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POWER SYSTEM STEADY STATE WITH CONSIDERING THE TRANSMISSION LINE THERMAL BALANCE EQUATIONS

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Abstract- In known power flow calculations of the electrical network, the dependences of the active resistances of the power transmission line wire taken into on the ambient temperature and loading currents are not accounting. To decrease the error of steady-state calculations, a temperature correction of the resistance is necessary. Method based on the joint solution of nonlinear equations of the steady-state electric network mode and the thermal balance of the wires of overhead lines proposed in this paper. The numerical example shows that temperature has effect on the power flows and losses of power system. Steady-state regime simulation results on various test circuits shows that the non-account of the temperature dependence of the active resistances can lead to errors in power loss for individual loaded lines up to 10%. For total system losses error reached to 30%. Power flow simulation results are shown for the 6-bus circuits.

Keywords: Electric Network, Overhead Line, Steady State, Thermal Balance Equations, Weather Conditions, Active Resistance, Wire Temperature, Nonlinear Equations.

I. INTRODUCTION

It is known that steady state is the most important mode of operation of a power system. Power flow studies are necessary for power system planning, operation, control.

Power flow data are used for contingency analysis, security assessment, optimal dispatching and stability. Power system steady state equations are presented below:

$$\Delta P_i = U_i \sum_{j=1}^{n} U_j \left(g_{ij} \cos\left(\delta_i - \delta_j\right) - b_{ij} \sin\left(\delta_i - \delta_j\right)\right) \quad (1)$$

$$\Delta Q_i = U_i \sum_{j=1}^{n} U_j \left(g_{ij} \sin\left(\delta_i - \delta_j\right) - b_{ij} \cos\left(\delta_i - \delta_j\right)\right) \quad (2)$$

where, U_i, δ_i and U_j, δ_j are nodal voltage magnitudes and angles, whereas $y_{ij}=g_{ij}+b_{ij}$ is the bus admittances.

In connection with the increase in the load, the maximum using of the overhead line (OL) capacity can be achieved by using of reliable information on the line status, as well as actual data on the temperature of the wires and the density of the current across line.

To increase the accuracy of calculating power losses in overhead transmission lines, it is necessary to evaluate the active resistances of the wires taking into account the operating current flowing along the lines, meteorological data, such us ambient temperature, wind speed and solar radiation.

However, the known algorithms for calculating the steady-state mode of electrical networks and state estimation neglect temperature dependencies resistance of transformers, overhead lines, and cables and fixed in the corresponding programs. In this regard, the results of power flow have some error.

The simulation of s usually assumes a constant wire resistance at an initial temperature of 20 °C. However, the actual temperature of the overhead line usually reaches 90-120 °C or more.

Thus, it becomes important to analyze the effect of temperature rise during operation of the transmission line on electrical quantities such as losses and power flows.

In [1-6] a model of OL based on the heat balance equation was proposed. It is assumed here that the heat loss due to radiation and convection can be approximated as a linear function of the ambient temperature.

It was shown in [8-10] that neglecting the correction of the branch resistance as a function of temperature can lead to significant errors in losses under heavily loaded modes up to 10% for the general scheme, and for individual branches up to 30%.

In [7, 8, 11, 13] the temperature dependence of the power flow is considered. There several algorithms of temperature-dependent steady-state has been considered:
- the full Newton-Raphson method;
-partially decoupled method. In this method temperature is updated separately from traditional variables;
- fast decoupled method;
- sequentially decoupled method.

An electro-thermal overhead line model in for steady-state and time-depending simulations has been presented in [8].

The model fully incorporates the thermal behavior of overhead line according to IEEE Std.738 [6]. Presented model enables the simulation of thermal and electrical processes in a combined simulation.

A novel method for measuring temperature along transmission lines based on phasor measurements and weather data has been proposed in paper [9]. In the traditional calculations of variable power losses, active resistances are taken from the directories in which they are given at a temperature of 20 °C.

The aim of the article is to develop an algorithm and estimate the influence of the load current, wire temperature, wind speed, solar radiation on the active resistance of wires, and also to determine the errors in calculating annual variable energy losses.

