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A Cyber-physical Approach to Control and Management of Railway Power Supply Systems

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ABSTRACT
This paper develops digital models that can be used to build cyber-physical railway power supply systems (RPSS). We employed methods of modeling that were developed at the Irkutsk State Transport University. These methods, implemented in the Fazonord industrial software package and are based on the use of phase coordinates and lattice equivalent circuits that present complete graphs with branches formed by electrical impedances. They allow calculating complex non-symmetric, non-sinusoidal and limiting modes; provide adequate modeling of active elements of smart grids; contribute to solving additional problems, for example, determining electro-magnetic influences on adjacent power lines and modeling electromagnetic fields created by power lines and traction networks. The distinctive feature of the methods are their multi-phase, multi-mode and multitasking performance.

Keywords: *Cyber-physical systems, Railway power supply systems, Modeling, Control.*

1. INTRODUCTION

Modern AC railway power supply systems (RPSS) are complex objects [1] that incorporate two closely interconnected segments: (i) physical segment, consisting of power elements that provide the supply of electrical energy to rolling stock and stationary transport facilities, and (ii) segment of information and control. In the ongoing implementation of individual stages for digital transformation of the electric power industry [2–7], the complexity of the second segment that provides control becomes comparable to the physical (technological) part of the RPSS. Therefore, it can be viewed as a class of cyber-physical power systems (CPPS) that comprise power objects (power lines, transformers, catenary, etc.), measuring complexes, information transmission networks and control computers that use intelligent algorithms. The CPPS concept is based on deep integration of computing resources into physical processes [5]. In contrast to automated control systems for industrial facilities, the CPPS provides a closer connection and coordination between computing and physical resources. Monitoring and control of energy processes is carried out using a large number of feedbacks; in this case, performance results of algorithms influence physical components, and the information on the operation modes of RPSS and current parameters of its individual elements is used to modify the control algorithms and reconfigure the automatic regulators. The enlarged structure of the CPPS is shown in Figure 1.

2. LITERATURE REVIEW AND PROBLEM STATEMENT

A significant number of works address design and development of cyber-physical power systems and power supply systems, some of which are presented in References [8–26]. Analysis of reliability of CPPS can be found in [9–15]. Issues of the CPPS cyber security are considered in [5, 16, 17]. Some particular aspects of the CPPS modeling and control are studied in [18–26]. However, the problems of using the cyber-physical approach to modernize the power supply systems of railways are not considered in the works available to the authors. The design and creation of cyber-physical power supply systems implies the use of the most modern information and computer technologies [27]: artificial intelligence, big data, the Internet of things, quantum computing, etc. However, the core of the virtual part of the CPPS should comprise digital models based on algorithms for solving traditional electrical problems. These include the tasks of calculating regular and emergency modes, determination of power quality indicators for deviations and voltage fluctuations, as well as the levels of asymmetry of harmonic distortions [28-30]. In addition, operational practice requires addressing the issues of ensuring the personnel safety [31], planning ice-melting modes, determining the heating temperatures of wires and thermal wear of transformers [32]. To solve these problems, methods and algorithms proposed in [28-31] and based on application of phase coordinates can be used.

The models implemented on the basis of these methods satisfy the following requirements: •

• They predict complex non-symmetric (regular and emergency), non-sinusoidal, and limit modes;

• They provide adequate simulation of active elements, such as variable reactive power sources, harmonic conditioners, DC links, etc.;

• They can be used to solve additional problems, for example, such as determining electromagnetic influences on adjacent power lines, as well as modeling electromagnetic fields generated by power lines and traction networks.

