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INTELLIGENT COMPUTER NETWORK FOR OPTIMIZING POWER SUPPLY MODES OF RAILWAY INFRASTRUCTURE: MATHEMATICAL MODEL AND FUNCTIONING ALGORITHM

Troianivskyi V.I.

ІНТЕЛЕКТУАЛЬНА КОМП'ЮТЕРНА МЕРЕЖА ДЛЯ ОПТИМІЗАЦІЇ РЕЖИМІВ ЕЛЕКТРОПОСТАЧАННЯ ЗАЛІЗНИЧНОЇ ІНФРАСТРУКТУРИ: МАТЕМАТИЧНА МОДЕЛЬ ТА АЛГОРИТМ ФУНКЦІОНУВАННЯ

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The article examines the problem of increasing the energy efficiency of traction and non-traction power supply systems of railway infrastructure in conditions of increasing unevenness of load, significant wear and tear of the main equipment and the urgent need to restore the transport network of Ukraine after war destruction. The relevance of the study is due to the fact that traditional approaches to the management of power supply modes do not provide sufficient flexibility and promptness of response to changing operating conditions, which is especially critical during the period of reconstruction of energy and transport infrastructure with limited material and financial resources.

The purpose of the work is to substantiate the feasibility of building an intelligent computer network (ICM), which unites traction substations, sectioning posts, means of measuring electricity quality indicators and dispatch centers into a single information and control circuit with the possibility of automated decision-making support. Such a network allows continuous monitoring of the condition of the equipment, collection and processing of data on power supply parameters in real time and formation of recommendations for optimal system operation modes.

A mathematical model for optimizing power supply modes has been developed, which takes into account the train schedule, uneven traction load, power losses in the traction network and restrictions on electricity quality. The task is formulated as a multi-criteria optimization with the objective function of minimizing total power losses and voltage deviations, provided that technological limitations are observed, which allows simultaneously taking into account several contradictory efficiency criteria.

An algorithm for the functioning of the ICM is proposed, which implements a full control cycle: data collection, identification of the current mode, short-term load forecasting, solving the optimization problem, ranking variants of control influences and their implementation in automatic or dispatch mode with further adaptation of the digital counterpart of the network. The practical implementation of the model is based on a two-level decision-making scheme: strategic daily planning of modes by

nonlinear programming methods and evolutionary algorithms, as well as operational adjustment based on expert logical rules within acceptable technological limitations. This approach ensures the flexibility of the system in conditions of limited resources for the restoration of energy and transport infrastructure.

The article provides a structural diagram of the three-tier ICM architecture and a block diagram of the algorithm for its functioning. The expected effect of the application of the proposed approach in the form of reducing electricity losses in the traction network and improving the quality indicators of electricity supply is illustrated on the conditional calculation example of the railway section. The results of the study can be used during the design of intelligent power supply management systems in the process of restoration and modernization of the railway infrastructure of Ukraine, as well as serve as a basis for further research in the field of digitalization of energy transport systems.

Keywords: *intelligent computer network; railway power supply; mathematical model; optimization algorithm; digital twin; energy saving; power quality*

Problem statement. Railway transport remains the main consumer of electricity among the modes of transport of Ukraine: about 90–95% of freight and passenger transportation is carried out on electric traction, which determines the high sensitivity of the industry to the quality and reliability of electricity supply. Traction power supply (STE) systems are characterized by a sharply variable time and space nature of the load due to the train schedule, which causes significant uneven loading of traction substations, increased power losses in the catenary network and voltage deviations beyond the permissible values.

The situation is complicated by the wear and tear of a significant part of the equipment of power supply systems, as well as large-scale destruction of energy and transport infrastructure facilities as a result of full-scale armed aggression against Ukraine. Restoration and modernization of railway infrastructure should be carried out not by simply reproducing previous technical solutions, but on the basis of digitalization and implementation of intelligent management systems (Smart Grid technologies) [1], capable of ensuring energy saving, increasing the reliability and survivability of the power supply network in conditions of limited resources for restoration, which is consistent with the priorities of the National Transport Strategy of Ukraine for the period until 2030 [2].

