Improving the Control Method of Energy Losses in Contact Line

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Summary

Purpose. Today energy losses in contact line are determined by calculation, but this method gives approximate values. It is proved that it is more effective control of the energy losses in contact line using indirect methods, but existing methods give the error of 7,5%. It is necessary to improve the control method of energy losses in contact line by taking into account additional factors.

Methods. The method of integral and matrix calculus used to develop a mathematical model for determining energy losses coefficient. Theory of experiment planning used for development a regression.

The Results. Regression equations of the second order for determining energy losses coefficient for areas of direct and alternating currents were received on the basis of full factorial experiment. Character of energy losses coefficient was defined, the limits of its changes were set and recommendations of its regulations were provided on the basis of the Monte Carlo method. An experimental confirmation of the results was done. It showed that the proposed improved method reduces error in the determination of energy losses.

Scientific novelty. For the first time, an analytical expression for estimating energy losses coefficient, which takes into account the number of trains on the zone between traction substations was found. This allows determining energy losses in contact line more accurately. First established the law of the statistical distribution of the energy losses coefficient, which makes it possible to evaluate its limits and advice on regulations change it.

Practical significance. The method of determination of the loss factor, which takes into account additional factors was found. This makes it possible to reduce the taking into account error of loss of 2,1% as compared with the existing indirect method.

Keywords: overhead contact system, power supply system, electrical energy loses, mathematical model

Railway transport is one of the biggest consumers of electricity in Ukraine. It was consumed 5 249,5 TWh in the last year. The main part of energy losses is losses in contact line. The average losses in contact line is 10,84%. The structure of

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energy losses in percentage of the total number of consumption electricity is different in Ukrainian Railways. There are 16% in Donetska railway, 15,07% in Prydniprovska railway, 11,44% in South railway, 17,26% in Lvivska railway, 5,06% in Odeska railway, 6,53% in South-West railway. The decrease of electricity losses is the state problem corresponding to the state target economic program of energy efficiency and the development of energy production from renewable energy resources and alternative fuels for 2012–2015 years.

All Ukrainian Railways buy electricity at the wholesale electricity market (WEM). Buying electricity in the WEM to satisfy their own needs and needs of third-party customers is the strategic direction of their activities. It is confirmed by both the experience of the railways in the WEM and the development concept of WEM that is approved by the Cabinet Ministers of Ukraine. Conditions of WEM require continuous analysis of energy losses in a contact line.

Energy losses in contact line are determined by calculating according to the „Instructions for calculation technological Energy losses in devices Traction Power Supply" approved by order of Ukrzaliznytsia on 29.08.2003 № 342-CH. But this method gives fairly approximate values. Accuracy and efficiency of controlling energy losses could be increased by using the indirect method. This method has an average error of 7,5%. This figure could be reduced by taking into account factors that affect the energy losses in the contact line. These factors are the scheme of electric power supply of railway section, the wear (reduction of the area) of contact line, the number of trains on railway section, the environment temperature, speed and current of trains.

In this way the problem of improving the control method of energy losses in contact line is really important. For improving the control method of energy losses in contact line were solved next problems:

1. The factors that affect the energy losses coefficient were selected and their mathematical models were developed.
2. Laws of distribution influencing factors and the limits of their change were found.
3. Analytical expressions for determining the energy losses coefficient for direct current and alternating current based on full factorial experiment were received.
4. Law of distribution and the limits of change for the energy losses coefficient were found.
5. Recommendations for regulations the energy losses coefficient were given.
6. Received theoretical results were verified experimentally.

Determining the energy losses in contact line has a lot of features. At first it can be explained by the changing current and place of the trains. The indirect method for determining the energy losses in contact line was described in the works of A.V. Bardushko, O.L. Bykadorov, V.T. Domanskyy, M.E. Krestyanov, A.N. Kuvichynski, K.G. Marquardt, V.T. Cheremysin [1, 3, 4, 5, 6, 8, 13]. This method is based on the register values of per square ampere – hours on the feeders of traction substations. The meter is located on the feeder. It measures values of per square ampere – hours in the unit of time and scales them to the energy losses using the energy losses coefficient. The energy losses in contact line are calculated by the next formula [14]:

$$\Delta W = k_l \cdot \int_0^T I_f^2(t)\,dt\,, \tag{1}$$

where: ΔW – energy losses in contact line, kWh,

k_l – energy losses coefficient,

$I_f^2(t)$ – square of feeder's current in the given time, A^2,

T – time of moving the train in the area, h.

