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DEVELOPMENT OF TECHNOLOGIES FOR SELECTING ENERGY-EFFICIENT POWER SUPPLY CIRCUITS OF RAILWAY TRACTION NETWORKS

The object of the study is the process of operation of traction and external power supply systems as objects of inextricable interconnection while reducing energy costs in the cost of railway transportation in real time. One of the most problematic areas is the technology for choosing energy-efficient power supply schemes for railway traction networks in real time. The methods of forming and transforming graphs of complex schemes of traction and external power supply systems and building expert control systems for the implementation of energy-saving technologies of electrified railways were further developed in the work.

In the course of the study, to increase the efficiency of simulation modeling of electric traction networks, the statistical characteristics of the loads of feeders that supply the final boundary sections, stations, depot access tracks, railway junctions and idle voltages on the traction substation tires were obtained. Methods of calculation and modeling of traction power supply have been developed, which take into account the inseparable relationship with power systems and allow choosing rational modes with minimal power flows and energy losses. Proposed methods of managing the modes of operation of the traction power supply system based on a vague description of their states and an expert system that allow solving new problems. Including, the choice of energy-saving power supply schemes in the case of power flows, economic modes of network operation in case of intensification of the transportation process. Thanks to this, ways of reducing power consumption and minimizing energy losses of traction power supply systems are proposed, which allow minimizing power flows and power losses by adjusting load flow parameters and voltage levels of traction substations. And also to increase the energy efficiency of electrified railway lines.

The technique of technical and economic feasibility of power supply schemes of traction networks and evaluation of the possibility of switching to cantilever or loop power supply schemes with parallel connection points has been developed. The implemented recommendations save about 25 thousand kWh per 1 km of two-track section.

Keywords: *energy saving technologies, traction networks, power flows, energy losses, knowledge bases, expert systems.*

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1. Introduction

The need for resource and energy saving requires the use of energy-saving technologies of traction power supply systems (TPS), which minimize energy costs in the process of transportation [1–3]. In the modern world, there are various technologies for implementing energy-saving modes of operation of external and traction power supply systems [4–6].

At the same time, the minimization of power flows and energy losses and the creation of information databases for integrated control systems require a compatible consideration of their operation modes [7, 8]. Even more consideration of the operation modes of external power supply systems (EPS) is required by energy saving technologies during high-speed train movement [9, 10].

Ensuring energy-saving modes of operation has always received much attention, both in electric traction networks and in power grid networks. It is necessary to develop an approach to the implementation of energy-saving technologies of traction power supply of railways using simulation models and expert systems (ES) for TPS operation mode control. Filling databases of simulation models of the electric traction network sections requires knowledge of a number of parameters: traction loads of feeders, no-load voltages of traction substations, specific resistances of the traction network and external power supply system.

Modelling of TPS taking into account the modes of operation of their power supply systems can be carried out on specialized simulation models [11–13], as well as by using universal programs such as Electronics Workbench and others developed in the MATLAB environment in recent years.

The most universal specialized models [12–14] using matrices have created a unified approach to calculating circuits of any degree of TPS complexity for direct and alternating current sections. The matrix method of forming probabilistic and completed schedules of train movement on single-track and double-track sections makes it easy to combine vectors of train set currents into a single vector of currents for the entire section. The unified simulation complex for units with complex train traffic organisation allows taking into account an unlimited number of train types, their stops, overtaking, power flows on the contact line, the operation of compensators and voltage boosters. The model makes it possible to determine instantaneous, average, effective currents, voltage and power losses at any point in the overhead contact network, taking into account the EPS operating modes. The latter is very important for the development of real-time models in intelligent power control systems [5, 15, 16].

Therefore, the work aimed at creating energy-saving technologies in traction power supply and saving electricity is relevant. Thus, *the object of research* is the process of operation of traction and external power supply systems as objects of inextricable interconnection while reducing energy costs in the cost of railway transportation in real time. *The aim of research* is to develop the scientific basis for energy saving in railway traction networks from the standpoint of considering their inextricable connection with external power supply systems.

2. Research methodology

All feeders supplying energy to the contact network, according to the specifics of the loads, can be divided into those feeding the train performance calculation section, final boundary sections, intermediate stations, shed access tracks, large railway junctions, marshalling yards. The loads of the feeders that feed the calculated spans are determined by solving a series of sequential moment circuits created by modelling the rolling stock loads and their schedules using the algorithms given in [8].

At the final boundary sections of the simulation model, the loads of the feeders that feed the calculated spans can be determined using the distribution functions by working out the current value at each simulation step without reproducing the train schedule. This approach significantly reduces the machine time required.

Let's elaborate on an elementary one-way circuit of a single-track section of length L. Let's suppose that at equal intervals Δ with probability P there are trains of the same type that move discretely between nodes (points) at time intervals Δ, 2Δ, ..., $N\Delta$. Let's denote the configuration of trains that are on the section at time t by $X(t)=(X_0(t), ..., X_N(t))$. The random variable $X_k(t)$ equals 1 if there is a train at point k at time t and equals 0 otherwise. Time t is discrete and varies in steps Δ.

Let's denote by I_k the current at point k, if there is a train there (the value I_k is determined by the relief of the area and other conditions and is taken as constant at point k). In this case, the feeder current at the starting point of the section $I_f(t)$ is determined by the formula:

$$I_f(t)=\sum_{k=0}^{N} I_k X_k(t). \qquad (1)$$

Random variables $X_k(t)$, corresponding to different moments of time are connected by relations $X_k(t)=X_{k+1}(t+\Delta)$.