In this model temperatures and resistances of branches are linked with the steady-state equations. The specific resistance of the overhead lines wires is as Equation (3).

$$R = R_{20}\left[1+\alpha\left(t_w-20\right)\right] \tag{3}$$

where, R_{20} is the specific resistance at wire temperature of 20 °C in Ohm/km; α = 0.00403 is the temperature coefficient of electrical resistance of steel-aluminum wires in 1/deg; and t_w is the wire temperature in °C.

II. HEAT BALANCE EQUATION

The heat balance equation for the steady-state thermal regime of a high-voltage line can be represented as follows [7]:

$$I^2R_{20}\left[1+\alpha\left(t_w-20\right)\right]+P_s=\pi d_{np}\left(k_c+k_r\right)\left(t_w-t_a\right) \tag{4}$$

where, I is the current of line in A; R_{20} is resistance of the wire at 20 °C in Ohm/km; α is temperature coefficient of wire resistance; t_w is wire temperature; t_a is ambient temperature; k_c, k_r are the convective and radiation heat emitted from the conductor; P_s is the power of solar radiation, absorbed by 1 m of wire per unit time; and d_w is the diameter of the wire.

In Equation (4), the left side represents the absorbed heat of solar radiation and heat from the loading current, and the right side consists of the sum of convective and radiation losses.

Radiation heat emitted from the wirer given by expression:

$$k_r=\frac{5.67\varepsilon}{t_w-t_a}\left[\left(\frac{273+t_w}{100}\right)^4-\left(\frac{273+t_a}{100}\right)^4\right] \tag{5}$$

where, ε is emissivity coefficient of the conductor.

According to IEEE Standard 738-2006 heat loss-convection for wind speed lower than 0.6096 are equal to

$$q_c=\left[1.01+0.037\left(\frac{D\rho_f v_{wind}}{\mu_f}\right)^{0.52}\right]k_f K(T_c-T_a) \tag{6}$$

where, K is wind attack angle; μ_f is air viscosity; ρ_f is air density and v_{wind} is wind speed.

III. THERMAL RESISTANCE MODEL

According to [7] conductor's resistance dependent from temperature as shown below:

$$R_t=R_{20}\left(\frac{t_w+T_F}{20+T_F}\right) \tag{7}$$

where, R_{20} is conductor resistance at the reference temperature, and T_F is temperature constant.

In addition to Equation (7), it is also necessary equations for relate the temperature with the steady-state variables.

IV. CONDUCTOR TEMPERATURE

It is obvious that wire temperature can be expressed as:

$$t_w=t_a+\frac{\Delta P_{loss}}{\Delta P_{Rloss}}\left(t_w-t_a\right) \tag{8}$$

where, ΔP_{Loss} is total power loss within the resistance, and ΔP_{RLoss} is corresponding reference power loss.

If total power loss can be expressed as a function of the voltage and temperature, then presented above equation can be directly included in a steady-state algorithm.

V. POWER FLOW AND THERMAL BALANCE EQUATIONS

Temperature-dependent steady-state equations may be written in form presented below [7]:

$$\Delta P_i=U_i\sum_{j=1}^{n}U_j\left(g_{ij}(t)\cos\left(\delta_i-\delta_j\right)-b_{ij}(t)\sin\left(\delta_i-\delta_j\right)\right) \tag{9}$$

$$\Delta Q_i=U_i\sum_{j=1}^{n}U_j\left(g_{ij}(t)\sin\left(\delta_i-\delta_j\right)-b_{ij}(t)\cos\left(\delta_i-\delta_j\right)\right) \tag{10}$$

$$\begin{aligned}\Delta H_{ij}&=t_{ij}-\left(t_a+R_{\theta,ij}g_{ij}(t)\left(U_i^2+U_j^2\right)\right)-\\&-2g_{ij}(t)U_iU_j\cos\left(\delta_i-\delta_j\right)\end{aligned} \tag{11}$$

The Equations (9)-(11) differ from the traditional ones in that G_{ij} and B_{ij} are a function of temperature.