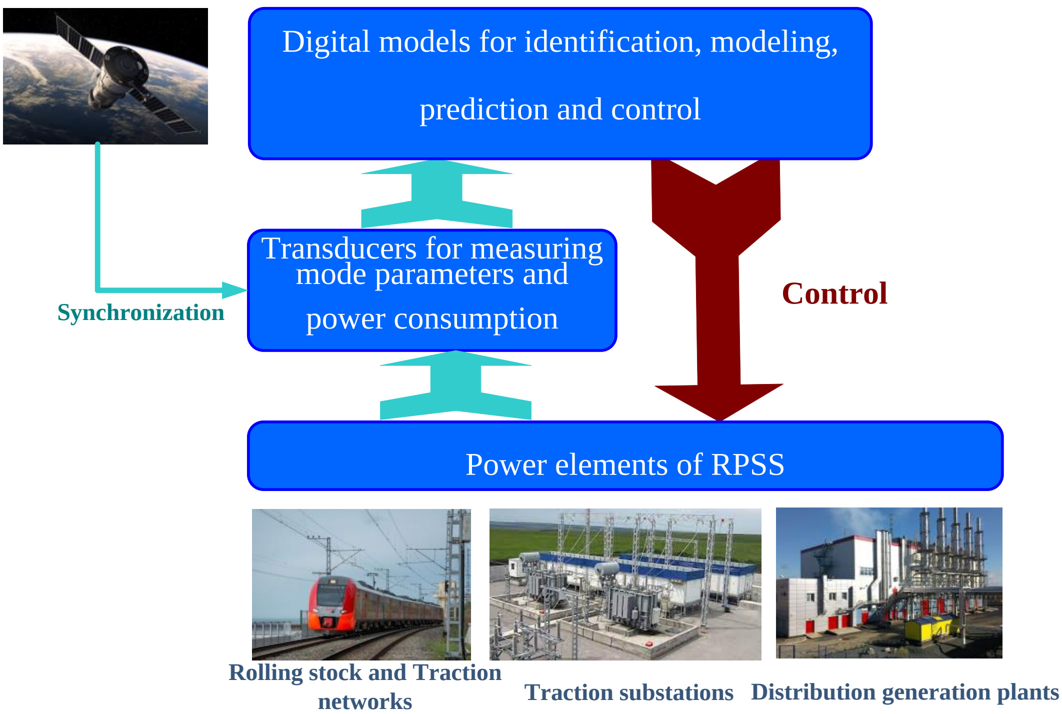

Figure 1 Diagram of a cyber-physical power supply system.

3. METHODS FOR MODELING CPPS

The methods described in [28–31] and implemented in the Fazonord industrial software package [28] are based on the ideas of constructing models of elements of electric power systems (EPS) and RPSS using phase coordinates; at the same time, the main power elements of EPS and RPSS, which include power lines, transformers and contact networks, are considered as multi-wire or multi-winding objects and are represented in the form of lattice equivalent circuits with a fully connected topology.

On the basis of this approach, we developed methods and computer technologies with the following key features (Figure 2):

• multiphase performance, i.e. the ability to simulate multiphase systems (single-phase, three-phase, four-phase, six-phase and their various combinations in one network);

• multimode performance, which allows simulation of a wide range of EPS and RPSS modes: regular and emergency, asymmetric, non-sinusoidal, limiting in terms of static aperiodic stability;

• multitasking performance, which provides solution of additional tasks important in practice: determination of induced voltages on adjacent ETLs [28]; calculation of the strengths of electromagnetic fields generated by traction networks [31]; parametric identification of ETLs and transformers according to measurement data obtained from the PMU WAMS devices [33]; taking into account active elements in modeling of RPSS [29]; modeling of thermal processes during ice melting.

A block diagram explaining the relationship between the tasks solved during the multifunctional modeling is shown in Figure 3.

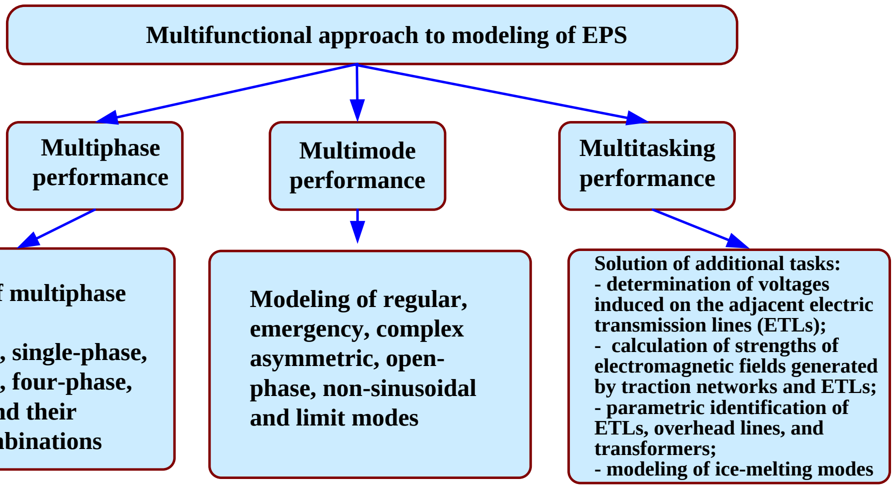

Figure 2 A fragment of the RPSS model in MALAB.