The train, which is at point k at time t, moves to point k+1 at time t+Δ. Therefore, the feeder current will have the form:

$$I_f(n\Delta)=\sum_{k=0}^{N} I_k X_{k+n}, \qquad (2)$$

where X_1 is short designation for $X_0(-1\Delta)$.

On the one hand, the current J consumed by the train is a random function of time, because it is affected by a large number of random factors (deviation of the main resistance to motion, meteorological conditions, train mass deviation, driver's skill, etc.), and on the other hand, it contains a very significant component, which is a deterministic function of time. However, according to works [17, 18], there are reasons to believe that the random process $I_f(t)$ of the feeder load variations over time is stationary.

Let's calculate the mathematical expectation and covariance function of this process, using the independence of random variables X_1:

$$\begin{aligned}
&MI_f(t)=\sum_{k=0}^{N} J_k Mx_k(t)=\\
&=P\sum_{k=0}^{N} J_k=\frac{J_0+\ldots+J_{N+1}}{N+1}P(N+1),\\
&DI_f(t)=\sum_{k=1}^{N} J_k^2 DX_k(t)=\\
&=p(1-p)\sum_{k=u}^{N} J_k^2=\frac{J_0^2+\ldots+J_{N=1}^2}{N+1}\times\\
&\times P(N+1)(1-P)\operatorname{cov}(I_f(t),I_f(t+u\Delta))=0,\ \text{if } U>N,\\
&\operatorname{cov}(I_f(t)),I_f(t+u\Delta))=\operatorname{cov}(I_f(0),I_f(u\Delta))=\\
&=\operatorname{cov}\left(\sum_{k=0}^{N} J_k X_k\cdot\sum_{k=0}^{N} J_k X_{k+u}\right)=P(1-P)\sum_{k=u}^{N} J_k J_{k-u}=\\
&=\frac{J_0 J_u+\ldots+J_{N-u}J_N}{N+1}P(N+1)(1-P),\ \text{if } U\le N. \qquad (3)
\end{aligned}$$

Here, the value $P(N+1)=\lambda$ is the average number of trains located at a fixed moment in time on the section (traffic intensity).

It can be assumed that the number of nodes (points) N is quite large, the intensity λ is fixed, and $P=\lambda/N+1$ is therefore small. Then, according to the central limit theorem with the specified degree of accuracy, the value $I_f(t)$ has a normal distribution. Since the parameters of the normal distribution are the mathematical expectation and variance, and for the corresponding random process also the covariance function, it is possible in formulas (3) to go to the limit at $N\to\infty$ and consider the limit values as the parameters of the normal approximation.

Let's assume the train passing time on the span $T=N\Delta$, and instead of a discrete set of currents J_0, J_N let's introduce the function J(l), $0\le 1\le L$ with the same meaning, so that $J_k=J\left(\frac{K}{N}L\right)$. Then get:

$$\begin{aligned}
&MI_f(t)=\frac{\lambda\sum_{k=0}^{N} J\left(\frac{K}{N}L\right)}{N+1}\underset{N\to\infty}{\rightarrow}\lambda\frac{1}{L}\int_0^L J(1)dl=\lambda\bar{J},\\
&DI_f(t)=\lambda\left(1-\frac{\lambda}{N+1}\right)\frac{\sum_{K=0}^{N} J^2\left(\frac{K}{N}L\right)}{N+1}\underset{N\to\infty}{\rightarrow}\\
&\underset{N\to\infty}{\rightarrow}\lambda\frac{1}{L}\int_0^L J^2(I)dl=\lambda J_*^2. \qquad (4)
\end{aligned}$$

To find the covariance limit, let's consider that:

$$U=\frac{t}{\Delta}=\frac{t}{T}N,$$

then:

$$\operatorname{cov}\left(I_f(0),I_f(u\Delta)\right)=$$

$$=\lambda\left(1-\frac{\lambda}{N+1}\frac{\sum_{k=\frac{t}{T}N}^{N}I\left(\frac{K}{N}L\right)I\left(\left(K-\frac{t}{T}N\right)\frac{L}{N}\right)}{N+1}\right)\underset{N\to\infty}{\rightarrow}$$

$$\underset{N\to\infty}{\rightarrow}\lambda\frac{1}{L}\int_{\frac{t}{T}L}^{L}J(1)J\left(1-\frac{t}{T}L\right)dl=K(t). \quad (5)$$

Thus, it is possible to approximate the random process $I_f(t)$ by an idealized Gaussian process $\tilde{I}_f(t)$ with the appropriate characteristics: the mean λJ, the variance λJ_*^2 and the covariance function $K(t)$ (it is equal to 0 at $t\geq T$).

