Algorithms For Considering The Temperature Of Overhead Conductors In The Calculation Of Steady States Of An Electrical Network

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***Abstract* — This paper presents an algorithm developed and implemented in software to calculate the normal steady state of an electrical network based on jointly solving a system of the nodal power balance equations using the Newton – Raphson method and the heat balance equation for overhead conductors. The algorithm allows considering the resistance of overhead conductors as a function of the magnitude of current in the conductors of various voltage levels based on the calculation of their temperature. The improved expressions for determining the coefficients of the heat balance equation for a conductor are obtained subject to the actual environment parameters (atmospheric pressure, air temperature, etc.), which were calculated by V.V. Burgsdorf and recommended by the regulatory documents for normal values of air parameters. Consideration of the actual temperature of overhead conductors also allowed improving the value of the conductor sag in the span and expanding a set of inequality constraints in the calculation of feasible steady states of electrical networks.**

***Index Terms* — conductor heat balance equation, conductor state equation, conductor sag in the span, feasible steady state, overhead line resistance, normal steady state.**

I. Introduction

The current conditions of electrical network operation give rise to new information opportunities for improving the accuracy of mathematical description of network components.

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http://dx.doi.org/10.25729/esr.2019.02.0002
Received February 13, 2019. Revised July 7, 2019.
Accepted September 5, 2019. Available online October 31, 2019.

The current conditions of electrical network operation give rise to new information opportunities for improving the accuracy of mathematical description of network components.

One of the directions for improvement of the models of the electrical network components and, as a result, the parameters of its steady states is to consider the influence of the actual temperature of overhead conductors on the parameters of network components. The conductor resistance and sag in the span are highly sensitive to changes in the conductor temperature.

The temperature and resistance of conductors are known to depend on their current load and a number of environment parameters, such as wind speed and direction, air temperature and pressure, and solar radiation intensity. This dependence can be represented by the conductor heat balance equation. Dependence of the conductor sag on temperature can be represented by the conductor state equation.

Most present-day software for the calculation of electrical network steady states does not include the heat balance and conductor state equations [11, 36, 39, 40, 51-55, 66, 67] The temperature of overhead conductors in them is often set equal to either the normalized value of 20°C or the air temperature [1, 5, 10, 16] This simplification makes it impossible to consider the actual temperature condition of conductors and results in erroneous determination of the steady state parameters of electrical networks.

At the same time, numerous theoretical [2,6-8,10,12-14,43,44,59-62,64,65] and practical [3,17-22,45-48] methods have been developed to determine the conductor parameters with varying degrees of accuracy subject to the actual temperature condition. Moreover, in most cases, these methods are not considered in the existing algorithms for steady state calculation.

Note the method described in [2], in which a quadratic approximation of the conductor heat balance equation is applied to determine the conductor temperature, and the approximation coefficients must be determined for each specific value of air temperature changing in a wide range. In this case, a large array of the coefficients for each conductor brand must be stored and processed in the computer memory, which is irrational from the software point of view.

Expressions and, for some conductors, available numerical values of the adjusting coefficients to the heat balance equation, which are difficult to determine due to the complexity of considering many unstable natural factors such as the degree of air pollution, the angles of sun rays slope and wind attack, the duration of sunny and cloudy weather, etc., are proposed in [3,6-9,12-15,27-34,49,50,59-62,64]

When determining the conductor sag in the span, in most cases its temperature in the state equation is also taken into consideration approximately. It is either set by a required value, or equated to the air temperature [3,7,14,32,37]

At present, the algorithms for calculating normal steady states in 0.4-110 kV distribution networks, given the actual temperature of overhead conductors, which is determined by numerically solving the heat balance equation as in [3], are proposed only in [7,13,63] Due to the topological features of distribution networks, the algorithms have simplifications and a limited area of application. Their application to networks of higher voltage classes requires consideration of a number of additional factors analyzed in the proposed paper.

There is also no known algorithm, besides the one developed by the authors of this paper, for calculating the feasible steady state of an electrical network, which takes into account the conductor sag in the span along with other parameters of overhead conductors.