Existing systems of dispatch control and data collection (SCADA) in railway transport mostly perform monitoring and signaling functions, but do not ensure the automated formation of optimal control influences in real time. This determines the relevance of the development of an intelligent computer network (ICM), which combines the functions of monitoring, mathematical modeling of modes and decision-making support by dispatching personnel in a single circuit for managing the power supply of railway infrastructure.

Analysis of basic research and publications. The issue of modeling and optimization of modes of power supply and power consumption systems is considered in the work of V. G. Yagupa and K. IN. Yagupa [3], where modern methods of optimizing the modes of electrical networks are systematized, in particular using symmetro-compensating devices and active filters. Variational methods of mathematical modeling of optimal modes of electric power systems based on the principle of least action are highlighted in work [4].

The results given in work [5], devoted to the synthesis of distributed computer-integrated networks and technologies of intellectualization, monitoring and optimization of power supply modes and energy saving of railways, are close to the topic of this article, in which a model of the system of monitoring and management of power supply network modes is proposed and the expediency of organizing synchronously registered primary data in the form of a single information space is substantiated. The issue of the application of intelligent technologies for the selection of capacitive compensation parameters in traction networks in order to increase energy efficiency is considered in work [6]. Certain aspects of the construction of decision support systems for operational rail transport personnel, in particular with the application of the IEC 62290-1 standard, are highlighted in the work [7].

Among foreign studies, the methods of energy management and optimization of modes of traction power supply systems are summarized in an overview work [8]; the issue of operational optimization of train-network interaction for urban rail transport is considered in works [9; 10]; the issue of building a digital double of the traction network of high-speed trains is highlighted in works [11; 12].

At the same time, the analysis of available publications shows that most of the research concerns either the separate mathematical modeling and simulation of power supply system modes, or the separate construction of information-measuring and monitoring networks, while the issue of integrating a mathematical model of mode optimization with an algorithm for the functioning of a single intelligent computer network, focused on the conditions of the post-war restoration of the railway infrastructure of Ukraine, remains insufficiently developed. This defines the purpose of this study.

The purpose and tasks of the research. The purpose of the research is to develop a mathematical model and algorithm for the functioning of an intelligent computer network to optimize the power supply modes of railway infrastructure, aimed at reducing electricity losses and improving the quality of electricity supply.

- To achieve the goal, the following tasks were set:
 - - justify the architecture of the intelligent computer network for the power supply of railway infrastructure;
 - - formulate a mathematical model of the problem of optimization of power supply modes;
 - - to develop an algorithm for the functioning of ICM, which implements a cycle of monitoring, optimization and decision support;
 - - carry out simulation modeling of the proposed approach on a conventional section of the railway and evaluate its impact on electricity losses and indicators of the quality of electricity supply.

Statement of the main research material

Architecture of an intelligent computer network.

The proposed ICM is built according to the three-tier principle (Fig. 1). The field level combines direct control objects: traction substations, sectioning posts, compensating devices, as well as current, voltage and electricity quality indicators (in particular, the THD harmonic distortion coefficient) [13], integrated with relay protection and automation controllers. The level of local computing nodes (edge servers) provides preliminary processing of primary data, their filtering from emissions, synchronization by time stamps, as well as short-term load forecasting. The upper, dispatch level contains a mode database, a digital twin of the power supply network, an optimization problem solving unit, and a decision support system (DSS) with an automated dispatcher workplace.

The digital double as part of the ICM is used as a model information environment for assessing the current state of the network, predicting changes in modes and pre-checking the admissibility of the proposed control influences.

Data exchange between levels is carried out by fiber-optic communication channels laid along the railway track, with redundancy through wireless channels, which increases the survivability of the information infrastructure in conditions of possible damage.