Let's consider the time interval $[0,\ t_0]$ and introduce the random variable $Z(t_0)$ – time in the interval $[0,\ t_0]$, conducted by the process $\tilde{I}_f(t)$ above some level a. Then according to [19]:

$$MZ(t_0)=1-\Phi\left(\frac{a-\lambda\bar{J}}{\sqrt{K(0)}}\right), \quad (6)$$

where

$$\Phi(E)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{E}e^{\frac{-y2}{2}}\mathrm{d}y.$$

The following expression is valid for dispersion:

$$DZ(t_0)=2\sum_{n=1}^{\infty}\frac{\left[\Phi^{(n)}\left(\frac{a-\lambda\bar{J}}{\sqrt{k(0)}}\right)\right]^2}{n!\left[k(0)\right]^n}\frac{1}{t_0}\int_0^{t_0}\left(1-\frac{t}{t_0}\right)K^n(t)\mathrm{d}t, \quad (7)$$

or

$$DZ(t_0)=\frac{1}{\pi t_0}\int_0^{t_0}\left(1-\frac{t}{t_0}\right)\mathrm{d}t\times$$

$$\times\int_0^{\frac{k(t)}{k(0)}}\exp\left\{-\frac{\left(a-\lambda\bar{j}\right)^2}{k(0)(1+V)}\right\}\left(1-V^2\right)^{-\frac{1}{2}}\mathrm{d}v. \quad (8)$$

Now let r type trains arrive on the span and each type have its own function $J_j(1)$, $1\leq j\leq r$, and the intensity of train traffic is high. Let's assume that the speeds of trains of all types at each node (point) of the span under consideration are the same, which means that the times of passing the span for trains of all types are equal. Then two variants of the description of the incoming flow of trains are possible.

In the first variant, each type has its own flow of trains with intensity λ_j and these flows overlap each other independently, while in the second variant, the train currently arriving at the starting point of the span is of type J with probability P_j ($J=1,\ ...,\ r$). $P_1+...+P_r\leq 1$. At transitions to normal approximation both of these descriptions give the same Gaussian process. Therefore, let's use the first description, where it is easier to get to the final formulas.

Indeed, for type 1 trains, as before, it is possible to use an idealized Gaussian process $\tilde{I}_f J(t)$ with mean $\lambda_j\bar{J}_j$ and covariance function $K_j(t)$ $\left(D\tilde{I}_{fj}(t)=K_j(0)\right)$. The total current of the feeder (idealized) is determined by the formula:

$$\tilde{I}_{f\sum(t)}=\sum_{j=1}^{r}\tilde{I}_{fj}(t). \quad (9)$$

Due to its independence, it is again a Gaussian process with mean $\sum_{j=1}^{r}\lambda_j J_j$ and covariance function $\sum_{j=1}^{r}K_j(t)$. Accounting for train traffic irregularity does not negate the Gaussian process $I_{f\Sigma}(t)$.

Studies [17, 20] show that the Pearson type III distribution curve or the truncated normal distribution can be used to describe the feeder currents feeding the spans. If the capacity utilization factor is in the range of 0.45–0.65, then according to [20], the truncated normal distribution should be used instead of the Pearson distribution.

In order to verify the distribution laws of the feeder currents feeding the span, we carried out a series of statistical current measurements with recording devices at AC and DC traction substations of railways. The results of the calculation of the main numerical characteristics for a number of the empirical distribution samples are summarized in Table 1.

Table 1

Calculation results of the main numerical characteristics of the empirical distribution of random variables

Parameters of empirical distributions	Average value	Mean-square deviation	Asymmetry	Kurtosis	Variation coefficient
I_{f1}, A	143.67	62.55	–	–	–
I_{f2}, A	107.61	45.92	–	–	–
I_{fc}, A	64.9	21.8	0.96	1.96	33.5
ΔU_x, kV	0.122	1.0	–0.238	1.523	82193
σ, deg	1.576	0.877	–0.523	–0.523	55.67

The value of the criterion $\chi^2=21.7$ allows to confirm with a probability of 0.2 for a number of samples that the value of the feeder current feeding the span corresponds to a normal distribution. At the same time, for a number of samples (the value of the criterion $\chi^2=20.1$ with a probability of 0.2), the value of the feeder current corresponds more to the logarithmic normal distribution. Empirical distributions of I_f and logarithmic normal distribution with parameters $I_f=163.6$ A and $\sigma_I=62.5$ A are shown in Fig. 1, *a*.

The results of the experimental verification of the random variable $Z(t_0)$, which shows the time that the process $\tilde{I}_f(t)$ spends above some level a, are shown in the Table 2.

Usually, large railway junctions, marshalling yards, depots are fed by separate feeders from the buses of traction substations or sectioning posts. The load distribution laws of these feeders are unknown. In order to eliminate them, let's conduct a series of static measurements with the recording devices on the feeder, which feeds the station load and the locomotive shed spur tracks. The results of the calculation of the main numerical characteristics of the empirical distribution are summarized in the Table 1.

