Specific aspects of forecasting electrical energy losses in electricity networks

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Abstract. The present paper considers methods of predicting load losses under varied types of electrical energy loss characteristics. The method of forecasting electrical energy losses with the use of one-factor (planned electrical supply to network) and multi-factor (planned values of electrical supply to network, energy output from electric power stations, etc.) characteristics of power and energy losses is proposed. Static models of nodal loads and parameters of equivalent network are used. The paper substantiates the application of multi-factor characteristics for assessing electrical energy losses during regulatory period. The paper provides the solution of the system of nonlinear equations describing long-term balance plans for electrical energy and gives the results of predicting load losses of electrical energy.

1. Introduction
When determining long-term levels of electricity supply to networks of electric power systems (EPS), it is necessary to predict the transmission of electricity to consumers and technological electricity losses (TEL). Mutually agreed forecasts of the values of electrical supply to networks of various nominal voltages, and corresponding TELs can be obtained by solving a system of nonlinear equations describing long-term energy balances [1]. TEL forecasts for both the whole network and individual steps of nominal voltage are performed according to the characteristics of electric energy losses [2, 3].

Characteristic of Electricity Losses (CEL) describes the interdependence of energy losses in electric networks of EPS as an explicit function where the predicted components of energy balances (factors) are the independent variables. When planning energy balances for a year or more, flows for particular interconnection lines are not even planned on the balance basis. Therefore, CEL for planning can express the dependence of losses on the balance value of the total energy exchange, or in other words the total supply to the networks of the system, and a number of other general indicators (for example, plans for the generation of electricity in power plants).

2. Materials and Methods
To this day, several methods have been proposed for calculating CEL [2, 4, 5]. Statistical CELs are presented in the form of a regression equation, the coefficients of which are calculated by the series of variant TEL calculations:

$$\Delta W_t = a_0 + a_1 W_{sn,t} + a_2 W_{sn,t}^2,$$

where $\Delta W_t$ is the TEL forecast for year $t$; $a_0, a_1, a_2$ – regression coefficients; $W_{sn,t}$ – forecast of electricity supply to the network of territorial electricity transmitters.
To calculate coefficients \( a_0, a_1, a_2 \) in (1), the series of analytical results is needed that includes the results of TEL calculations for several years under condition of unchanging structure of the electric network. A characteristic of the form (1) can be built to predict monthly electricity losses. In this case, \( W_{sn,t} \) should be forecasted for each month of the next year.

When forecasting TEL in [6], the results of calculations of the components of TEL during only one reference year are used: conditionally constant \( \Delta W_{cc \ Ref} \), load \( \Delta W_{L \ Ref} \) and conditioned by permissible inaccuracy in electricity metering \( \Delta W_{inac \ Ref} \) [7 - 10]. For the next year (regulation period), it is possible to use adjusted conditionally constant losses \( \Delta W_{cc \ R} \), taking into account changes in equipment content in year \( t \). In this case, CEL takes the form:

\[
\Delta W_t = b_0 + b_1 W_{sn,Reg} + b_2 W_{sn,Reg}^2,
\]

where \( b_0 = \Delta W_{cc \ Ref} \); \( b_1 = \frac{\Delta W_{inac \ Ref}}{W_{sn,Ref}} \); \( b_2 = \frac{\Delta W_{L \ Ref}}{W_{sn,Ref}^2} \).

In territorial electricity transmitters (regional and interregional), the share of reverse energy flows in electric network lines is not large. For such electric networks, factors \( W_{sn,Ref} \), \( W_{sn,Reg} \) in (2) and further are the supply of electricity to the network during reference year and regulatory year. In electric networks of the federal electricity transmitter (FET) and high level electricity transmitters (HLET), the modes of many intersystem power lines are reversible. When forecasting electricity losses in FET and HLET networks \( W_{sn,Ref} \), \( W_{sn,Reg} \) they represent the supply of electricity from the network during the corresponding period.

