance. In the simulation of the EHV TL operation the above algorithm takes into account the impact of the corona losses in the ρth degree and reactive corona effect. This is the difference of the proposed method from the methods based on equations of a line with distributed parameters. In the next section we will consider the proposed simulation method, taking into account the exact corona losses.

3. Proposed simulation method

As noted above the proposed simulation method is based on equations with distributed parameters, in which the first component of the corona losses is accounted as a function of line voltage squared and the second component is represented as an additional load on the ends of transmission line sections:

$$\Delta P_{ic\Sigma} = \Delta P_{ic1} + \Delta P_{ic2}. \tag{6}$$

The second component of corona power losses is defined as:

$$\Delta P_{ic2} = \Delta P_{c0} \cdot \left\{ \int_0^L \left(\frac{U_\ell}{U_{nom}} \right)^\rho d\ell - \int_0^L \left(\frac{U_\ell}{U_{nom}} \right)^2 d\ell \right\}. \tag{7}$$

During normal operation of the power system, values of power flow and voltage at the receiving and transmitting ends of the transmission line are connected to each other by analytic expressions, which include required parameters of transmission lines.

For more exact modeling of an operation mode, a TL is represented as chain-connected elements. The equivalent circuit consists of chain-connected π-shaped sections as presented in Figure 1. Increasing the number of cascaded elements makes the model more exact.

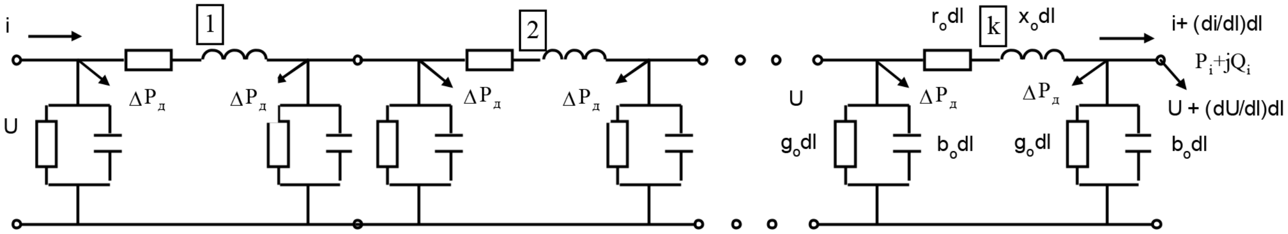

Figure 1. The equivalent circuit of a transmission line.

4. Simulation

Simulation of transmission line operation, taking into account the corona loss, is based on equations with distributed parameters. To take into account the actual characteristics of corona losses, it is necessary to apply the following algorithm:

1. Set the original parameters of transmission line. Set the exponential function of the corona loss for the given weather conditions.
2. Apply the long line equations and divide an additional load between the ends of the sections of transmission line.
3. Calculate the integral along the line section by using a second-degree function from voltage and defining the corona losses in line ΔP_{ic2}.
4. Calculate the integral along the line section by using the ρth degree function from voltage and defining the corona losses in line $\Delta P_{ic\rho}$.
5. Define the difference $\Delta P_{c\rho-c2} = (\Delta P_{ic1} - \Delta P_{ic2})/2$ and use it in TL ends as an additional load.

6. Model the reactive corona effect by using the additional conductivity of reactive corona effect.
7. Update powers at the ends of the line section.
8. Repeat steps 1–6 for all line sections.
9. To achieve a given accuracy between the two models of the EHV line (with n and n – 1 sections), repeat calculations 1–7 by increasing the number of line sections.
10. Check the voltage increase at the points of the TL and change the reactive power at the end of the TL.
11. To obtain the desired voltages at intermediate points of the line, repeat the calculations.
12. Get calculation results.

Below is the condition for ending the calculations:

$$\frac{\Delta\Pi_i - \Delta\Pi_{i-1}}{\Delta\Pi_i} \leq \varepsilon_i, \tag{8}$$

where Π_i is voltage, heat, and corona losses; ε is the accuracy to stop the calculations.

This condition defines the required number of line sections to achieve the desired modeling accuracy. On the basis of the proposed methodology the program for modeling EHV TL operation modes is developed.