When the temperature is added to the state vector, the Jacobi matrix can be represented as:

$$J\left(\delta,U,t\right)=\begin{bmatrix}\frac{\partial P}{\partial\delta} & \frac{\partial P}{\partial U} & \frac{\partial P}{\partial t}\\ \frac{\partial Q}{\partial\delta} & \frac{\partial Q}{\partial U} & \frac{\partial Q}{\partial t}\\ \frac{\partial H}{\partial\delta} & \frac{\partial H}{\partial U} & \frac{\partial H}{\partial t}\end{bmatrix} \tag{12}$$

State variables can be updated at ith iteration according to equation presented below:

$$\begin{bmatrix}\delta^{(i+1)}\\U^{(i+1)}\\t^{(i+1)}\end{bmatrix}=\begin{bmatrix}\delta^{(i)}\\U^{(i)}\\t^{(i)}\end{bmatrix}+J\left(\delta^{(i)},U^{(i)},t^{(i)}\right)^{-1}\cdot\begin{bmatrix}\Delta P^{(i)}\\\Delta Q^{(i)}\\\Delta H^{(i)}\end{bmatrix} \tag{13}$$

The nodal voltage and heat balance equations are solved as a coupled system by the Newton-Raphson method.

VI. SIMULATION

The MATLAB program for calculating steady-state taking into account the temperature dependence of the active resistance was developed.

The algorithm of temperature-dependent steady-state system is shown in Figure 1. The solution procedure performs the following steps:

1. The resistance of the branches is specified in accordance with the latest temperature of the wires;
2. The matrix of nodal conductivities are calculated
3. The Jacobi matrix is calculated;
4. Unbalances are calculated according to (9)-(11);
5. The state variables are recalculated in accordance with (13).

The cycle is repeated until the desired accuracy.

In a partially separated method for solving stationary equations, the nodal voltage equations are solved separately from the thermal equations:

$$\begin{bmatrix} \delta^{(i+1)} \\ U^{(i+1)} \end{bmatrix} = \begin{bmatrix} \delta^{(i)} \\ U^{(i)} \end{bmatrix} + J_{PQ}^{-1} \cdot \begin{bmatrix} \Delta P^{(i)} \\ \Delta Q^{(i)} \end{bmatrix} \quad (14)$$

$$\left[t^{(i+1)} \right] = \left[t^{(i)} \right] + J_H^{-1} \cdot \left[\Delta H^{(i)} \right] \quad (15)$$

Then, the state vector is updated in accordance with:

$$\left[\delta^{(i+1)} \right] = \left[\delta^{(i)} \right] + J_P^{-1} \cdot \left[\Delta P^{(i)} \right] \quad (16)$$

$$\left[U^{(i+1)} \right] = \left[U^{(i)} \right] + J_Q^{-1} \cdot \left[\Delta Q^{(i)} \right] \quad (17)$$

$$\left[t^{(i+1)} \right] = \left[t^{(i)} \right] + J_H^{-1} \cdot \left[\Delta H^{(i)} \right] \quad (18)$$

The 6-node test circuit in Table 1 is used for simulation in Figures 1 and 2.

All branches of test circuit were modeled using a common thermal model according to (7). The ambient temperature is assumed to be 25 °C.

As shown from the Table 2 and Figure 3, the maximum increase in power losses for the branches of the IEEE test circuit was 0.94÷9%.

The nominal load loss was obtained at a voltage of 1.0 pu. The loads of the 6-node IEEE test circuits are given in Table 1.

Results of steady-state calculating for the circuit in Figure 2 are given in Figure 3. Screen forms of the wire temperature simulation program are shown in Figure 3 also.

The results of steady-state for the test circuit taking into account the temperature dependence of the active resistance are presented in Table 2. Power losses in different branches are presented in Figure 3.

Separated algorithms can be included in existing steady-states programs since temperature calculations can be considered as an independent module.