The method for forecasting load losses in CEL of the form (2) is considered below.

\[
\Delta W_{L \ Reg} = b_2 W_{sn,Reg}^2 = \frac{\Delta W_{L \ Ref}}{W_{sn,Ref}^2} W_{sn,Reg}^2.
\]

Expression (3) presents \( \Delta W_{L \ Ref}, W_{sn,Ref}, W_{sn,Reg} \) as the product of corresponding average values of power losses, power supply and duration of period \( T \). Then we obtain

\[
\Delta W_{L \ Reg} = \frac{\Delta P_{av \ Ref} T}{P_{av \ Ref}^2} P_{av \ Reg}^2 T^2 = \frac{\Delta P_{av \ Ref}}{P_{av \ Ref}^2} P_{av \ Reg}^2 T.
\]

Power supply during reference and regulation periods can be determined as follows

\[
P_{av \ Ref} = U_{nom} I_{e \ Ref} \cos \varphi_{Ref} \quad \text{and} \quad P_{av \ Reg} = U_{nom} I_{e \ Reg} \cos \varphi_{Reg}.
\]

where \( I_{e \ Ref} \), \( I_{e \ Reg} \) are average network load in the form of the current of the periods under consideration; \( \cos \varphi_{Ref} \), \( \cos \varphi_{Reg} \) - average values of power factors in the considered periods.

Hereinafter, the currents are \( \sqrt{3} \) times larger than the phase quantities.

Forecasting load losses (3) by the method described in [6] is a calculation performed with the use of some equivalent network resistance as a whole \( R_{e \ Ref} \).

\[
\Delta W_{L \ Reg} = \frac{\Delta P_{av \ Ref}}{I_{e \ Ref}^2} I_{e \ Ref}^2 T = R_{e \ Ref} I_{e \ Reg}^2 T.
\]
The quadratic dependence of the load losses of electric energy on the average load $I_{\text{Reg}}$ or on supply of electric energy to the network $W_{\text{sn Reg}}$ in (2) and on the equivalent network resistance $R_{\text{e Reg}}$ approximately describes this dependence.

The disadvantages peculiar to CEL of type (2) can be reduced by forming a characteristic that reflects the structure and technical parameters of the electric network, the modes of generation and consumption of electricity. The methodology for constructing such CEL (hereinafter referred to as CEL-R) should be considered.

For the design scheme of the network containing N nodes, load power $\pi$ losses are equal to [11]

$$\pi = J'_a R J_a + J'_p R J_p,$n

where $J_a$ is a column matrix (column) of size N, the elements of which are the real parts (active components) of nodal currents; $R$ is a square matrix of size $N \times N$, the elements of which are the real parts of the nodal resistances; $J_p$ is a column of size N, the elements of which are imaginary parts (reactive components) of nodal currents.

In (4) and subsequent formulas, the symbol “$'$” denotes transposed matrices, i.e. $J'_a$ or $J'_p$ are lines of size N.

In an electric network of 35 - 220 kV, voltage regulation on power transformers is performed by Electrical Connection Permit devices or no-load tap changers that perform longitudinal voltage regulation [12]. This ensures the change of only the real component of the transformation ratios of the transformers. The matrix $R$ of such a network is symmetric, i.e. $R = R'$. Methods for calculation of the matrix of nodal resistances that do not require inversion of the matrix of nodal conductivities of large dimension are considered in [11].

The active and reactive nodal currents are expressed in the form of functions of some factors $F_i$ (i = 1, 2 ... M):

$$\begin{cases} J_a = a_a + b_a F; \\ J_p = a_p + b_p F, \end{cases}$$

where $a_a$, $a_p$ are columns of size N containing coefficients of linear regression equations that do not depend on factors; $b_a$, $b_p$ are rectangular matrices of coefficients of linear regression equations of size $N \times M$; $F$ is a column of factors of size M.

3. Results

When forecasting electricity losses in distribution networks, one factor, the planned supply of electricity to the network, is used. For system-forming networks, several factors should be used: planned values of supply of electricity to the network, generation of electricity by electric power plants, etc. [13, 14]. Dependences of the form (6) can be obtained by multiple regression analysis methods [10, 11] according to the data of general measurements, telemetry and systems for commercial electricity metering.