Energy losses in contact line were separated on feeders for calculating k_l. The reason of this was locating meters in the each feeder. Those meters are needed individual settings. The instant power losses in contact line for double scheme of power supply are calculated like the sum of multiply of squares of feeders' currents and appropriate resistance of contact line [9]:

$$\Delta P(t) = r_0 x(t)\left(I(t)\frac{L-x(t)}{L}\right)^2 + r_0\left(L-x(t)\right)\left(I(t)\frac{x(t)}{L}\right)^2 =$$

$$= r_0 \cdot I^2(t)\left[x(t)\frac{\left(L-x(t)\right)^2}{L^2} + \left(L-x(t)\right)\frac{x(t)^2}{L^2}\right], \tag{2}$$

where $\Delta P(t)$ – the instant power losses in contact line, W,

r_0 – resistance of 1 kilometer of contact line, Ohm/km,

$x(t)$ – coordinate of train, km,

$I(t)$ –train's current at a given time, A,

L – length of the zone between substations, km.

Denote $x(t)\frac{\left(L-x(t)\right)^2}{L^2} + \left(L-x(t)\right)\frac{x(t)^2}{L^2} = \lambda(x)$.

The form of the curve of instantaneous losses depends on the scheme of power supply. Curves of instantaneous losses are shown in the figure 1 (this situation was described for 1 train in the area). The first component $\lambda(x)$ is the part of the instant power losses from the first traction substation. The second one is the part of the instant power losses from the second traction substation.

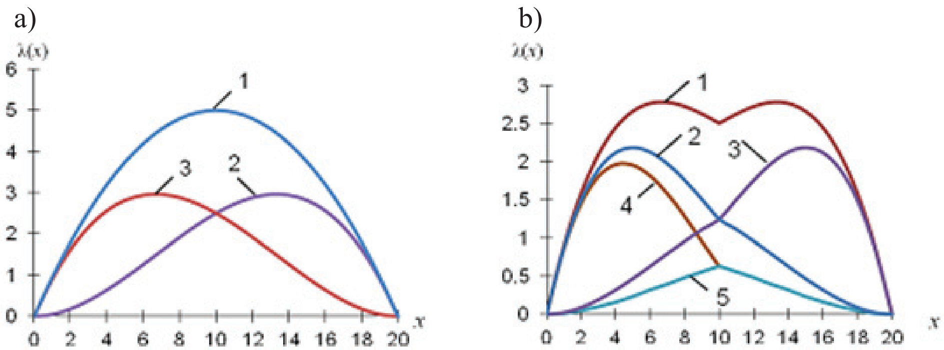

Fig. 1. Components of the instant power losses in the contact line: a) double scheme of power supply; b) junction scheme of power supply: 1) general, 2), 3) components of power losses from the first and second traction substation, 4) component of power losses from the current of the passing feeder, 5) component of power losses from the current of the adjacent feeder

The energy losses coefficient is function from the next values [12]:

$$k_l = f(k_s; k_n; k_w; k_V; k_I; k_t), \qquad (3)$$

where k_s – coefficient which takes into account the scheme of electric power supply of railway section,
k_n – coefficient which takes into account the number of trains on railway section,
k_w – coefficient which takes into account the wear (reduction of the area) of contact line,
k_v – coefficient which takes into account the speed of trains,
k_I – coefficient which takes into account the current of trains,
k_t – coefficient which takes into account the environment temperature.

Coefficient which takes into account the scheme of electric power supply of railway section k_s (table 1) was determined analytically.