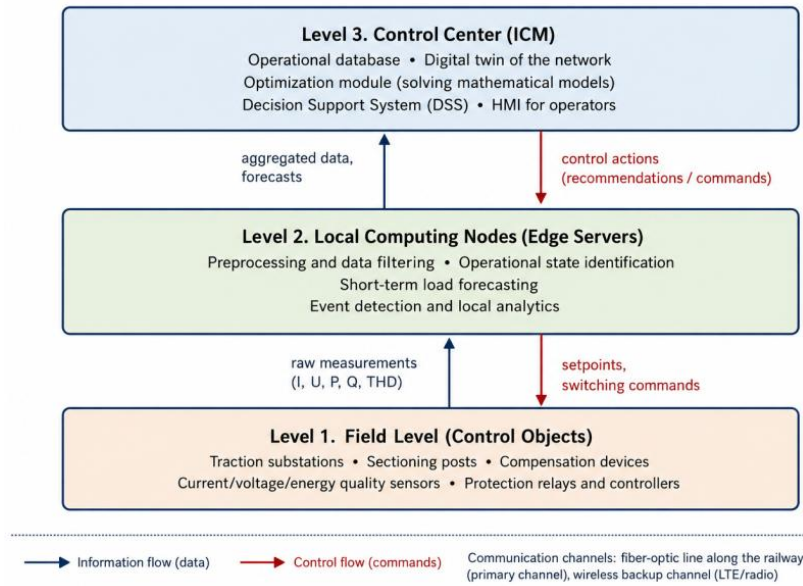


Fig. 1. Three-tier architecture of an intelligent computer network for the power supply of railway infrastructure

Mathematical model of optimization of power supply modes. The section of the railway, the power supply of which is carried out from N traction substations during the calculation period, divided into T discrete intervals with a duration of Δt (for example, a day with a step of 15–30 min), is considered. For each interval $t = 1, \dots, T$ and each substation $i = 1, \dots, N$ the following control and state variables are introduced:

$P_i(t)$ – active power supplied by substation i ;

$Q_i(t)$ – setting of the compensating (adjusting) device of the substation i ;

$U_j(t)$ – voltage at node j of the network;

$\Delta P_i(t)$ – power losses associated with the section served by substation i .

The traction load $P_{load}(t)$ is determined according to the train schedule (number, mass and speed characteristics of trains on the section at the moment t), and the load of non-traction consumers $P_{nt}(t)$ – according to statistical data of electricity consumption accounting.

Taking into account the need to simultaneously minimize energy losses and voltage deviations, the optimization problem is initially considered as multi-criteria. For practical implementation in ICM, it is reduced to a single-criteria problem by additive convolution of normalized criteria. The objective function of the optimization problem is formulated as the minimization of the weighted sum of the total electricity losses and voltage deviations from the nominal value for the calculation period:

$$F = \sum_{t=1}^T \sum_{i=1}^N [\Delta P_i(t) + \lambda_1 \cdot \sum_{j=1}^N (U_j(t) - U_{nom})^2] \cdot \Delta t \rightarrow \min \quad (1)$$

where λ_1 – is the weighting factor that agrees on the dimensionality and significance of the component of voltage deviations relative to power losses;

U_{nom} – is the nominal value of the voltage in the corresponding network node. The value λ_1 is chosen by bringing the terms of the objective function (1) to a comparable, dimensionless form (by normalizing the component of voltage deviations relative to U_{nom}^2) with subsequent analysis of the sensitivity of the solution in the range $\lambda_1 = 0.1-10$; for the calculation example given in the subsection «Estimation of expected efficiency», $\lambda_1 = 1.0$ was used, which corresponds to the point of compromise on the Pareto front between the minimization of power losses and voltage deviations.