Substituting (6) into (5), the dependence of power losses on the selected M factors is obtained.

$$\pi (F) = A + 2BF + F'CF,$$

where $A = a'_a R a_a + a'_p R a_p$; $B = a'_a R b_a + a'_p R b_p$; $C = b'_a R a_a + b'_p R b_p$.

$$\Delta W_i = M \pi T,$$

In formula (7), $B$ is a row matrix containing M coefficients; $C$ is a square matrix of coefficients of size $M \times M$.
Under the well-known assumption that power losses are a function of randomly changing factors [4, 5], load losses of electricity for the period $T$ are equal to

$$
\Delta W_L = M[\pi]T
$$

where $M[\pi]$ is the mathematical expectation of power losses for period $T$.

According to [15], the power loss function $\pi(F)$ can be replaced by expanding the function in Taylor series near the point of mathematical expectation of factors $F = (F_1, F_2, ..., F_M)$. Taylor series for quadratic function (6) contains three terms. Having calculated the mathematical expectation of the three terms of the series, the following is obtained:

$$
M[\pi] = \pi(F) + \frac{1}{2} \sum_{i=1}^{M} \sum_{j=1}^{M} \frac{\partial^2 \pi}{\partial F_i \partial F_j} K_{ij},
$$

(8)

where $K_{ij}$ – correlation moment of values $F_i, F_j$.

For function (7), the partial derivatives in (8) are equal to

$$
\frac{\partial^2 \pi}{\partial F_i \partial F_j} = 2C_{ij},
$$

where $C_{ij}$ – matrix element $C$.

The correlation moment $K_{ij}$ is expressed in terms of the mean square deviations $\sigma_i, \sigma_j$ of values $F_i, F_j$ and the correlation coefficient $r_{ij}$.

$$
K_{ij} = \sigma_i \sigma_j r_{ij}.
$$

Square matrix $D$ of size $M \times M$ is introduced, the elements of which are equal to $D_{ij} = C_{ij} r_{ij}$. Load losses of electricity, or CEL-R, in the base period, taking into account (7) and (8) are equal to

$$
\Delta W_{L, \text{Ref}} = \left( A + 2B \bar{F} + \bar{C} \bar{F} + \sigma' D \sigma \right) T,
$$

(9)

where $\sigma$ is the column of size $M$ of average square factor deviations from their mathematical expectation.

Load losses of electricity in the regulation period $s$ are determined by CEL-R (9) using indicators of planned values of factors $\bar{F}_{i, \text{Reg}}, (i = 1, 2, ..., M)$. The correlation coefficients $r_{ij, \text{Reg}}$ of factors in the regulatory period can be taken equal to the corresponding values of the reference period or obtained by processing prospective graphs of selected factors. The average square deviations $\sigma_{i, \text{Reg}}$ for the regulatory period can also be determined from perspective graphs of factors or adjusted according to the reference and regulatory period.

$$
\sigma_{i, \text{Reg}} = \frac{\sigma_{i, \text{Ref}}}{F_{i, \text{Ref}}} \bar{F}_{i, \text{Reg}} = \gamma_{i, \text{Ref}} \bar{F}_{i, \text{Reg}}.
$$

Load losses of electricity during regulation periods are equal to

$$
\Delta W_{L, \text{Reg}} = \left( A + 2\bar{F}_{\text{Reg}} + \bar{F}_{\text{Reg}} \bar{C} \bar{F}_{\text{Reg}} + \sigma_{\text{Reg}}' D_{\text{Reg}} \sigma_{\text{Reg}} \right) T.
$$
Further, some simplifications of CEL-R of the form (9) are considered. Assume that nodal currents \(J_a\) and \(J_p\) are proportional to one factor \(F\) (for example, the total supply to the network or output from network \(J_E\)).

\[
\begin{align*}
J_a &= Fk_a; \\
J_p &= Fk_p,
\end{align*}
\]

where \(k_a, k_p\) are the columns of load participation coefficients of each node in the total network load.