5. Additional capacity caused by the corona

In the equations of the line with distributed parameters (Eq. (1)), the generation of reactive power in the TL is considered as capacitance per unit length.

Additional capacitance is determined through corona loss and the phase angle of the corona current's first harmonic with respect to voltage [6,8]:

$$\Delta C = \frac{\Delta P_c}{\omega \cdot U^2} \cdot tg\psi, \tag{9}$$

where ΔP_c is corona power losses on the line; ω is angular frequency; U is line voltage; ψ is the phase shift angle of the corona current's first harmonic with respect to voltage.

To simulate TL operation mode we used a 750 kV line with total length equal to 400 km.

TL parameters are as follows: resistance per unit length $r_0 = 0.01875\ \Omega$/km, inductance per unit length $x_0 = 0.289\ \Omega$/km, capacitance per unit length $b_0 = 4.12 \times 10^{-6}$ S/km, $U_2 = 750$ kV, $P_2 = 1500$ MW, $Q_2 = 300$ MVA, $\Delta P_{c0} = 320$ W/m, exponent of the function $\rho = 2$. As noted in [6,7], for the measurement results of corona losses on the 750 kV line, maximum values occur in rain and in frost.

Calculations were performed by dividing the line into sections of up to 10 km by using specific corona losses equal to 14, 30, 90, 150, 320, 600, and 900 W/m. The exponent of the corona-loss characteristics was selected equal to 2–8.

Table 1. An additional capacitance of 750 kV line.

Specific corona losses, W/m	30	90	150	320	600	900
Additional capacitance caused by corona, %	1	3	5	10	20	30

6. Simulation results

Calculation results for the 750 kV line at different values of specific corona losses and additional capacitances are presented in Table 1.

Additional capacitance for good weather conditions is accepted as 0%. Probable values of the additional capacitance for other weather conditions are taken within 1%–10%. The maximum additional capacitance on frosty days can be 30% [7,8].

Table 2 shows the operation mode parameters at the ends of the line and the results of calculations based on the equations of the line with distributed parameters.

Table 2. Calculation results for 750 kV EHV line.

No	Wire temperature, °C	Specific corona losses, W/m	Power losses, MW			Line charging power, MVAr	Sending-end voltage, kV
			Due to corona	Loading	Total		
	U_2 = 750 kV,P_2 = 1500 MW, Q_2 = 300 MVAr						
1	20	14	5.8704	30.0333	35.9036	971.7528	772.5309
2	20	30	12.5805	30.1604	42.7408	971.8416	772.6585
3	–20	90	37.6309	25.393	63.0239	968.9955	770.6899
4	–20	150	62.7387	25.7948	88.5335	969.313	771.1529
5	–20	320	133.9679	26.957	160.9249	970.2208	772.4796
6	–20	600	251.5839	28.948	280.5319	971.7429	774.7124
7	–20	900	378.0236	31.1874	409.211	973.4109	777.1700
	U_2 =750 kV,P_2= 2100 MW,Q_2 =0 MVAr						
8	–20	14	5.7216	49.6267	55.3483	947.1255	765.2554
9	–20	30	12.2619	49.7742	62.0361	947.2338	765.4166
10	–20	90	36.8016	50.3299	87.1315	947.6409	766.0230
11	–20	320	131.0675	52.5003	183.5678	949.2153	768.3705
12	–20	900	370.2078	58.2561	428.4639	953.2851	774.4530

Table 2 shows the results for temperatures of –20 °C to 20 °C ($r_0 = 0.01875\ \Omega$/km). Calculation results with ΔP_{c0} =320 W/m, ΔC =0%, and ρ =4 are shown in Table 3. Results for the 25 km line section are chosen as accurate calculations. Errors in the EHV operation simulation were calculated according to the formula:

$$\Delta \Pi_i = \frac{(\Pi_i - \Pi_{16}) \cdot 100\%}{\Pi_{16}},$$

where Π_i is the calculation result obtained for the ith length of the TL; Π_{16} is the calculation result obtained for the TL with number of sections n =16 (each section is 25 km).

The dependence of the modeling error from the EHV TL section length is shown in Table 4.