Table 1. Loads of the 6-node IEEE test circuit

Node	P_{gen}	Q_{gen}	P_{load}	Q_{load}
1	1.0569	0.1715	0	0
2	0.5	0.74	0	0
3	0.6	0.8812	0	0
4	0	0	0.75	0.7
5	0	0	0.68	0.7
6	0	0	0.65	0.7

Table 2. The results of steady-state

Branches	t_c	Load flow results	
		Temperature dependent, MW	Change, %
1-2	37.75	7.99	7.99
1-4	40.1	6.42	6.42
1-5	44.2	8.78	8.78
2-3	26.01	1.00	1.00
2-4	47.02	8.23	8.23
2-5	37.82	5.91	5.91
2-6	27.06	0.94	0.94
3-5	29.33	3.10	3.10
3-6	43.3	7.69	7.69
4-5	25.57	6.18	6.18
5-6	25.69	6.49	6.49

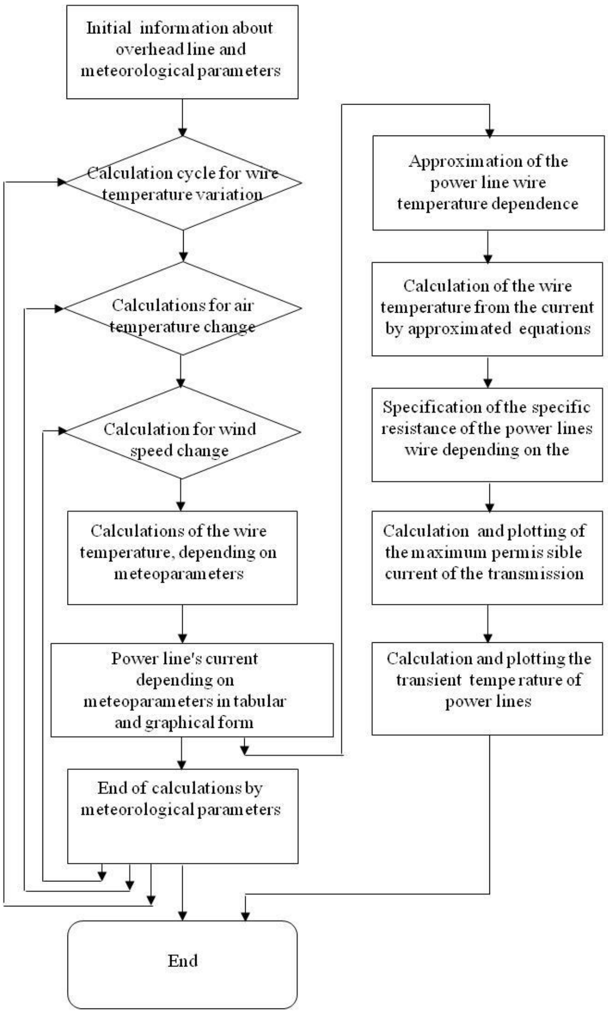


Figure 1. Flowchart of the developed software

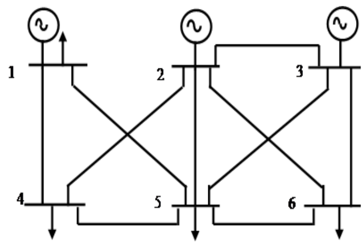
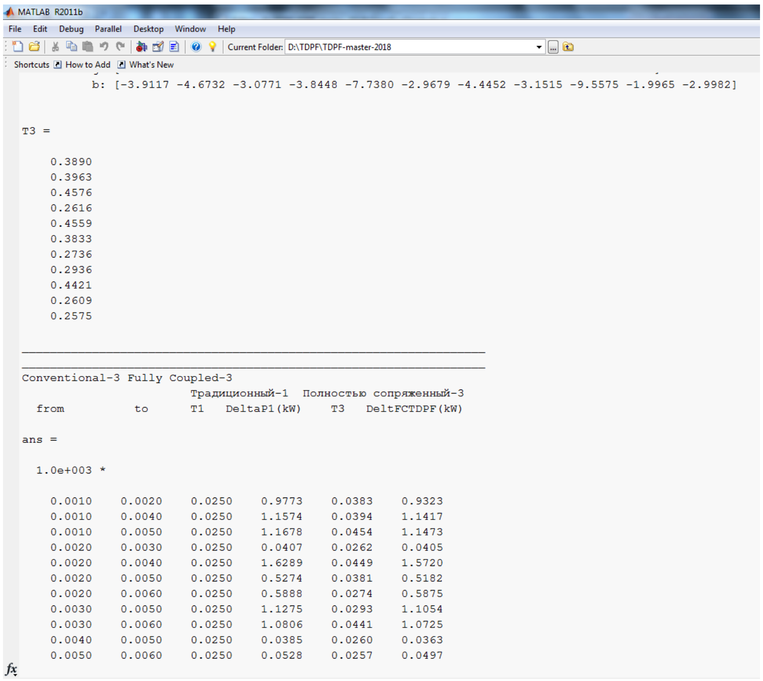