This paper presents an algorithm implemented in the software for calculating the normal steady states of electrical networks of different voltage classes. The algorithm was developed by jointly solving a system of nodal power balance equations, which is the heart of the algorithm [40,42], and the conductor heat balance equation, which was solved analytically by the Newton method [23-26] We also propose an algorithm for calculating the feasible steady states of electrical networks by jointly solving the normal steady state equations and the conductor state equation, which is accurately solved by Cardano's formulas [38]

For the first time in the practice of calculating the feasible steady states, the conductor sag in the span is considered as an additional inequality constraint imposed on the steady state parameters, which allows expanding the list of "traditional" inequality constraints and increasing the calculation accuracy of steady feasible, optimal and heavy states of power systems, when it is necessary to calculate the state variables as accurately as possible.

The proposed algorithms for calculating the steady states of electrical networks are implemented in the certified software SDO-7 (developed at Melentiev Energy Systems Institute of SB RAS) [41] and have been extensively tested on some overhead transmission lines and calculation schemes of real power systems of various sizes in the Irkutsk region [25, 38,56,58]

II. Methodology For Calculating Steady State Of An Electrical Network

1. Determination of temperature and resistance of overhead conductors

The unit resistance of an overhead conductor subject to its temperature T_{con} is determined by the known expression:

$$r_{0\,(T_{con})} = r_{0\,(20)} \cdot [1 + \alpha_T \cdot (T_{con} - 20)] \quad (1)$$

where α_T, $r_{0\,(20)}$ is the temperature coefficient of conductor resistance and its unit resistance at $T_{con} = 20°C$.

The algorithm for calculating T_{con} suggests analytically solving the algebraically transformed "traditional" nonlinear quadratic equation of the conductor heat balance, which is recommended by the regulatory documents [9].

The algorithm for calculating T_{con} suggests analytically solving the algebraically transformed "traditional" nonlinear quadratic equation of the conductor heat balance, which is recommended by the regulatory documents [9]:

$$I_{ij} = \sqrt{\frac{[(W_l + W_{k,1,2,3}) \cdot (T_{con} - T_в)] - Q_r}{r_{0\,(T_{con})}}} \quad (2)$$

where I_{ij} is the phase current of branch ij, A; $T_в$ is the air temperature, $°C$;

$W_l = 7.24 \cdot \beta \cdot d_{con} \cdot \left[\frac{(T_{con} - T_в)/2 + 273}{1000} \right]^3$ is the radiation heat transfer coefficient, $W/(m \cdot °C)$;

$W_{k,1} = 0.16 \cdot d_{con}^{0.75} \cdot (T_{con} - T_в)^{0.3}$,

$W_{k,2} = 1.1 \cdot \sqrt{v \cdot d_{con}}$, $W_{k,3} = 0.55 \cdot \sqrt{v \cdot d_{con}}$

is the convective heat transfer coefficient at a wind speed of $v < 1.2$ m/s, $v \geq 1.2$ m/s and the wind direction perpendicular to the conductor, at $v \geq 1.2$ m/s and the wind direction along the conductor, respectively, $W/(m \cdot °C)$ $Q_r = 100 \cdot \varepsilon_П \cdot q \cdot d_{con}$ is the solar radiation power, $W/(m \cdot °C)$; d_{con} is the conductor diameter, cm; $\varepsilon_П$ is the absorption coefficient equal to the radiation coefficient $\varepsilon_П = \beta = 0.6$; q is the mean monthly total (direct plus reflected) solar radiation power taken on the basis of the observed data of meteorological stations, W/cm^2, or, in the case of their absence, assigned equal to $q = [0;0,07]\ W/cm^2$ in the winter and summer periods.

As a result of algebraic transformations and replacement of the variables in expression (2): $I_{ij} = U_{ij} / (\sqrt{3} \cdot Z_{ij})$, where Z_{ij}, U_{ij} is the impedance and the voltage drop magnitude in a conductor that is equal to the magnitude of difference in the vectors of nodal voltages $\left| \overline{U}_i - \overline{U}_j \right|$, Ohm, V, respectively; the initial quadratic equation (2) of form $I_{ij}(T_{con}) = f(T_{con}, T_в, Q_r, v)$

is transformed into the sextic equation of form $\Delta T = T_{con} - T_в = f(U_{ij}, T_в, Q_r, v, P_в)$, which shows the dependence of difference in conductor and air temperatures on the conductor voltage drop and actual environment parameters.