Results of calculations at ΔP_{c0} =320 W/m, ΔC =10% are shown in Figure 2.

Table 3. Operation parameters for the 750 kV line depending on section length.

Operation parameters	Line section length, km					
	400	200	133.33	100	50	25
ΔP_c, MW	141.2616	141.2352	141.2300	141.2282	141.2264	141.2260
$\Delta P_{loading}$, MW	32.6652	32.6427	32.6388	32.6374	32.6361	32.6358
U_1, kV	775.1882	775.1197	775.1055	775.1004	775.0954	775.0942

Table 4. Dependence of modeling error from the EHV TL section length.

Operation parameters	Line section length, km					
	400	200	133.33	100	50	25
ΔP_c, MW	0.0252	0.0065	0.0029	0.0016	0.0003	0.0000
ΔPl_{oading}, MW	0.0902	0.0214	0.0092	0.0050	0.0010	0.0000
ΔU_1, kV	0.0121	0.0033	0.0015	0.0008	0.0002	0.0000

It can be concluded that the methodological error of simulation using line equations with distributed parameters are equal: 0.0116% for voltage, 0.32% for the heating loss, and 0.11% for the corona losses. Errors in TL operation mode simulation parameters are comparable with PMU accuracy. Representation of TL by cascade-connected sections with section lengths of less than 100 km provides almost equivalent accuracy. We can conclude that with an increase of line section length, the modeling errors of heating losses, corona losses, and voltage drop in the TL increase. Relatively large error of operation mode parameters modeling has heating losses. It is required to use a circuit with more sections.

The simulation results showed that neglecting specific corona losses leads to errors of 1.4% in the sending-end voltage.

The relative change of sending-end voltage in the 750 kV line in dependence from the specific corona power losses is shown in Figure 3. Results of modeling for the 750 kV line operation parameters at $\rho = 4, P_2 = 1500$ MW, $Q_2 = 300$ MVAr are presented in Table 5.

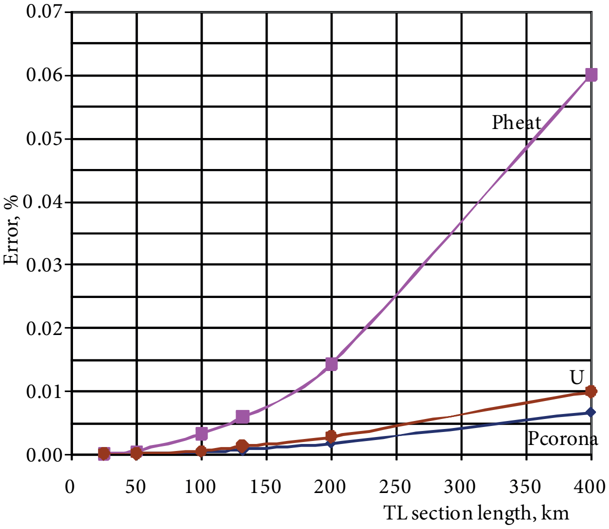

Figure 2. The dependence of the modeling error for 750 kV line from the line section length.

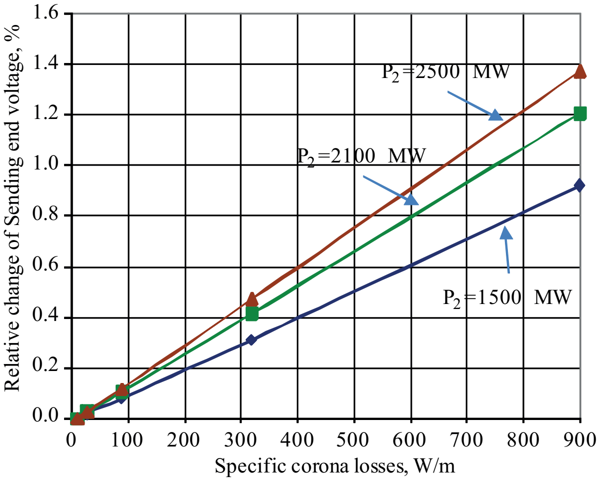

Figure 3. Sending-end voltage as a function of specific corona loss.

Table 5. The dependence of charging power of 750 kV line on specific corona losses.