Figure 2. The 6-bus test circuit



```
MATLAB R2011b
File Edit Debug Parallel Desktop Window Help
Current Folder: D:\TDPF\TDPF-master-2018
Shortcuts  How to Add  What's New
        b: [-3.9117 -4.6732 -3.0771 -3.8448 -7.7380 -2.9679 -4.4452 -3.1515 -9.5575 -1.9965 -2.9982]

T3 =

    0.3890
    0.3963
    0.4576
    0.2616
    0.4559
    0.3833
    0.2736
    0.2936
    0.4421
    0.2609
    0.2575

_______________________________________________________________
_______________________________________________________________
Conventional-3 Fully Coupled-3
                        Традиционный-1  Полностью сопряженный-3
  from         to       T1    DeltaP1(kW)     T3    DeltFCTDPF(kW)

ans =

  1.0e+003 *

    0.0010    0.0020    0.0250    0.9773    0.0383    0.9323
    0.0010    0.0040    0.0250    1.1574    0.0394    1.1417
    0.0010    0.0050    0.0250    1.1678    0.0454    1.1473
    0.0020    0.0030    0.0250    0.0407    0.0262    0.0405
    0.0020    0.0040    0.0250    1.6289    0.0449    1.5720
    0.0020    0.0050    0.0250    0.5274    0.0381    0.5182
    0.0020    0.0060    0.0250    0.5888    0.0274    0.5875
    0.0030    0.0050    0.0250    1.1275    0.0293    1.1054
    0.0030    0.0060    0.0250    1.0806    0.0441    1.0725
    0.0040    0.0050    0.0250    0.0385    0.0260    0.0363
    0.0050    0.0060    0.0250    0.0528    0.0257    0.0497
fx
```

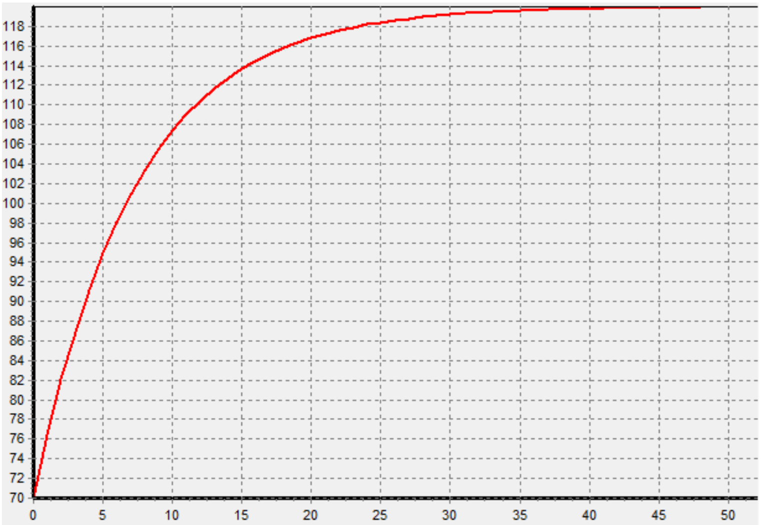


Figure 3. Results of steady-state calculating

VII. DISCUSSION AND CONCLUSION

The method based on the joint solution of nonlinear equations of the steady-state electric network mode and the thermal balance of the wires of overhead lines have been developed in this paper. The developed method realized as MATLAB based software. The results of the calculations of the steady-state regime on various test schemes shows that the non-considering of the temperature dependence of the active resistances can lead to errors in power flows and losses. The results of simulation of steady-state are presented for the example of 6-bus schemes.