It is worth noting that the environment parameters additionally include the actual value of atmospheric pressure that differs from its standard value equal to $P_в$*=760 mm Hg*, traditionally applied in the regulatory documents [9]

The current atmospheric pressure value can be taken into account by the mathematical transformation of the criterion equations of convective heat exchange, which are the basis for determining the convective heat transfer coefficient in the conductor heat balance equation [27,29,35,36], given their actual value of $P_в \neq const$

In the expanded form, the transformed heat balance equation is the transcendent and algebraic equations (3), (4) for a wind speed $v < 1.2$ *m/s* and $v \geq 1.2$ *m/s* with its direction perpendicular to the conductor:

$$\Delta T^6 + a_5 \cdot \Delta T^5 + a_4 \cdot \Delta T^4 + a_{33} \cdot \Delta T^{3,3} + a_3 \cdot \Delta T^3 + a_{23} \cdot \Delta T^{2,3} + a_2 \cdot \Delta T^2 + a_{13} \cdot \Delta T^{1,3} + a_1 \cdot \Delta T + a_0 = 0, \quad (3)$$

where

$$a_{33} = m\ a_3 = 3b \cdot x_{np}^2 / f + b^3 + 6b^2 c + 3bc^2$$

$$a_{23} = 2mc\,;\ a_2 = p + 3b^3 c + 3b^2 \cdot x_{np}^2 / f + 3b^2 c^2\,;$$

$$a_{13} = m \cdot x_{np}^2 / f + mc^2$$

$$a_1 = b^3 \cdot x_{np}^2 / f + 2cp + b^3 c^2 - n \cdot U_{ij}^2 / f\,;$$

$$m = \frac{0,39 \cdot P_в^{0,5} \cdot d_{np}^{0,75} \Big/ T_в^{0,75}}{a}$$

$$\Delta T^6 + a_5 \cdot \Delta T^5 + a_4 \cdot \Delta T^4 + a_3 \cdot \Delta T^3 + a_2 \cdot \Delta T^2 + a_1 \cdot \Delta T + a_0, \quad (4)$$

where

$$a_3 = g_1 + 3b \cdot x_{np}^2 / f + 6b^2 c + 3bc^2\,;$$

$$a_2 = 3b^2 \cdot x_{np}^2 / f + p + 2cg_1 + 3b^2 c^2\,;$$

$$a_1 = g_1 \cdot x_{np}^2 / f + 2cp + g_1 c^2 - n \cdot U_{ij}^2 / f.$$

The other coefficients in (3), (4) are the same and determined as follows:

$$a_5 = 3b + 2c\,;\ a_4 = x_{np}^2 / f + 3b^2 + 6cb + c^2\,;$$

$$a_0 = p \cdot x_{np}^2 / f + pc^2 - nc \cdot U_{ij}^2 / f\,;$$

$$a = 0,543 \cdot 10^{-9} \cdot d_{np}\,;\ b = 2 \cdot T_в + 546\,;$$

$$c = 1/\alpha_T - 20 + T_в\,;\ f = (l_{ij} \cdot r_{0(20)} \cdot \alpha_T)^2\,;$$

$$p = -\frac{60 \cdot q \cdot d_{np}}{a}\,;\ n = \frac{r_{0(20)} \cdot \alpha_T}{3a}\,;$$ x_{np} is the inductive impedance of a conductor, *Ohm/m*

At a wind speed of $v > 1.2$ *m/s* with its direction along the conductor, the coefficient g_1 in (4) is replaced with g_2, where $g_1 = b^3 + \frac{0.661 \cdot \sqrt{P_в / T_в} \cdot \sqrt{v \cdot d_{con}}}{a}$,

$$g_2 = b^3 + \frac{0.33 \cdot \sqrt{P_в / T_в} \cdot \sqrt{v \cdot d_{con}}}{a}.$$

Expressions (3), (4) are the higher-order equations and solved by the Newton method with the low required accuracy equal to $\xi_{\Delta T} = 10^{-9}$ given in advance.

The experimental MAPLE-program was used to investigate the structure and properties of the coefficients, roots and first derivative of the equations for a number of conductors of various brands.

The performed studies have showed that the transcendent equation (3) has five roots at any combinations of its parameters U_{ij}, $T_в$, Q_r, v, $P_в$, , the algebraic equation (4) has six roots. At all the combinations of the parameters, both equations have the only positive real root that has a physical meaning and is accepted as the solution. The results of the studies are presented in Paragraph III.1.