Table 1

Instantaneous, equivalent resistances and k_S for different schemes of electric power supply

Scheme of electric power supply	$r(t)$	r_e	k_S
Cantilever scheme	$r_0 L \frac{t}{T}$	$\frac{1}{2} r_0 L$	$\frac{1}{2}$
Double scheme		$\frac{1}{4} r_0 L$	$\frac{1}{4}$
Junction scheme*		$\frac{2}{11} r_0 L \Big/ \frac{1}{2} r_0 L$	$\frac{2}{11} \Big/ \frac{1}{2}$
*Note: Value for passing feeder is in the numerator. Value for adjacent feeder is in the denominator.			

Expressions for determining power losses in the contact line for different schemes of electric power supply and squares of feeders' currents had been written. Dependence between energy losses and the wear (reduction of the area) of contact line was proposed to take into account by the coefficient k_w ΔS%. Journals of condition of contact line were analyzed and medium wear was calculated for defining the wear of contact line. Dependence between k_w and medium wear of contact line (fig. 2) is calculated in next way:

$$k_w = \frac{1}{1 - \frac{\Delta S\%}{100}}, \tag{4}$$

where ΔS% – medium wear of contact line in percentage.

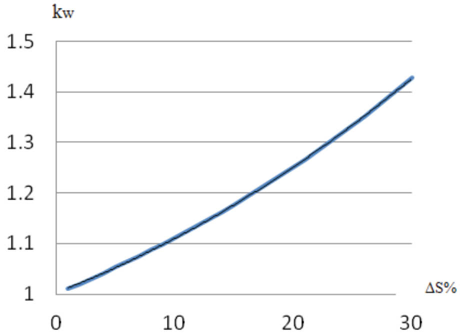

Fig. 2. Dependence between k_w and medium wear of contact line

Influence the number of trains on railway section to the energy losses in the contact line was proposed to take into account by the coefficient k_n [12]. The scheme for calculating is shown on the figure 3. Formula (5) was gotten using this one. Let do tolerance that currents of trains are equal and distances between trains are equal too.

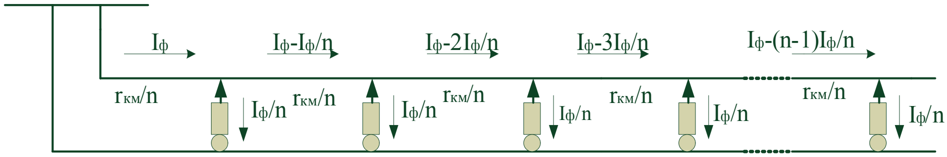

Fig. 3. Cantilever scheme with *n* trains

Next formula was written according to the figure 3:

$$\Delta P = I_f^2 \frac{r_\kappa}{n} + \left(I_f - \frac{I_f}{n} \right)^2 \frac{r_\kappa}{n} + \left(I_f - \frac{2I_f}{n} \right)^2 \frac{r_\kappa}{n} + \left(I_f - \frac{3I_f}{n} \right)^2 \frac{r_\kappa}{n} + \ldots +$$

$$+ \left(I_f - \frac{(n-1)I_f}{n} \right)^2 \frac{r_\kappa}{n} = \frac{r_\kappa}{n} \sum_{i=1}^{n} \left(\frac{nI_f - (i-1)I_f}{n} \right)^2, \qquad (5)$$

where I_f^2 – square of feeder's current, A²,
r_κ – resistance of contact line between traction substations, Ohm,
n – number of trains on railway section,
i – index number of the train.

For real and equivalent schemes ΔP are equal. This way the next expressions can be written.

$$r_e I_f^2 = \frac{r_\kappa}{n} \sum_{i=1}^{n} \left(\frac{nI_f - (i-1)I_f}{n} \right)^2, \qquad (6)$$

$$r_e = r_0 L \frac{\sum_{i=1}^{n} (n+1-i)^2}{n^3}. \qquad (7)$$

The sum of the squares of the first n natural numbers was written for receiving the expression for coefficient k_n (fig. 6). The number of these ones was defined by the numbers of trains in the area between traction substations.