In this case, CEL-R for the regulatory period takes the following form:

\[
\Delta W_{L_{\text{Reg}}} = C_e \left( \overline{F}_{\text{Reg}}^2 + \sigma_{\text{Reg}}^2 \right) T = C_e \overline{F}_{\text{Reg}}^2 K_{\overline{F}}^2 T, \tag{10}
\]

or

\[
\Delta W_{L_{\text{Reg}}} = C_e I_{\text{Reg}}^2 K_{\overline{F}}^2 T,
\]

where \(C_e = k'_a R_k a + k'_p R_k p\) is the coefficient corresponding to the equivalent resistance \(R_{e_{\text{Reg}}}\) in (4); \(K_{\overline{F}}^2\) - the squared coefficient of the form of graph \(F\) within the calculation period \(T\).

CEL-R (10) differs from formula (4) by the use of form factor \(K_{\overline{F}}^2\).

The application of the described methodology for developing CEL-R using the test example from [16] is considered further. The design circuit of the section of systemic network is shown in Figure 1.

![Figure 1. Circuit of equivalent network (resistance in Ohms).](image)

Matrix of nodal resistances for the circuit in Figure 1 is equal to
With the known daily schedule ($T=24$) of loads and generation $P_{l1}(t), P_{l2}(t), P_{EN}(t)$, calculations of a series of modes for the reference period (Ref) and the regulation period were performed following three scenarios (P1, P2, P3), and graphs of three nodal currents for the reference period $J_{aRef}(t), J_{pRef}(t)$ were plotted. These calculations were used to determine the sample value of energy losses within the considered scenarios of the regulatory period $\Delta W_{sam1}, \Delta W_{sam2}, \Delta W_{sam3}$.

Using power supply from the network and power generation at electric power station EPS during the reference period $F^r = (P_n, P_{EPS})$ (Fig. 2) as the factors, models of nodal currents of form (6) were developed using the multiple regression method. All models satisfy the Fisher criterion [8].

\[
Z = \begin{pmatrix}
10 + j100 & 10 + j100 & 10 + j100 \\
10 + j100 & 23.6 + j236.4 & 12.3 + j122.7 \\
10 + j100 & 12.3 + j122.7 & 14.5 + j145.5
\end{pmatrix}.
\]

Figure 2. Graphs of factors for calculating electricity losses: a - supply from the network; b - EPS generation.

The regression models of the active and reactive components of the nodal currents of the network circuit are as follows:

\[
\begin{pmatrix}
J_{a1} \\
J_{a2} \\
J_{a3}
\end{pmatrix} = \begin{pmatrix}
0.4214 \\
0.0404 \\
-0.0102
\end{pmatrix} + \begin{pmatrix}
0.0005 & -0.0012 \\
0.0050 & -0.0046 \\
0.0008 & -0.0035
\end{pmatrix} \begin{pmatrix}
P_n \\
P_{EPS}
\end{pmatrix};
\]

\[
\begin{pmatrix}
J_{p1} \\
J_{p2} \\
J_{p3}
\end{pmatrix} = \begin{pmatrix}
0.0618 \\
-0.0004 \\
-0.3325
\end{pmatrix} + \begin{pmatrix}
0.0009 & -0.0015 \\
0.0033 & -0.0034 \\
0.0012 & 0.0049
\end{pmatrix} \begin{pmatrix}
P_n \\
P_{EPS}
\end{pmatrix}.
\]

Figure 3 shows some models of nodal currents for the problem under consideration.
Figure 3. Modeling of nodal currents of node 1: a - active components of nodal currents of a network circuit; b - reactive components of nodal currents of the network circuit.