REFERENCES

[1] V.V. Burgsdorf, L.G. Nikitina, "Determination of Permissible Current of Load of Overhead Power Lines by Current of their Wires", Electricity, No. 11, pp. 1-8, 1989 [Russian].

[2] "Guide for Thermal Rating Calculations of Overhead Lines", WG B2.43, Tech. Rep. 601, CIGRE, p. 95, 2014.

[3] E.P. Figurnov, Yu.I. Zharkov, T.E. Petrova, "Refined Methodology for Calculating the Heating of Wires of Overhead Transmission Lines", Electric Stations, No. 9, pp. 54-59, 2013 [Russian].

[4] J.R. Santos, A.G. Exposito, F.P. Sanchez, "Assessment of Conductor Thermal Models for Grid Studies", IET Generation Transmission & Distribution, Vol. 1, No. 1, pp. 155-161, January 2007.

[5] I.I. Levchenko, E.I. Satsuk, "Load Capacity of Overhead Transmission Lines in Extreme Weather Conditions", Electricity, No. 4, pp. 2-8, 2008 [Russian].

[6] "IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors", IEEE Standard 738, 2006.

[7] S. Frank, J. Sexauer, S. Mohagheghi, "Temperature Dependent Power Flow Source Code", https://github.com/ TDPF/TDPF, 2013.
[8] A. Kubis, C. Rehtanz, "Application of a Combined Electro-Thermal Overhead Line Model in Power Flow and Time-Domain Power System Simulations", IET Generation, Transmission & Distribution, Vol. 11, Issue 8, pp. 1-18, April 2017.
[9] A. Kubis, C. Rehtanz, "Synchrophasor Based Thermal Overhead Line Monitoring Considering Line Spans and Thermal Transients", Vol. 10, Issue 5, pp. 1232-1239, 7 April 2016.
[10] A.B. Balametov, M.P. Bayramov, "Modeling of Wire Temperature for Calculation of Electric Power Losses of Overhead Lines", Journal of Power Engineering Problems, No. 2, pp. 3-12, 2013 [Russian].
[11] A.B. Balametov, E.D. Halilov, M.P. Bayramov, K.A. Agahanova, "Program for Modeling of the Temperature of Wire and Power Losses Based on Consideration of the Regime and Atmospheric Factors", Software and Systems, Vol. 2, No. 31, 2018.
[12] A.B. Balametov, E.D. Halilov, M.P. Bayramov, "Modelling of Active Power Losses in Airlines Considering Regime and Atmospheric Factors", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 24, Vol. 7, No. 3, pp. 58-62, September 2015.
[13] A.B. Balametov, E.D. Halilov, "Power Flow and Thermal Balance Equations for Power System Simulation", 14th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE-2018), Nakhchivan State University, Nakhchivan, Azerbaijan, pp. 17-20, 15-17 October 2018.

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Ashraf B. Balametov was born in Qusar, Azerbaijan, on January 27, 1947. He received the M.Sc. degree in the field of Power Plants of Electrical Engineering from Azerbaijan Institute of Oil and Chemistry, Baku, Azerbaijan in 1971, and the Candidate of Technical Sciences (Ph.D.) degree from Energy Institute named G.M. Krgiganovskiy, Moscow, Russia and Doctor of Technical Sciences degree from Novosibirsk Technical University, Russia in 1994. He is a Professor in Azerbaijan Research Institute of Energetics and Energy Design, Baku, Azerbaijan. His research interests are steady state regimes, optimization, and power system control.

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