Optimization is carried out under the following restrictions:

$$\sum_{i=1}^N P_i(t) = P_{load}(t) + P_{nt}(t) + \sum_{i=1}^N \Delta P_i(t), \quad \forall t; \quad (2)$$

$$U_{min} \leq U_j(t) \leq U_{max}, \quad \forall j, t; \quad (3)$$

$$0 \leq P_i(t) \leq P_{i,max}, \quad Q_{i,min} \leq Q_i(t) \leq Q_{i,max}, \quad \forall i, t; \quad (4)$$

$$THD_j(t) \leq THD_{allow}, \quad \forall j, t; \quad (5)$$

$$\sum_{t=1}^T k_i(t) \leq n_{max}, \quad \forall i. \quad (6)$$

where equation (2) – is the power balance in the network; expressions (3) – is the limit on the voltage level in the controlled nodes that meet the current regulatory requirements [14]; expressions (4) – is the limit on the power of substations and the adjustment range of compensating devices; expression (5) – is the limit on the coefficient of harmonic voltage distortions; expression (6) – limit on the number of commutations $k_i(t)$ of the sectioning and adjusting devices of the substation I during the calculation period in order to reduce the wear of the switching equipment. The limit value n_{max} is set in accordance with the permissible switching resource of a

specific device and the requirements of its operational documentation.

Problem (1)–(6) is a nonlinear conditional optimization problem with mixed continuous and discrete variables (due to the discrete nature of commutations), which generally belongs to the class of NP-complex. For practical implementation within the ICM, a two-level solution scheme is proposed: at the strategic level (daily mode planning), the problem is solved by nonlinear programming methods or evolutionary methods (genetic algorithm, particle swarm method) with the formation of a plan-graph of substation modes; at the operational level, between cycles of full recalculation, the adjustment is performed by an expert subsystem based on logical rules which takes into account the current deviations from the planned regime and ensures a quick reaction without violating the restrictions (3)–(6).

Algorithm of functioning of ICM. The functioning of ICM is implemented in the form of a cyclic process (Fig. 2), covering the following stages:

1st stage – collection of measurement data from field-level objects;

2 stage – verification and data preprocessing (emission filtering, synchronization);

3 stage – identification of the current network mode by comparing the received data with a digital twin and calculating current voltage losses and deviations;

4 stage – short-term load forecasting based on train schedule and statistical models (with a forecasting horizon of 2–4 h, i.e. 4–8 intervals Δt , which is specified at each calculation cycle);

5 stage – of solving the optimization problem (1)–(6) for the forecasting horizon;

6 stage – formation and ranking of control impact options (optimization of load distribution between power zones according to available network adjustment capabilities) with assessment of the expected technical and economic effect of each option.

Next, in step 7, depending on the criticality of the control influence for traffic safety and stability of the power supply, the algorithm branches: non-critical, reversible actions (for example, changing the compensation settings within the permissible range) are performed automatically (step 7a); actions potentially affecting the train schedule or the reliability of the power supply are transmitted to the dispatcher for confirmation through an automated workplace (step 7b). The selected control influence is implemented at field-level facilities (step 8), after which the achieved effect is controlled, the parameters of the digital network counterpart are adapted, and the results are logged for further improvement of the forecasting model (step 9). The cycle is repeated according to the schedule with the period Δt , and is also initiated unscheduled in case of detection of an emergency deviation of the mode parameters (step 10).