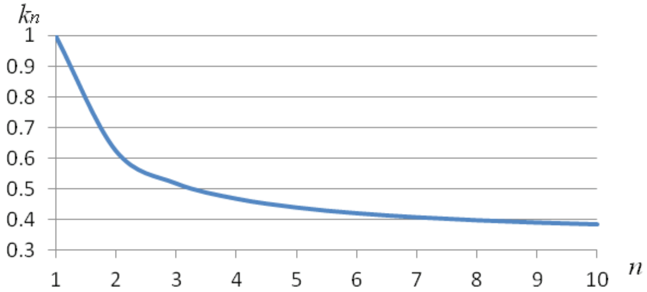

Fig. 4. Dependence between k_n and number of trains on railway section

$$S = 1^2 + 2^2 + 3^2 + \ldots = \sum_{i=1}^{n} i^2. \qquad (8)$$

Next expression was written on the base of method undefined coefficients:

$$r_e = r_0 L \frac{2n^2 + 3n + 1}{6n^2}, \tag{9}$$

where: $\frac{2n^2 + 3n + 1}{6n^2} = k_n$

$$k_n = \frac{1}{3} + \frac{1}{2n} + \frac{1}{6n^2}. \tag{10}$$

Influence the environment temperature to the energy losses in the contact line was proposed to take into account by the coefficient k_t (11). Expression (11) was written on the base of thermal system equation.

$$k_t = \frac{cS}{I^2} \frac{\beta S\left(T + T\left(e^{-\frac{T}{T^0}} - 1\right)\right) - t_e^0 T}{T + \alpha\left[\beta S\left(T + T\left(e^{-\frac{T}{T^0}} - 1\right)\right) - 20T\right]}, \tag{11}$$

where: c – heat transfer coefficient,

S – cross-section area of contact line, mm^2,

I – current in the contact line, A,

α – temperature coefficient, 1/°C,

T^0 – heating constant,

t_e^0 – environment temperature, °C,

β – heat transfer coefficient in heat exchange, W/(m·°C).

Distribution lows of factors affecting to the coefficient of energy losses in the contact line was received on the base of analysis of trains diagrams, journals of condition of contact line, weather forecasts (table 2) [10].

Table 2

Distribution lows of factors affecting to the coefficient of energy losses

Parameter	Distribution low	Low's parameter
The number of trains on railway section	Binomial	P = 0,0822, n = 43
The wear of contact line	Lognormal	m = 17,2, σ = 5,67
The environment temperature	Weibull	k = 50,51, ν = 4,6924
The speed of trains	Lognormal	m = 47,52, σ = 22,07

The average energy losses in contact line for Pridneprovskaya and Odesskaya railways were 12,4% and 6,3%. These numbers were identified as a result of mathematical modeling of the train situation for these areas. The model adequacy was tested using Fisher’s exact test. Regression equations of the second order for determining coefficient of losses for areas of direct and alternating currents were obtained on the basis of full factorial experiment [7].

The regression equation was obtained. Advanced matrix that takes into account the interaction of factors was written for calculating the coefficients of the equation. Coefficients of the equation which absolute value is equal or larger than confidence interval were named statistically significant and the final equation was written. The model adequacy was tested using Fisher’s exact test and it was recognized an inadequate. In this way the experimental plan been built to the plan of the second order (composite plan) and the response function as a complete quadratic polynomial was formed. The final equation for area of direct current is as follows:

$$k_l = 1{,}439 + 0{,}021n^2 - 0{,}378n + 0{,}003nV_m + 0{,}004\Delta S\% + 0{,}005t_e^0 . \qquad (12)$$

The calculated value of Fisher’s exact test for this model is F_c=1,091. For the given parameters tabulated values is F_t=1,6. In this way the model was recognized as adequate. The final equation for area of alternating current was gotten analogically:

$$k_l = 9{,}022 + 0{,}056n^2 - 0{,}72n + 0{,}024\Delta S\% + 0{,}033t_e^0 . \qquad (13)$$

Values of the energy losses coefficients witch were identified as a result of mathematical modeling and values of the energy losses coefficients witch were calculated using the equations (12) and (13) were compared. Looking at the figure 5 we can see that those values are almost equal. This fact is proves high accuracy of the results.