2. Determination of the conductor sag and length in the span of an overhead line

For the first time, the algorithm for determination of mechanical parameters of overhead line conductors (the sag and length of conductors in the span) involves solving the conductor state equation analytically as distinct from other known algorithms suggesting solving it numerically:

$$\sigma_n - \frac{E \cdot \gamma_n^2 \cdot l^3}{24 \cdot \sigma_n^2 \cdot l_{np}} = \sigma_m \frac{E \cdot \gamma_m^2 \cdot l^3}{24 \cdot \sigma_m^2 \cdot l_{np}} - \alpha \cdot E \cdot (T_{np,n} - T_{np,m}), \quad (5)$$

where α, E are the temperature coefficient of the linear expansion of conductor material, degrees^{-1} and modulus the conductor elasticity, Pa, whose values are taken in accordance with the data of reference books; $l \neq l_{con}$, where l, l_{con} are the span length and the conductor length in the span, m.

The parameters with the subscript "*m*" in expression (5) correspond to the known initial climatic conditions, according to which the conductor is affected by the highest permissible tension $\sigma_m = \sigma_{perm}$. The conductor temperature is taken equal to the lowest air temperature of $T_{con,m} = T_{в,m} = -40°C$, there are no wind and icy spots. The conductor is affected by its own weight of $\gamma_m = \gamma_1$. The values of σ_{perm}, γ_1 are taken in accordance with the data of the regulatory documents.

The parameters with the subscript *"n"* correspond to the design climatic conditions, under which there are no icy spots, $v \le 1.2\,m/s$, $\gamma_n = \gamma_1$. The conductor temperature is not equal to the air temperature $T_{con,m}$ = $T_{в,m}$ and is determined by solving the conductor heat balance equation during power flow calculation.

Equation (5) is cubic with respect to σ_n and solved by Cardano's formulas, whose application makes it possible to obtain an accurate solution by meaпs of simple arithmetic operations: add, subtract, multiply, divide.

The structure and properties of equation (5) were studied by the example of a number of conductors of various brands using the experimental MAPLE-program. As a result of the studies, the equation for any combinations of its parameters proved to have a positive discriminant and three roots. In this case, in accordance with [57], among the roots of the equation there is one real root that has a physical meaning, which is taken as the solution.

After equation (5) is solved and σ_n is determined, the conductor sag and its length in the span are determined from expressions (6):

$$f_n = \frac{\gamma_n \cdot l^2}{8 \cdot \sigma_n}, \; l_{np} = l + \frac{\gamma_n^2 \cdot l}{24 \cdot \sigma_n^2}. \qquad (6)$$

The experimental program was also applied to study the influence of the actual temperature of overhead conductors, which was taken into account in the state equation, on the conductor sag and its length in the span.

The findings indicate that adjustment of the sag, in comparison with the situation, when the conductor temperature in the equation was taken equal to the air temperature, is sizable and can exceed 30%. Adjustment of the conductor length in the span does not exceed 1% and can be neglected. The results of the studies are described in Paragraph III.2.

3. An algorithm for calculating the normal steady state of an electrical network

The conductor heat balance equation (2) included in the "traditional" algorithm for calculating the normal steady state of an electrical network as one of the additional points improves the accuracy of determining electrical parameters of overhead line conductors: their temperature and resistance, and hence, the steady state parameters of an electrical network.

To do this, in the proposed calculation algorithm, the Jacobian matrix elements should be adjusted by inclusion of additional components, which are a derivative of the implicit function of the conductor resistance with respect to the steady state parameters (nodal voltage magnitudes and phases):

$$\frac{\partial r_s}{\partial U_s} = -\left(\frac{\partial Wr_s}{\partial r_s}\right)^{-1} \cdot \frac{\partial Wr_s}{\partial U_s}, \qquad (7)$$

where *s* is the branch containing an overhead line conductor. Expression (7) is a derivative of the conductor heat balance equation with respect to the steady state parameters.

The proposed improved algorithm for calculating the normal steady state of an electrical network differs from its "traditional" version in two new additional blocks: determination of the temperature and resistance of overhead line conductors by analytically solving the conductor heat balance equation (2) and calculation of the derivative of the conductor resistance with respect to the steady state parameters (7).

4. An algorithm for calculating the feasible steady state of an electrical network

The conductor state equation (5) included in the "traditional" algorithm for calculating the feasible steady state of an electrical network increases the accuracy of determining the mechanical parameters of overhead conductors: the conductor sag and its length in the span, as well as the feasible steady state parameters of an electrical network.