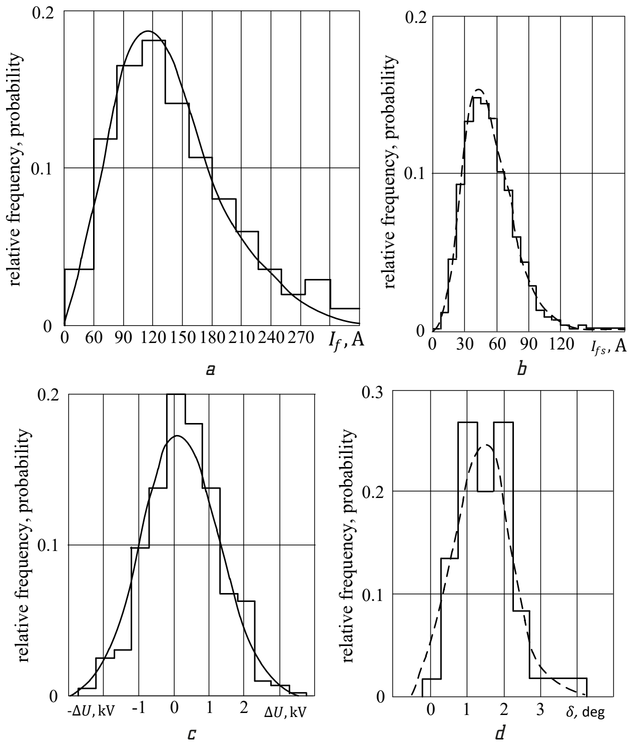

Fig. 1. Empirical distributions of: feeder currents feeding the spans I_f, station load I_{fs}, modules of the no-load voltage deviations ΔU, angles between the voltages of adjacent substations Δ

Table 2

Calculation results of the main numerical characteristics of the empirical distribution

Level	Theoretical	Empirical
Excesses at levels $\tilde{I}_{f1}$ and $\tilde{I}_{f2}$		
36.00/16.80	0.9574/0.9760	1.0000/1.0000
60.00/40.80	0.9095/0.9271	0.9608/0.9668
84.00/64.80	0.8300/0.8244	0.8252/0.8152
108.00/88.80	0.7158/0.6589	0.6701/0.6253
132.00/112.80	0.5740/0.4550	0.4902/0.3942
156.00/136.80	0.4219/0.2625	0.3611/0.2383
180.00/160.80	0.2807/0.1234	0.2589/0.1350
204.00/184.80	0.1674/0.0464	0.1755/0.0708
228.00/208.80	0.0888/0.0138	0.1189/0.0282
252.00/232.80	0.0416/0.0032	0.0653/0.0101
276.00/256.80	0.0172/0.0006	0.0428/0.0000
300.00	0.0062	0.0138
324.00	0.0012	0.000

Note: in the numerator – excesses at the level $\tilde{I}_{f1}$; in the denominator – excesses at the level $\tilde{I}_{f2}$

Based on the measurement data, we have built a theoretical logarithmic normal distribution curve with parameters I_{fs}=64.9 A, σ_I=21.8 A and a histogram of the feeder current feeding the station load (Fig. 1, *b*). The value of the criterion χ^2=29.5 allow confirming with a probability of 0.1 that the value of the feeder current feeding the station load is distributed according to the logarithmic normal law:

$$F\left(I,\bar{I},\sigma_I\right)=\begin{cases}\dfrac{1}{\sigma_I I\sqrt{2\pi}}\displaystyle\int_{-\infty}^{I_{\max}}\exp\left[-\dfrac{1}{2\sigma_I^2}\left(In\,I-\bar{I}\right)^2\right],\\ \text{if } I>0,\ -\infty\langle I\rangle\infty,\ \sigma_I>0,\\ 0,\\ \text{in other cases.}\end{cases} \quad (10)$$

Loads of the intermediate station tracks are created by starting currents of electric locomotives and currents consumed by electric locomotives during standing. Herewith, the total load of the station tracks can be determined by the formula:

$$\dot{J}(t)=\left(N_m-N_I-N_M\right)\dot{J}_c+\sum_{k=1}^{N_I}\dot{J}_{SC}+\sum_{j=1}^{N_M}\dot{J}_{Mj}, \quad (11)$$

where $j(t)$ is value of the total current of the station tracks of the intermediate station at the moment of time t; j_c is current consumed by the electric locomotive for needs during standing; j_{sc} is starting current at the time of departure of the k-th train from the intermediate station; j_{Mj} is current consumed by the electric locomotive when passing the intermediate station on the main tracks without stopping; N_m is current number of trains at the intermediate station at the same time; N_I is the number of trains at the intermediate station that are in start-up mode; N_M is number of trains on the main tracks.

In the process of simulating the schedule of trains, the values N_m, N_I, N_M of each intermediate station are known at each simulation step. Herewith, it is convenient to create a simulation matrix for the IMS stops in Fig. 2. Each row of the matrix characterizes one intermediate station. The number of station tracks determines the number of matrix columns. The matrix element at the intersection of the i-th row and j-th column indicates the presence (1) or absence (0) of a train at the i-th intermediate station of the j-th track.

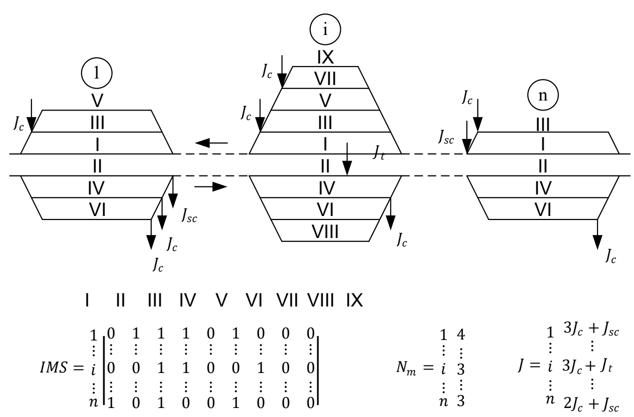

Fig. 2. Load of station tracks

The number of trains at each station can be determined by summing the elements of the columns of the corresponding row of the IMS matrix:

$$N_m(i)=\sum_{j=1}^{s}IMS(i,J), \quad (12)$$

where S is the maximum number of station tracks.