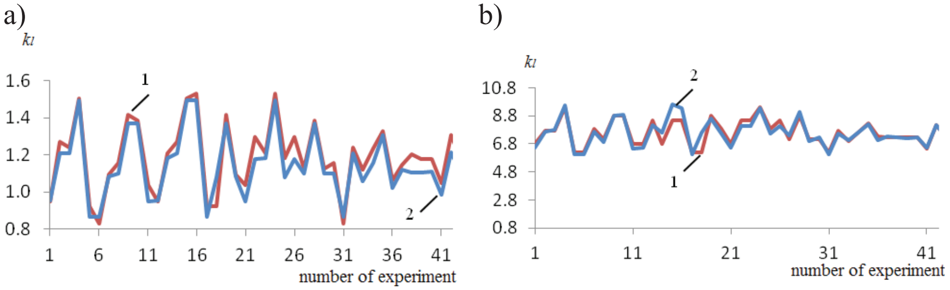

Fig. 5. Comparing of the energy losses coefficients witch were identified as a result of mathematical modeling and calculated using the regression equations; a) area of direct current, b) area of alternating current: 1) k_1 witch were calculated using the regression equations, 2) k_1 witch were identified as a result of mathematical modeling

The character of changing coefficient of losses for areas of direct and alternating currents was identified by using the Monte Carlo method. There is the lognormal distribution (figure 6a, 6b). Next characteristics of the energy losses coefficients distribution were gotten (table 3).

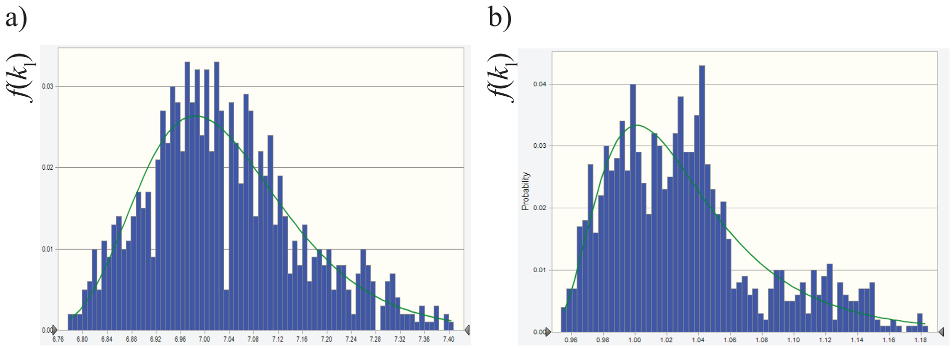

Fig. 6. Histograms of the energy losses coefficients distributions;
a) area of alternating current, b) area of direct current

Table 3

Characteristics of the energy losses coefficients distribution

Mathematical expectation μ	**Median Me**	**Mode Mo**	**Expected Mean Square σ**	**Dispersion D**	**Asymmetry γ1**	**Excess γ2**	**Coefficient of variation V**
Area of direct current							
1,03	1,02	1,0	0,06	0,00	1,79	9,19	0,05
Area of alternating current							
7,04	7,02	6,98	0,13	0,02	0,87	4,38	0,02

Limits of changing the energy losses coefficient were identified. They are from 0,94 to 1,33 for the area of direct current and from 6,56 to 7,79 for the area of alternating current. The average value of energy losses coefficient for areas of direct and alternating currents are 1,03 and 7,04. Influence factors were examined for giving the recommendations of changing this coefficient. The main influence on energy losses coefficient is the number of trains on railway section. The correlation coefficients for areas of direct and alternating currents are –0,7942 and –0,8562. Instantaneous and equivalent energy losses coefficient for different numbers of trains for double scheme were studied (figure 7).