To determine the feasible steady state, the proposed algorithm must take into account the conductor sag as an additional inequality constraint imposed on the steady state parameters U_s:

$$f_{s,min} \le f_s \le f_{s,max}, \qquad (8)$$

where $f_{s,min}$, $f_{s,max}$ are the minimum and maximum sag values.

For the functional relation $f_s(U_s)$, it is also necessary to determine the derivative of the complex function of equation (5) at each iteration of feasible steady state calculation:

$$\frac{\partial f_s}{\partial U_s} = \frac{\partial f_s}{\partial T_{con,n}} \cdot \frac{\partial T_{con,n}}{\partial U_s}, \qquad (9)$$

where the first multiplier is the derivative of the explicit function $\sigma_n(T_{con,n})$ of expression (5), the second multiplier is the derivative of the explicit function $r_{0(T_{con,n})}(U_s)$ of the equation of the conductor heat balance (2) that is determined in the calculation of the normal steady state.

The developed algorithm for calculating the feasible steady state differs from its "traditional" version in three additional blocks: calculation of the normal steady state of electrical networks in accordance with the algorithm described in paragraphs *1-3*, determination of the mechanical parameters of overhead conductors by solving the conductor state equation (5) and inclusion of the complex function derivative of the conductor sag with respect to the steady state parameters (9).

III. Testing the approaches and algorithms

1. A numerical study on the properties of the conductor heat balance equation

The properties of the conductor heat balance equation were studied for some conductor brands.

Table 1 presents the values of the equation

Table 1. Roots of the heat balance equation for the AC-120/27 conductor at $I_{con,\ perrm}$ =375A.

v, m/s	U_{ij}, V	Values of equation roots ΔT, °C	$T_{con} = T_в + \Delta T$, °C
≤ 1.2	709.11	**46.59**; – 123.41 ± j1232.6; – 277.51 ± j443.94	66.59
= 5	684.25	**11.53**; – 2161.16; – 243.25 ± j443.64; 189.07 ± j1367,55	31.53

roots that were calculated for the *AC-120/27* conductor at the following environment parameters: $T_в = 20°C$, $Q_r = 0$, $v \le 1.2$ *m/s* and $v = 5$ *m/s* with the wind direction perpendicular to the conductor. In the calculations, the conductor length was taken equal to $l_{ij} = 2000\ m$, the current load corresponded to the maximum permissible value of $I_{con,\ perm} = 375\ A$ the table presents the values of the conductor linear voltage that correspond to $I_{con,\ perm}$ at $v \le 1.2$ *m/s* and $v = 5$ *m/s*. The equation roots selected as a solution are given in bold type.

Similar calculations performed for some other conductors of various brands at different combinations of currents (voltage drop) in the conductors and environment parameters have showed that the number and structure of the equation roots, as well as the nature of the relations themselves are preserved at any combinations of the parameters studied. In this case, the equations have a real solution at the conductor overcurrent equal to .

2. Impact of the actual temperature of conductors on their mechanical parameters

The impact of the actual temperature of overhead line conductors, which is taken into consideration in the conductor state equation ($T_{con,n} \ne T_в$), on the values of the calculated mechanical parameters: f and l_{np} in comparison with the "traditional" situation when $T_{con} = T_в$ is shown in table 2 by the example of the *AC-150/19* conductor.

Table 2. Mechanical parameters of the *AC-150/19* conductor versus its temperature.

$\Delta T = T_{con,n,i} - T_в$, °C	$\Delta f = f_{T_{np,n,i}} - f_{T_в}$, cm	$\Delta l = l_{T_{np,n,i}} - l_{T_в}$, cm
10	16	0.62
20	35	1.39
30	56	2.34
40	80	3.51
50	108	6.97

Table 3. Values of the conductor temperature and overheating, relative total active power losses.

Conditions	Heavily loaded	Lightly loaded	D of OLP, $Q_r = 0$	D of OLP, $Q_r \ne 0$
1	2	3	4	5
T_{con}, °C	62.9-95.5	40-62.9	-	-
ΔT, °C	41.9-75.5	10-37.9	-	-
$\delta\Delta\pi$, %	10.1-35.3	0.2-3	1.48-3.71	2.76-6.78

The calculations were performed on the assumption of no-wind conditions and absence of icy spots: $v < 1.2$ *m/s*, $\gamma_n = \gamma_1$, at an air temperature of $T_в = 20°C$ and a span length of $l = 300\ m$. The conductor temperature, which was preliminarily determined by solving the heat balance equation, changed in a range of $T_{con,n,i} = (30, 40, 50, 60, 70)°C$.