The total load of the station tracks at each step of the simulation is applied to the node of the intermediate station and is taken into account when calculating moment circuits.

Parameters for simulating no-load voltages on traction substation bus-bars are important elements in compiling simulation model databases. The theoretical prerequisites for the possibility of probabilistic modelling of the no-load voltage on the traction substation bus-bars are given in [2, 17, 20]. It is appropriate to note that the equalizing current can flow through the traction network due to different slopes of the external characteristics of the traction substations, as well as under different loads of feeder zones adjacent to the calculated one. Taking into account the above, the voltage on the bus-bars of the traction substation $\dot{U}_x$, necessary for the calculation of the equalizing current, should be determined by the formula:

$$\dot{U}_x = \dot{U}_{xx} - \Delta \dot{U}_c, \tag{13}$$

where $\dot{U}_{xx}$ is no-load voltage; $\Delta \dot{U}_c$ is voltage drop in the external power supply system and on the traction transformer due to the loads of the adjacent feeder zones.

The voltage $\dot{U}_x$ is modelled at each substation for two phases. When determining the voltage drop $\Delta \dot{U}_c$ the currents of the adjacent feeder zones are calculated in advance under the assumption of equal voltage on the bus-bares of the adjacent traction substations. At the final boundary sections, the currents of the power arms of the adjacent zones are determined according to the predetermined distribution law.

The process of modelling the voltage $\dot{U}_x$ on the traction substation bus-bars takes place in several stages. First, the no-load voltage module is determined by the formula:

$$U_{xx} = \bar{U}_{xx} \pm \Delta U_x, \tag{14}$$

where ΔU_x is a random variable determined according to the truncated normal distribution.

The no-load voltage $\dot{U}_{xx}$ at one of the substations is oriented according to the phase feeding the simulated zone. Then the angle δ is modelled, and the no-load voltage of the adjacent traction substation is determined on the complex plane.

After the no-load voltage $\dot{U}_{xx}$ is simulated for all substations, let's determine the voltage drop in the EPS and on the traction transformer from the loads of the adjacent feeder zones $\Delta \dot{U}_c$ and calculate the voltage $\dot{U}_x$ according to formula (13) to determine the current distribution, voltage loss in the circuit nodes and power losses of electric traction networks.

The angles δ between the no-load voltages of adjacent traction substations could be measured by having identical reference voltage sources at each of the substations. In practice, such a solution is difficult to implement. Therefore, a circuit with two-way power supply was assembled to determine the angles δ. In this case, the equalizing current $\dot{I}_y$ is taken as a reference vector in relation to which the angles can be measured. The measurements were made when there were no trains on the feeder zone.

In the process of measuring voltage modules on the traction substation bus-bars U_{B1} and U_{B2}, the equalizing currents I_{y1} and I_{y2}, and the phase shift angles φ_1 and φ_2 between voltages and equalizing currents were simultaneously recorded.

To determine the angles Δ, let's consider the vector diagram shown in Fig. 3. The voltage vectors on the bus-bars of adjacent substations $\dot{U}_{\text{B1}}$ and $\dot{U}_{\text{B2}}$ can be constructed, when we know their measured modules and the angles φ_1 and φ_2 in relation to the equalizing current. The voltage drop on the traction substation transformers from the equalizing current, without taking into account the active component, is equal to $I_y X_1$ and $I_y X_2$ respectively. Then, the no-load voltage on the traction substation bus-bars can be easily found by the formula:

$$\dot{U}_X = \dot{U}_{\text{B}} + \dot{I}_{yX}. \tag{15}$$

By substituting the value $\dot{U}_X$ let's obtain:

$$\delta = \operatorname{arctg}\frac{J_m \dot{U}_{\text{B1}} + J_m \dot{I}_y X_1}{Re \dot{U}_{\text{B1}}} - \operatorname{arctg}\frac{J_m \dot{U}_{\text{B2}} + J_m \dot{I}_y X_2}{Re \dot{U}_{\text{B2}}}, \tag{16}$$

where

$$\dot{U}_{\text{B1}} = U_{\text{B1}} e^{j\varphi 1}; \ \dot{U}_{\text{B2}} = U_{\text{B2}} e^{j\varphi 2}.$$

In formula (16), all quantities can be measured. The angle, $\delta > \delta'$, if $\varphi_1 > \varphi_2 - 180°$, and $\delta < \delta'$, if $\varphi_1 < \varphi_2 - 180°$ (Fig. 3, *b*, *c*).

It should be noted that some current $\dot{I}_{si}$, may be superimposed on the equalizing current, due to the loads of station consumers and the capacitive leakage current. The vector diagram is shown in Fig. 3, *a*.