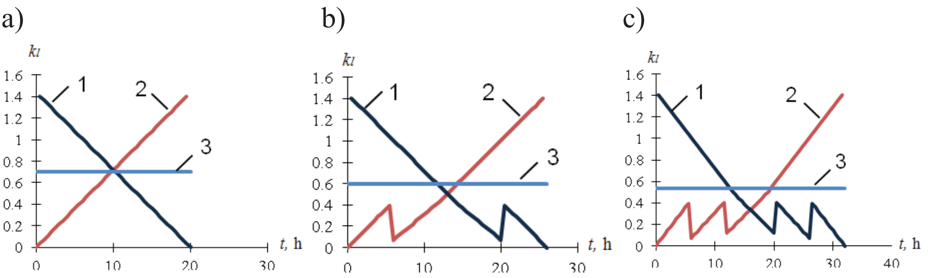

Fig. 7. Instantaneous energy losses coefficients for first and second feeders and there equivalent values; a) one train, b) two trains, 3) three trains: 1), 2) instantaneous energy losses coefficients for first and second feeders, 3) equivalent energy losses coefficient

Dependence between energy losses coefficient and time (fig. 8) was received on the base of information on the distribution of trains on the section of direct current and received energy losses coefficients.

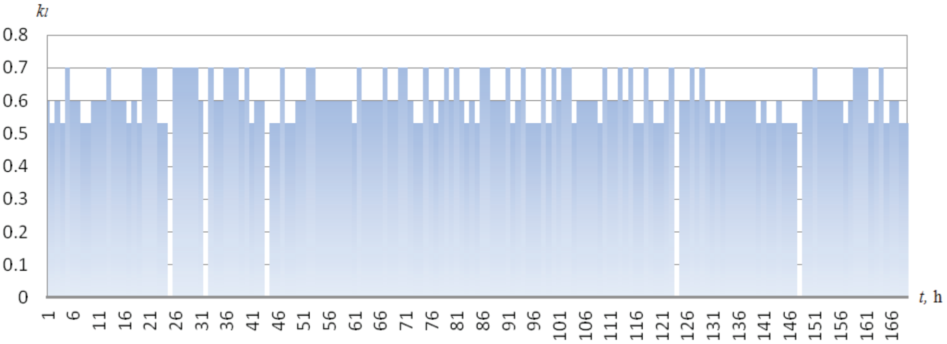

Fig. 8. Changing of energy losses coefficient in a week on the section of direct current

Analogically studies were done on the section of alternating current. Error of averaging of energy losses coefficient in two, three, four hours to 168 hours was calculated for giving recommendations for regulations the energy losses coefficient. Researches showed that error changed just a little over time. After one weak it established at the level 5,8% for alternating current and 4,3% for direct current and after this increases by a few hundredths of a percent. Experiment was done in the area of Odesskaya railway for confirmation of the received theoretical results [11]. Error was 5,4% that shows high precision.

As a result of the research the next results were obtained:

1. Expression for determining the energy losses coefficient was found on the basis of the method of undetermined coefficients. This expression takes into account the number of trains at the experimental area. It was established that

the resistance of the equivalent circuit for different number of trains in general is the sum of squares the natural series numbers.

2. Probabilistic nature of factors that affect the loss factor was determined. Limits of their changes and laws of distribution were identified. It was established that the number of trains at the experimental area obeys the binomial distribution. Speed of trains at the experimental area, the wear (reduction of the area) of contact line and the current of trains obey lognormal distribution. The environment temperature obeys Weibull distribution.
3. Based on the mathematical modeling for areas of Prydniprovska railway and Odessa railway was found that the average losses at the studied areas are 12,4% and 6,3%. Regression equation for determining the energy losses coefficient for direct current and alternating current were obtained from the full factorial experiment.
4. The energy losses coefficient for areas direct current and alternating current obeys the lognormal distribution. These facts were proved on the basis of statistical tests. Mean values of the energy losses coefficient are 1,03 for the areas of direct current and 7,04 for the areas of alternating current. The correlation coefficients for areas of direct and alternating currents are –0,7942 and –0,8562.
5. The recommendations for changes in regulations the energy losses coefficient were given. They ensure error of less than 5%.
6. The measuring complex was developed. This complex consists of an adapter and portable power analyzer.