No	Specific corona losses, W/m	Additional capacitance, %	Charging power of line, MVAr
1	30	1	980.96
2	90	3	999.50
3	150	5	1018.01
4	320	10	1064.27
5	600	20	1155.86
6	900	30	1246.83

Comparison of the calculation results in Tables 2 and 5 makes it evident that the additional power charging caused by the corona according to the level of specific corona losses increases. The relative change of the 750 kV line's operation parameters from a relative change of TL capacitance is presented in Figure 4.

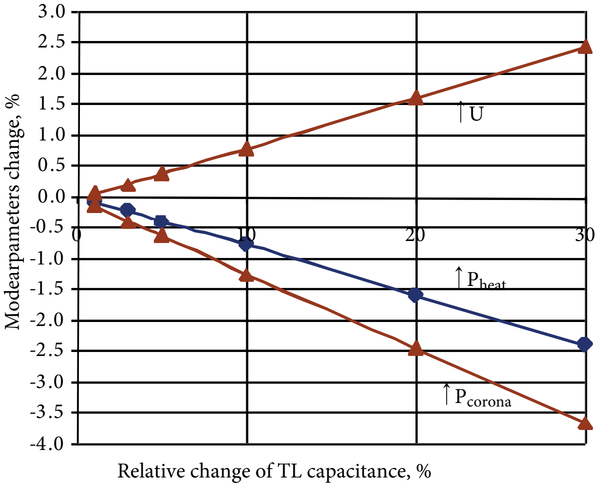

Figure 4. Relative change of 750 kV line operation mode parameters from a relative change of TL capacitance.

From Figure 4 it follows that the modeling error for the 750 kV TL compared with the simplified calculations can be 2.5% for voltage, 2.4% for loading losses, and 3.6% for corona losses.

The results of the proposed method were compared with the measurements from the Kalinin–Vladimir TL [15] and other traditional methods. TL parameters are: U = 750 kV, L = 396.7 km, $r_0 = 0.029\Omega/\text{km}$, $x_0 = 0.308\Omega/\text{km}$, $b_0 = 3.604 \times 10^{-6}$ S/km.

Results of measurements, heating losses, and corona losses based on the traditional method are presented in Table 6.

Table 6. Results of measurements, heating losses, and corona losses (based on traditional method).

Measurements	U_1, kV	U_2, kV	P_1, MW	P_2, MW	Q_1, MVAr	Q_2, MVAr	$\Delta_{heating}$, MW	Δ_{corona}, MW
No 1	761.0	750	616.5	591.3	432.4	–156.2	8.5	11.9
No 47	760.8	750	807.2	738.2	428.5	–114.3	12.5	51.6

Results of measurements, heating losses, and corona losses based on the proposed method for $\rho = 5$ are presented in Table 7.

Table 7. Results of measurements, heating losses, and corona losses (based on proposed method).

Measurements	U_1, kV	U_2, kV	P_1, MW	P_2, MW	Q_1, MVAr	Q_2, MVAr	$\Delta_{heating}$, MW	Δ_{corona}, MW
1	761.04	750	612.54	591.3	366.74	–385.8	8.07	13.17
47	760.85	750	807.59	738.2	357.4	–345.5	12.54	56.81

Modeling errors equal:

more than 10% for the corona losses;

from –5% to –0.3% for the loading losses:

16% for the line charging.

These errors do not correspond to the accuracy of the data received from the PMU.

7. Conclusion

The proposed and substantiated transmission line model is based on chain-connected sections. In this model, actual corona loss was modeled by two components. The first component of corona losses was considered as a function of the line voltage squared (i.e. in the form of g_0). The second component was modeled as additional loading. The software for simulation of EHV TL operation mode was developed. It was proved that using equations of line with distributed parameters for simulation of EHV TL operation has significant methodological error.

The use of a well-known simplified calculation model based on the example of a 750 kV line showed that modeling errors can reach 4% for voltage, 2.6% for loading losses, 11% for corona losses, and 30% for line charging. A new method to calculate the EHV TL operation is proposed, which is based on a line equations model with segmentation and actual corona loss characteristics. The proposed method provides a significant increase of simulation accuracy.

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