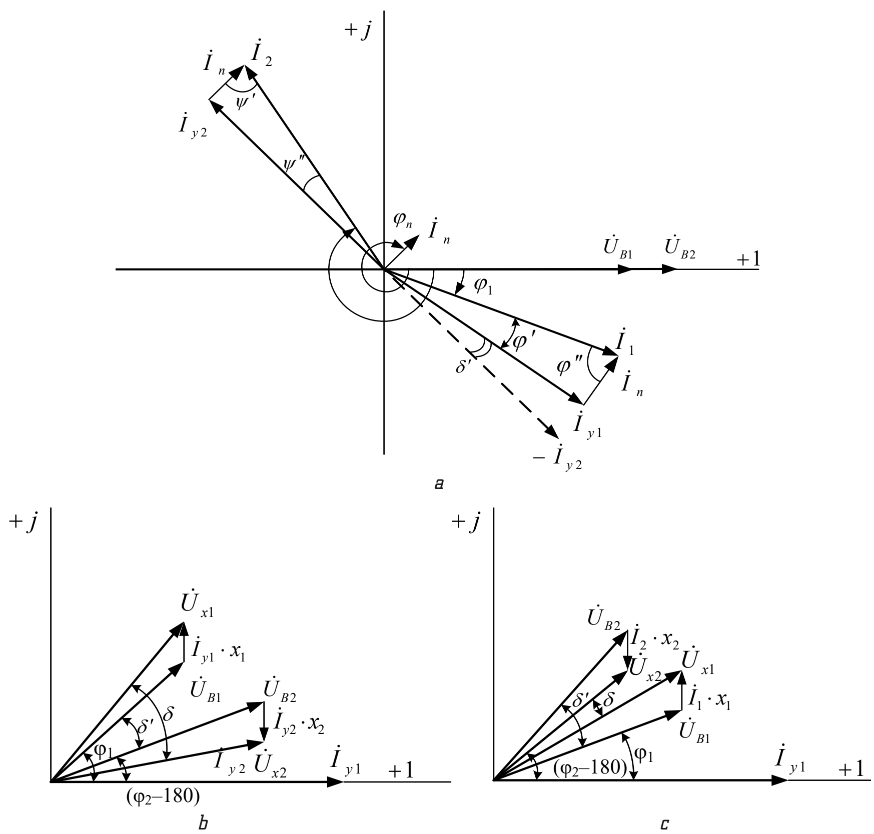

Fig. 3. Determination of angles: *a* – angles φ_1 and φ_2; *b*, *c* – δ between the voltage vectors of adjacent traction substations

3. Research results and discussion

Under conditions of necessity to save energy and reduce the cost of railway transportation, the greatest effect (from 5 to 15 %) is achieved through the introduction of complex information technologies, which are based on tariffs that are rational in terms of the electricity cost, energy-efficient train traction modes, and modes of operation of the traction and external power supply rational in terms of power flows.

Power flows on traction networks are mainly determined by the operation mode of the EPS. In some cases, power flows in lines reach values that are incompatible with the reliability of that line or system and require dispatcher regulation.

Given that the total power consumption of a traction substation consists of train traction power consumption, losses and power flows in the traction network, the following formula can be proposed to determine the flows:

$$W_{fl}=W-\Delta W-W_{tt}=\sum_{i=1}^{T}(\overset{*}{I}_{ai}\dot{U}_{bi}-\Delta S_i)-W_{tt\,i},$$

where W is the total electric power consumption of the traction substation; $\overset{*}{I}_{ai}$ is the conjugated complex of instantaneous values of power arm currents; $\dot{U}_{bi}$ is the instantaneous voltage value; W_{tt} is the power consumption for train traction; ΔW is the energy losses in traction networks.

To populate the databases of the expert systems (ES), let's develop a simulation model of TPS (Fig. 4), taking into account the modes of operation of EPS, which is based on the synthesis of the matrix method of calculating instantaneous circuits, the method of calculating loads of electric rolling stock (ERS) and the method of statistical tests to take into account the train traffic organization.

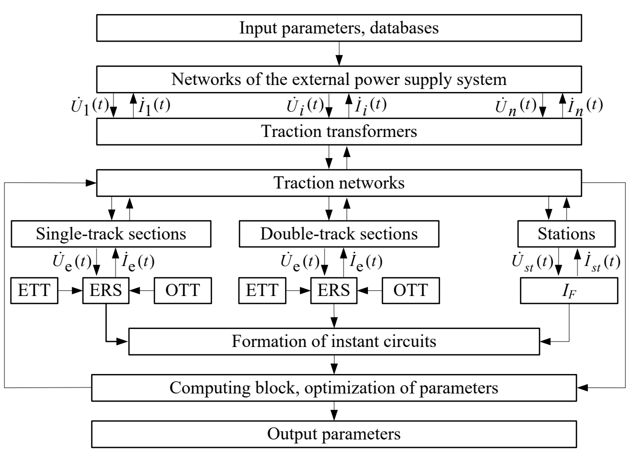

Fig. 4. Structural diagram of the simulation model: ETT – even train traffic; ERS – electric rolling stock; OTT – odd train traffic

The proposed ES implementing the energy-saving technologies for the operation of TPS allows increasing the energy efficiency of control actions by combining heuristic, retrospective and causal knowledge in local and global power supply device control systems (Fig. 5).