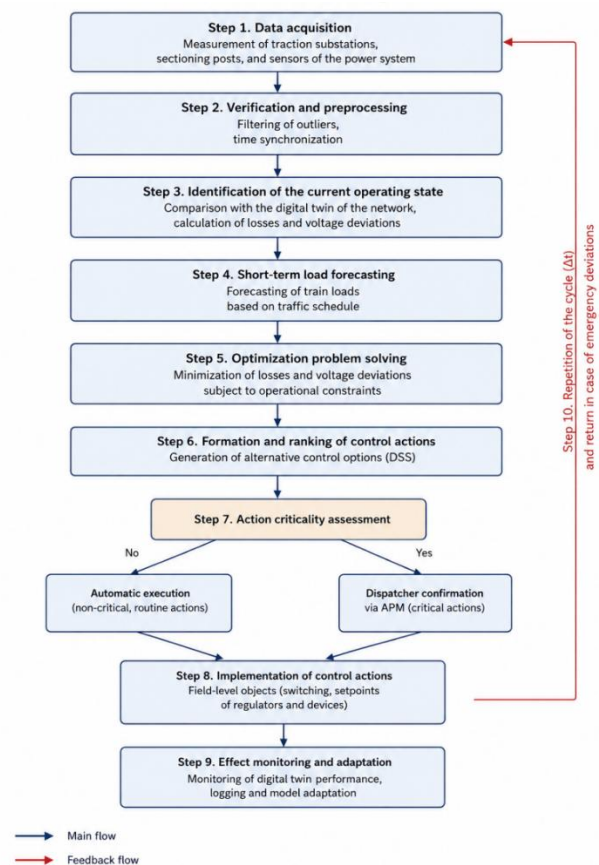


Fig. 2. Algorithm for the functioning of an intelligent computer network for managing power supply modes

Results of simulation modeling. To illustrate the proposed approach, a conditional calculation example of a railway section with three traction substations ($N = 3$) is considered according to the daily train schedule, divided into $T = 48$ intervals with a duration of $\Delta t = 30$ minutes. Two modes were compared: the basic mode, in which the load is distributed in proportion to the service areas of substations without applying optimization, and the mode formed according to the model (1)–(6) with $\lambda_I = 1.0$. The summarized results of the comparison are given in the table.

The results obtained from the conventional example illustrate that the redistribution of the load between substations and the adjustment of the settings of compensating devices during periods of peak traction load allow to reduce the total loss of electricity in the traction network by approximately 15 % and to reduce the duration of intervals with a voltage deviation beyond the permissible range by more than three times, while not exceeding the limit (6) on the number of equipment switches. The given quantitative values are obtained on model input data and are illustrative in nature: they are not the result of processing measurements of a real section of the railway and serve only to demonstrate the order of the expected effect of applying the proposed approach.

The quantitative results obtained on a conditional example are consistent with the conclusions of works [3;

5] on the effectiveness of intellectualization of the management of railway power supply modes and confirm the expediency of further testing of the proposed model and algorithm on the data of the real section of the railway network using software tools for modeling electrical modes.

Table

Comparison of indicators of power supply modes of the railway section (conditional example)

Indicator	No optimization	By model (1)–(6)	Change
Total power losses in the traction network per day, kWh	842	715	–15,1 %
Maximum voltage deviation from U_{nom} , %	9,8	6,2	–3,6 percentage points
Total duration of intervals with U outside the permissible range, min	180	45	–75 %
The number of commutations of compensating devices per day	6	5	within limits $n_{max} = 8$

Conclusions. The paper proposes an intelligent computer network for optimizing power supply modes of railway infrastructure, which integrates means of monitoring, local data processing, mathematical optimization, digital model information environment and decision support. The proposed three-level architecture ensures the formation of a closed information and control circuit from obtaining data on the current state of the electrical network to the formation and implementation of control influences.

A mathematical problem of optimizing power supply modes is formulated, in which energy losses and voltage deviations are simultaneously taken into account. For practical implementation, the multi-criteria formulation is reduced to a single-criteria formulation by additive convolution of normalized criteria. The restriction system takes into account the power balance, permissible voltage limits, power limits of traction substations, reactive power compensation parameters, electricity quality indicators and the permissible number of switching of the regulating equipment.

An algorithm for the functioning of an intelligent computer network has been developed, which involves the sequential implementation of the stages of data collection and verification, assessment of the current state of the network, load forecasting, solving the optimization problem, formation and ranking of control solutions, their implementation and further control of results. It is provided to distinguish between automatic control actions and decisions that require confirmation of dispatching personnel.

Based on the results of simulation modeling of a conventional section of the railway, it was established

that the application of the proposed approach ensures a reduction of daily energy losses from 842 to 715 kWh, that is, by 15.1%. The maximum voltage deviation is reduced from 9.8 to 6.2 %, and the duration of the voltage output intervals beyond the permissible limits – is reduced from 180 to 45 min. The number of switches in the calculation mode is reduced from 6 to 5, which corresponds to the set limit on the number of switches.