Load losses of electricity within the regulation period are calculated according to CEL-R (9) when substituting numerical values of the coefficients and characteristics of the factors of scenarios P1, P2, P3 (Table 1). CEL-R takes the following form:

\[
\Delta W_{L,\text{Reg}} = \left[ 3.2984 + 2 \begin{pmatrix} 0.0301 \\ -0.0987 \end{pmatrix} \begin{pmatrix} P_{sn} \\ P_{EPS} \end{pmatrix} + \begin{pmatrix} 0.0008 \\ -0.0009 \end{pmatrix} \right] + \\
\left( \sigma_{sn} \sigma_{EPS} \begin{pmatrix} 0.0008 \\ -0.0009r_{sn-EPS} \\ 0.0015 \end{pmatrix} \right) \begin{pmatrix} \frac{P_{sn}}{P_{EPS}} \\ \frac{P_{sn}}{P_{EPS}} \end{pmatrix} \right] + \\
\left( \sigma_{sn} \sigma_{EPS} \begin{pmatrix} 0.0008 \\ -0.0009r_{sn-EPS} \\ 0.0015 \end{pmatrix} \right) \begin{pmatrix} \frac{P_{sn}}{P_{EPS}} \\ \frac{P_{sn}}{P_{EPS}} \end{pmatrix} \right] 
\]

Table 1. Integrated indexes of network mode.

| Scenario | $W_{\text{sn}}$, MW·h | $W_{\text{EPS}}$, MW·h | $P_{\text{sn}}$, MW | $P_{\text{EPS}}$, MW | $\sigma_{\text{sn}}$, MW | $\sigma_{\text{EPS}}$, MW | $r_{\text{sn-EPS}}$ |
|----------|-----------------------|-----------------------|---------------------|---------------------|----------------------|----------------------|---------------|
| P1       | 3032.0                | 2400                  | 126.3               | 100                 | 38.8                 | 0                    | 0             |
| P2       | 3795.2                | 3600                  | 158.1               | 150                 | 15.8                 | 0                    | 0             |
| P3       | 4100.0                | 3600                  | 170.8               | 150                 | 38.3                 | 51.1                 | 0.794         |
| Reference period | 4155.2            | 3600                  | 173.1               | 150                 | 33.6                 | 51.1                 | 0.595         |

The results of forecasting load losses of electricity using CEL-R and methodology [6] are given in table 2.

Table 2. Electricity loss forecast.

| Scenario | Sample $\Delta W_{\text{sam}}$, MW·h | CEL-R $\Delta W_{L,\text{Reg}}$, MW·h | Inaccuracy, % | Methodology $\Delta W_{L,\text{Reg}}$, MW·h | Inaccuracy, % |
|----------|--------------------------------------|--------------------------------------|---------------|------------------------------------------|---------------|
| P1       | 65.2                                 | 65.0                                 | -0.25         | 75.5                                     | 13.67         |
| P2       | 91.8                                 | 73.6                                 | -24.7         | 118.3                                    | 22.45         |
| P3       | 130.4                                | 125.86                               | -3.48         | 138.1                                    | 5.93          |
To determine the “standard sample of electricity losses”, in table 2, in all cases, 24 modes were calculated. The accuracy of the calculations is 0.001 MW. Energy losses over a period of 24 hours are calculated by summing the hourly power losses.

The reason for the significant inaccuracy of CEL-R forecast and the methodology [6] in the P2 scenario with respect to the relatively similar reference period in terms of average indicators is the significant changes in some characteristics of the graphs and factors used. Their values are given in table 1. Significant changes are observed with $\sigma_{sn}$, $\sigma_{EPS}$ and $r_{sn-EPS}$. However, average values of factors $\bar{P}_{sn}$ of the reference period and scenario P2 have changed only by -8.7%. Values $\bar{P}_{EPS}$ do not change within the compared periods. It is worth mentioning that the application of methodology [6] in this scenario also has worse accuracy.

This case one more time emphasizes that confidence in the reliability of energy loss forecasts should be based on a careful comparison of existing and long-term graphs of selected factors.

The method for predicting electricity losses proposed by the authors showed the best result in the test scheme for 2 cases out of 3.

4. Conclusions

1. The characteristic of CEL-R losses comprehensively reflects technical parameters of the electric network during the reference period and forecast periods.
2. The enhancement of the accuracy of CEL-R is conditioned by the improvement of models for forecasting nodal loads.
3. The proposed methodology for predicting the load component of electricity losses, using CEL-R characteristic of losses, provides acceptable stability of the results within regulation periods in comparison with the existing methodology for calculating the standards for technological losses of electricity.

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