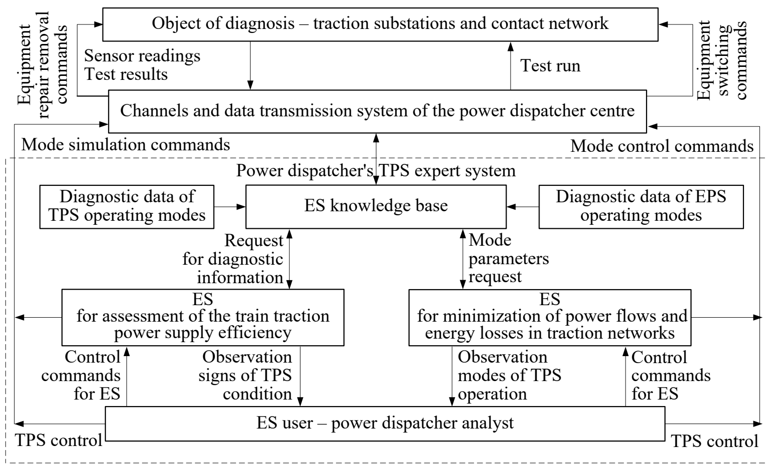

Fig. 5. Generalized diagram of the expert system

Rows of the mode matrix (*MM*) of the TPS are the states that characterize the TPS objects $X_i=(X_{i1},...,X_{in})$ with a set of parameters x_{ij}, $i=1,2,...,N$, $j=1,2,...,n$. The task of constructing an optimal *MM* classification consists in choosing a group of parameters G_k, $k=1,...,g$, and a class of objects T_{rk}, $r=1,...,t_k$, in each G_k, for a pair of elements (G_k^*,T_{rk}^*), which minimizes the given functional $F(G,T)$ of the distances of the elements from the «centres» of the classes T_{rk}.

Two forms of product rules have been developed, designed to evaluate the minimization of power flows and energy losses in the traction network:

$$\text{IF }[\text{AND}(N_k=g_r)]\text{ THEN}[y_j\in N_F;(\bar{Y}_j,\sigma_j^2)];$$
$$\text{IF }\underset{k\in q^*}{\text{AND}}[\underset{j\in G_k}{\text{OR}}(x_{ij}\approx x_j^*)]\text{THEN}[(y_j\approx y^*)], \quad (17)$$

where AND and OR – signs of logical operations; g_r – numbers of groups G_k with classes N_k, to which object parameters can be attributed; y_j – predicted parameter of the TPS mode for the i-th object $(x_{i1},x_{i2},...,x_{in})$; N_F – selected final classes; $(\bar{Y}_j,\sigma_j^2)$ – average values and variances of the output variables; the sign «≈» indicates «approximate equality»; x_j^*, y^* – subtable-derived element values of knowledge bases (KB).

When forming the rules (17), it is assumed that there is a possibility of assigning a conclusion variable to the construction of the classification. In this case, the classification quality functional will have the following form:

$$F(G,T)=\frac{1}{N\cdot n}\sum_{k=1}^{q}\sum_{r=1}^{t_r}[F_{rk}(G,T)*W_{rk}^{-1}]\Rightarrow\min_{(G,T)\in\pi}, \quad (18)$$

where $F_{rk}(G,T)$ – calculated measures of dispersion of elements $W_{rk}=|G_r|\cdot|I_{rk}|$; I_{rk} – set of submatrix object numbers T_{rk}.

The following form of rules for converting conditional data classification results to expert system KB is proposed:

$$\underset{s\in q^*}{\text{AND}}[\text{OR}(\underset{j_k\in K}{\text{OR}}(x_{ij_k}^s\approx w_{jk}^s),$$
$$B(x_{(i)}:\ j_i\notin K)\geq B_*^s)]\Rightarrow(y_{ij_G}\approx w_{j_G}^*), \quad (19)$$

where $j_i\notin K$ – variables defining the researched object $x_{(i)}=\{x_{ij_k},x_{ij}\}$; B_*^s – threshold values for comparing the proximity of objects according to the variables that make up the group G_s; indices «i» show the characteristics «j_k» of the situation «i» when compared with the given values $w_{j_k}^*$; indices «k», «j_G» show the numbers of the given reference variables k, $j_G\in K=\bigcup j_s$, where the number j_G shows the predicted characteristic $w_{j_G}^*$.

When forming the rules, the following parameters are established: ΔQ_i – deviation of the daily mass of transported goods on the i-th inter-substation zone of the double-track section of alternating current, for the characteristic of which the fuzzy values Q_p are entered: «lag (strong, weak, absent)» and «advance (absent, weak, strong)»; ΔS_{i} – deviation of daily active energy losses for inter-substation zone i, S_{p} quantity with values: «strong, absent, weak»; ΔW_i – difference in daily energy consumption of the i-th inter-substation zone, for the real operation mode of TPS and the reference mode of TPS uniform loading, the value W_p; K_i – track section, value K_p, where $i=0$, 1...n – the number of inter-substation zones of the given section. Fuzzy rules have the form:

$$\text{IF } (K_i \in K_p \text{ AND } \Delta W_i \in W_p \text{ AND } \Delta Q_i \in Q_p \text{ AND } \Delta S_i \in S_p), \text{ THEN } U_i \text{ AND } Cx_i, \quad (20)$$

where U_i – voltages of traction substations that provide close to optimal control in the i-th inter-substation zone of the section; Cx_i – zone supply circuit.

When building a control model in the form of fuzzy rules, each fuzzy characteristic is approximated by N fuzzy values with triangular membership functions. For a fuzzy characteristic, there are specified the minimum and maximum value within its permissible value interval. The approximating quantities have a triangular membership degree: the vertex lies in the centre and has a membership degree of 1, and two other vertices on its sides have a membership degree of 0. Fuzzy inference is based on Mamdani fuzzy implication rule.