The obtained quantitative results have the character of a simulation assessment, since they are formed on model input data and are not the result of processing operational measurements of a real section of the railway. Therefore, it is advisable to consider the proposed approach as a basis for further testing on real data of traction substations, train schedules and parameters of power supply modes.

It is advisable to direct further research to the calibration of the mathematical model based on operational data, the study of the sensitivity of the results to changes in the weighting coefficients of the target function, the expansion of the predictive component of the algorithm, taking into account the experience of integrating renewable energy sources and accumulators into traction power supply systems, as well as the software implementation of the optimization module as part of an intelligent computer network.

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Троянівський В.І. інтелектуальна комп'ютерна мережа для оптимізації режимів електропостачання залізничної інфраструктури: математична модель та алгоритм функціонування

У статті розглянуто проблему підвищення енергоефективності систем тягового та нетягового електропостачання залізничної інфраструктури в умовах зростаючої нерівномірності навантаження, значного зношення основного обладнання та загальної потреби у відновленні транспортної мережі України після воєнних руйнувань. Актуальність дослідження зумовлена тим, що традиційні підходи до управління режимами електропостачання не забезпечують достатньої гнучкості та оперативності реагування на змінні умови експлуатації, що особливо критично в період відбудови енергетичної та транспортної інфраструктури за обмежених матеріальних і фінансових ресурсів.

Метою роботи є обґрунтування доцільності побудови інтелектуальної комп'ютерної мережі (ІКМ), яка об'єднує тягові підстанції, пости секціонування, засоби вимірювання показників якості електроенергії та диспетчерські центри в єдиний інформаційно-керуючий контур з можливістю автоматизованої підтримки прийняття рішень. Така мережа дозволяє здійснювати безперервний моніторинг стану обладнання, збирати та обробляти дані про параметри електропостачання в

реальному часі та формувати рекомендації щодо оптимальних режимів роботи системи.

Розроблено математичну модель оптимізації режимів електропостачання, яка враховує графік руху поїздів, нерівномірність тягового навантаження, втрати потужності в тяговій мережі та обмеження щодо якості електроенергії. Задача сформульована як багатокритеріальна оптимізація з цільовою функцією мінімізації сумарних втрат електроенергії та відхилень напруги за умови дотримання технологічних обмежень, що дозволяє одночасно враховувати кілька суперечливих критеріїв ефективності.

Запропоновано алгоритм функціонування ІКМ, що реалізує повний цикл управління: збір даних, ідентифікацію поточного режиму, короткострокове прогнозування навантаження, розв'язання оптимізаційної задачі, ранжування варіантів керуючих впливів та їх реалізацію в автоматичному або диспетчерському режимі з подальшою адаптацією цифрового двійника мережі. Практична реалізація моделі спирається на дворовенну схему прийняття рішень: стратегічне добове планування режимів методами нелінійного програмування та еволюційними алгоритмами, а також оперативне коригування на основі експертних логічних правил у межах допустимих технологічних обмежень. Такий підхід забезпечує гнучкість системи в умовах обмежених ресурсів на відновлення енергетичної та транспортної інфраструктури.

У статті наведено структурну схему триярусної архітектури ІКМ та блок-схему алгоритму її функціонування. На умовному розрахунковому прикладі ділянки залізниці проілюстровано очікуваний ефект від застосування запропонованого підходу у вигляді зниження втрат електроенергії в тяговій мережі та покращення показників якості електропостачання. Результати дослідження можуть бути використані під час проектування систем інтелектуального управління електропостачанням у процесі відновлення та модернізації залізничної інфраструктури України, а також слугувати основою для подальших досліджень у сфері цифровізації енергетичних систем транспорту.

Ключові слова: інтелектуальна комп'ютерна мережа, електропостачання залізниць, математична модель, алгоритм оптимізації, цифровий двійник, енергозбереження, якість електроенергії

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