The Table presents the improved mechanical parameters Δf, Δl of the conductor as a result of the adjustment of its temperature from $Tcon,n = T_в = 20°C$ to $T_{con,n} = T_{con,n,i}$.

The data of the Table show that at the maximum overheating of the *AC-150/19* conductor above the air temperature from $T_{con,n,i} = T_в = 20°C$ to the value that is maximum permissible in terms of heating $T_{con,n,i} = 70°C$, the conductor sag improvement reaches Δf = 108 *cm* = 34.5%.

The adjustment of the conductor length in the span is negligible and is equal to Δl = 7 *cm* = 0.02%.

3. Testing of the algorithm for calculating the normal steady state of an electrical network

The improved algorithm for calculating the normal steady state of an electrical network, which takes into consideration the analytically solvable equation of the conductor heat balance, was tested on 10 real electrical networks of various dimensions in the Irkutsk Region. For testing, the results of two options of calculations were compared for each considered scheme: at a constant conductor temperature equal to the air temperature and the conductor temperature obtained by solving the heat balance equation. The calculation schemes had different current loads of overhead lines, which made it possible to divide them into two groups - heavily loaded and lightly loaded. The values of the conductor temperature for the two calculation options and the total active power losses were compared for each scheme in the first or second group.

The values of the conductor temperature and the total active power losses were compared for the air temperature ranging from *-20°C* to *+40°C*. The results of numerous calculations are compiled in Table 3, with indication of the conductor overheating values ΔT calculated as a difference in the conductor and air temperatures, the values of relative total active power losses $\delta\Delta\pi = \frac{\pi_2 - \pi_1}{\pi_1} 100$ %, where π_1, π_2 are the total active power losses in the first and second options, as well as the impact of distribution of overhead line parameters

(D of OLP) by length on the total active power losses.

The table shows that the improvement (correction) of the total active power losses owing to the consideration of the conductor temperature varies in a wide range of the values and depends on the environment parameters and the current load of conductors.

The total power losses are improved most effectively in the case of the overcurrent of conductors, whose temperature is T_{con} = (62,9 - 95,5)°C, and the overheating ΔT above the air temperature is within a range of ΔT = (41,9 - 75,5)°C. In this case, the improvement in the total active power losses is 10.1-35.3%.

The temperature of lightly loaded conductors does not exceed $T_{con} = 62,9°C$, and the improvement in losses is 3%.

The impact of the distribution of electrical parameters of overhead lines (D of OLP) and the distribution of the conductor temperature by length of overhead lines on power losses was assessed by dividing the overhead lines up to 300 km long into shorter sections (columns 4,5 of Table 3).

The impact of the division of the overhead line supplying one load was studied with and without regard to solar radiation .

The losses were calculated for the overhead line divided into 2, 4, 8, 16 identical sections, each of which was modeled by the U-shaped equivalent circuit. The obtained total losses were compared with the losses calculated without division.

As follows from the table 3, the line division into sections decreases the total power losses. For 16 sections, the reduction was 6.78% with regard to solar radiation, and 3.71% without regard to solar radiation ($Qr = 0, Qr \neq 0$).

The analysis of the presented findings shows that consideration of the actual temperature of overhead conductors makes it possible to significantly improve the calculation results of network steady states.

The analysis of the proposed improved algorithms has showed their performance. Users of the algorithms should only add data on the environment parameters and the overhead conductor parameters that are included in the heat balance and conductor state equations.

IV. Conclusion

The conducted studies made it possible to solve an important scientific and technical problem of increasing the accuracy of modeling steady states of an electrical network and modeling an overhead line, which is one of its main elements. The problem was solved by the improved algorithms for calculating steady states, which involved the determination of electrical and mechanical parameters of overhead line conductors, such as conductor temperature, resistance, and sag in the span. The electrical and mechanical parameters were determined by the improved algorithms for solving the heat balance and conductor state equations.

The performance of the proposed approaches was verified by their testing via the experimental programs and the SDO-7 program. The numerical results of testing confirm the efficiency of the developed algorithms.

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