The membership function (Fig. 6) of the fuzzy value of the difference in daily energy consumption of the real and reference mode of TPS operation is characterized by: $\Delta W_{\min}=32$ thousand kWh, $\Delta W_{\max}=30$ thousand kWh. The names of each value are given as follows: values close to 0 are called «ΔW_n» (no deviation), «$+\Delta W_1$» – «$+\Delta W_6$», «$-\Delta W_1$» – «$-\Delta W_6$» – fuzzy deviations according to $\Delta W_{\max}$ and $\Delta W_{\min}$ of classes 1...6.

When forming the base of rules, each value from the sample of reference traction modes is compared with the values of a fuzzy characteristic and is replaced by the one that has the maximum degree of membership among all those specified in the area. If the value of deviations $\Delta W_i=8000$ kW·h, $\Delta Q_i=-50$ thousand tons and $\Delta S_i=300$ kW·h, then let's obtain the following rule:

$$\text{IF } (\Delta W_i \in «\Delta W_n» \text{ AND } \Delta Q_i \in «-\Delta Q_2», \text{ AND } \Delta S_i \in «+\Delta S_4»), \text{ THEN } U_i \geq 27.5 \text{ AND } CxK_i,$$

where «$-\Delta Q_2$» – weak advance in the transported daily mass of class 2; «$+\Delta S_4$» –strong deviation of the daily active losses of class 4. This means that it is necessary to switch to the cantilever supply circuit of the traction network and maintain the voltage on the substation bus-bars to ensure the permissible 21 kV for ERS.

In the conditions of the need to save energy and reduce the cost of transportation on electrified railway lines, the greatest effect (from 5 to 15 %) is achieved through the introduction of complex information technologies, which are based on tariffs that are rational in terms of the cost of electricity, optimal train traction modes, and traction modes that are rational in terms of power flows and external power supply.

An improved expert decision-making system for regulating the operating modes of traction and external power supply systems, which allows to increase energy-economic efficiency and promptness of decision-making in the case of incomplete or contradictory information. The principles of forming algorithms and filling databases and knowledge of expert systems have been developed, and the tasks of ensuring energy-saving operation modes of traction power supply systems in the conditions of the functioning of the wholesale electricity market have been solved.

Expert systems are the basis of the intellectualization of automated power supply management systems and automated systems of commercial electricity accounting [1, 8]. The application of ES in the integrated control systems was held back by the lack of technical means of automation to solve traction power supply problems, taking into account the number and heterogeneity of information sources and the need to make decisions in conditions of incomplete or contradictory information. It is easiest to apply ES at the level of organizational and economic management of an integrated system. However, the high efficiency of their application will be at the level of organizational-technological and technological management.

The paper proposes an approach to the implementation of energy-saving technologies of traction power supply of railways, which uses fuzzy models and methods of presentation, analysis and selection of controls. This approach makes it possible to use heterogeneous and limited data to make a decision on the choice of rational modes of TPS, taking into account the modes of operation of their energy systems.

At the stage of forming the fuzzy control model, it is taken into account that the TPS regimes are influenced by many uncertain factors. Among them are such as the mode of operation of electric traction loads, voltage levels of traction substations, power supply schemes of traction networks. Despite the presence of such a constant factor as the track profile, on which the mode of driving the train directly depends, rational control is unique for each trip.

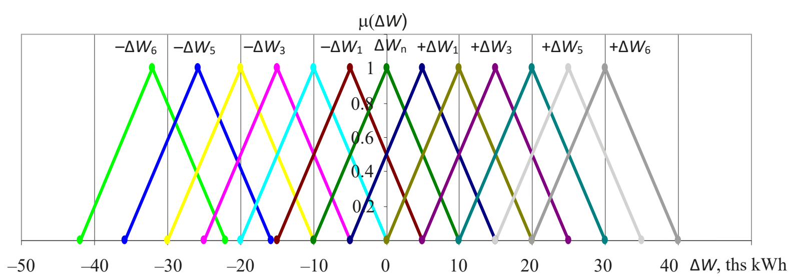

Fig. 6. Membership functions for approximation of the fuzzy value W_p

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The recommended control system seeks to increase the voltage level on the traction substation buses in order to reduce energy losses in the intersubstation area and ensure the required level of EMF. This is due to the fact that the mode of elimination of power flows by switching to the cantilever circuit of the power supply of the traction network was taken as the control, so increasing the voltage level brings the system closer to optimal control.

The conducted studies have shown sufficient accuracy of the received TPS control modes. The constructed base of fuzzy rules, which replaces the model of TPS regimes, can be used as an advisor to the energy dispatcher to choose management at the next time interval, taking into account the conditions of uncertainty.

4. Conclusions

The improved expert decision-making system for regulating the operation modes of the traction and external power supply systems makes it possible to enhance energy-economic and decision-making efficiency in the event of incomplete or conflicting information. The principles of formation of algorithms and filling of data and knowledge bases of expert systems are developed and the tasks of providing energy-saving modes of operation of the traction power supply systems in conditions of functioning of the wholesale power market are solved.

Based on simulations and conducted experiments, it has been found that cantilever power circuits can be economically viable for railways at low freight flows and high power flows. The transition to cantilever power supply circuits for AC traction networks recommended on the basis of the studies performed allows reducing the total power consumption of traction substations by about 2–5 %. The implemented recommendations made it possible to save about 25 thousand kW·h per 1 km of the double-track section.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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