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Udoskonalenie metody kontroli strat energii elektrycznej w sieci trakcyjnej

Cel: Obecnie pomiary strat w sieci trakcyjnej dokonywane są szacunkowo, jednak ten sposób pozwala uzyskać tylko przybliżone wyniki. Udowodniono, że bardziej efektywne jest kontrolowanie strat energii elektrycznej w sieci trakcyjnej za pomocą metod pośrednich, jednak istniejące metody dają wynik z błędem rzędu 7,5%. Niezbędne jest udoskonalenie metody kontroli strat energii w sieci trakcyjnej z uwzględnieniem dodatkowych czynników.

Metodyka: Przy opracowaniu matematycznego modelu do określenia współczynnika strat wykorzystano metody rachunku całkowego i macierzowego. Do opracowania zależności regresji wykorzystano teorię planowania eksperymentu.

Wyniki: Na podstawie pełnego doświadczenia czynnikowego, uzyskano równania regresji drugiego rzędu do określenia współczynnika straty energii na odcinkach z prądem stałym i prądem zmiennym. Na podstawie metody Monte Carlo określono charakter współczynnika straty energii, ustalono limit zmian i przedstawiono zalecenia dotyczące jego regulacji. Przedstawiono doświadczalne potwierdzenie uzyskanych wyników, które pokazało, że zaprezentowana udoskonalona metoda zmniejsza błąd pomiaru strat energii elektrycznej.

Innowacyjność: Po raz pierwszy uzyskano wyrażenie analityczne do określenia strat energii elektrycznej w sieci trakcyjnej, z uwzględnieniem liczby pociągów pomiędzy stacjami trakcyjnymi. Po raz pierwszy sformułowano prawo rozkładu prawdopodobieństwa współczynnika strat energii elektrycznej, które umożliwia ocenę jego granic i proponuje zmianę metodyki.

Znaczenie praktyczne: Opracowano metodykę określenia współczynnika strat uwzględniającą dodatkowe czynniki. Daje to możliwość zmniejszenia błędu wyliczenia straty o 2,1% w porównaniu z istniejącą metodą pośrednią.

Słowa kluczowe: sieć trakcyjna, systemy zasilania, straty energii elektrycznej, model matematyczny

Усовершенствование метода контроля потерь электроэнергии в контактной сети

Резьме

Цель. На сегодняшний день потери в контактной сети определяться расчетным путем, но этот способ дает приблизительные значения. Доказано, что более эффективным является контроль над потерями электроэнергии в контактной сети с помощью непрямых методов, но существующие методы дают погрешность 7,5%. Необходимо усовершенствовать метод контроля потерь электроэнергии путем учета дополнительных факторов.

Методика. При разработке математической модели для определения коэффициента потерь использованы методы интегрального и матричного исчисления. При разработке регрессионных зависимостей использована теория планирования эксперимента.

Результаты. На основе полного факторного эксперимента получены уравнения регрессии второго порядка для определения коэффициента потерь для участков постоянного и переменного токов. На основе метода Монте-Карло определен характер изменения коэффициента потерь, установлены границы его изменения и предоставлены рекомендации по регламенту его изменения. Проведено экспериментальное подтверждение полученных результатов, которые показали, что предложенный усовершенствованный метод уменьшает погрешность определения потерь электроэнергии.

Научная новизна. Впервые получена аналитическая зависимость для определения коэффициента потерь электроэнергии, которая учитывает количество поездов на межподстанционной зоне, и позволяет более точно определять потери электроэнергии в контактной сети. Впервые установлено закон статистического распределения коэффициента потерь, который дает возможность оценить его границы и дать рекомендации по регламенту его изменения.

Практическое значение. Разработана методика определения коэффициента потерь, которая учитывает дополнительные факторы. Это дает возможность уменьшить погрешность учета потерь на 2,1% по сравнению с существующим косвенным методом.

Ключевые слова: контактная сеть, потерь электроэнергии, математическая модель, системы электропитания