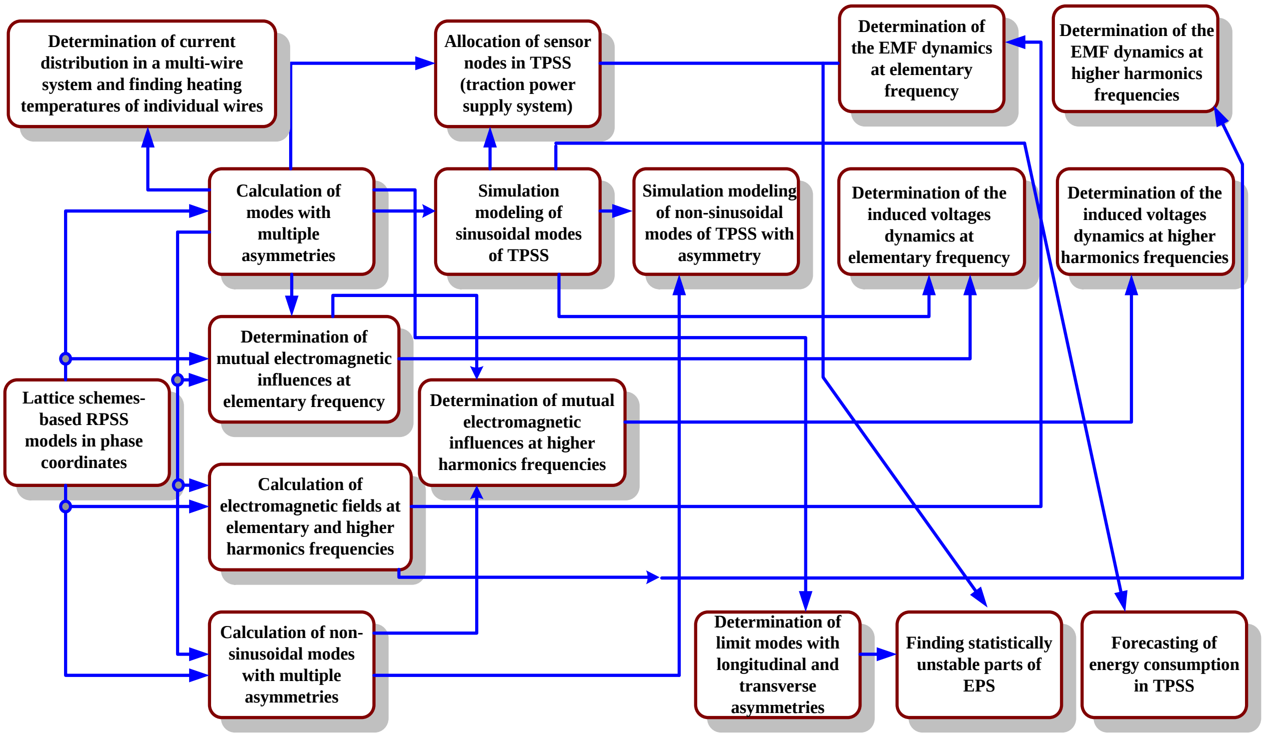

Figure 3 A fragment of the RPSS model in MALAB.

The power supply system of a railroad trunk line is a complex dynamic object that can be described by a system of nonlinear differential equations of large dimension

$$\frac{d\mathbf{X}}{dt} = \mathbf{\Phi}(\mathbf{X}, \mathbf{V}, \mathbf{S}, \mathbf{C}, t), \qquad (1)$$

where **X** is an *n*-dimensional vector of mode parameters; **Φ** is an *n*-dimensional vector-function; **V** is an *m*-dimensional vector of perturbations; **C** is an *l*-dimensional vector of controls; **S** is a *q*-dimensional vector that comprises structure parameters of the RPSS.

The diagram of this model is shown at Figure 4.

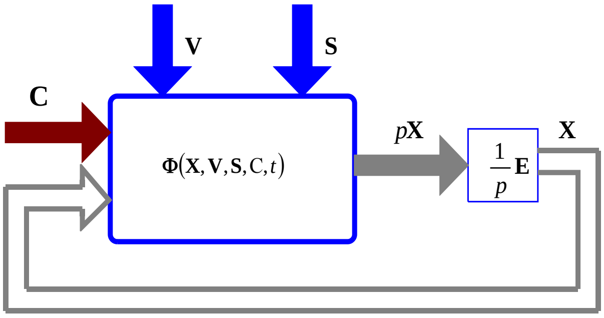

Figure 4 Diagram of model (1): $p = \frac{d}{dt}$ is a differential operator; **E** is an identity matrix.

Due to its large dimension and complexity, the practical use of model (1) at the present stage is not possible. Therefore, simulation methods are used to determine the RPSS modes [28]; in this case, we use the concept of instantaneous circuits and reduce model (1) to a set of static circuits. To carry out the simulation, the interval under study T_M is divided into small subintervals Δt . At each subinterval, the parameters $\mathbf{X,S,C,V}$ are taken constant.

Construction of a simulation model of the RPSS requires modeling of individual elements with an algorithm for their interaction and includes the following components: modeling of the train schedule; formation of instant schemes corresponding to each subinterval Δt and mode calculation for each of them; finding integral indicators of simulation modeling.

On all intervals, the following non-linear system describing the steady state mode of the corresponding instantaneous scheme is solved:

$$\mathbf{F}_k(\mathbf{X}_k,\mathbf{S}_k,\mathbf{C}_k,\mathbf{V}_k) = \mathbf{0}, \qquad (2)$$

where $\mathbf{X}_k,\mathbf{S}_k,\mathbf{C}_k,\mathbf{V}_k$ are the values of the vectors $\mathbf{X,S,C,V}$ for a *k*th instantaneous scheme.

The modeling methodology [28], implemented in the Fazonord software package, makes it possible to calculate modes of the RPSS that includes three complex subsystems: traction power supply system (TPSS); external power supply system (EPSS) formed by high-voltage power grids adjacent to traction substations; regions of power supply (RPS) to non-traction and non-transport consumers. The modeling algorithm can also include the stage of taking into account the graphs of changes in stationary loads supplied from the PSS and RPS networks. The block diagram of the system is shown in Figure 5, and an enlarged diagram of the algorithm is shown in Figure 6.

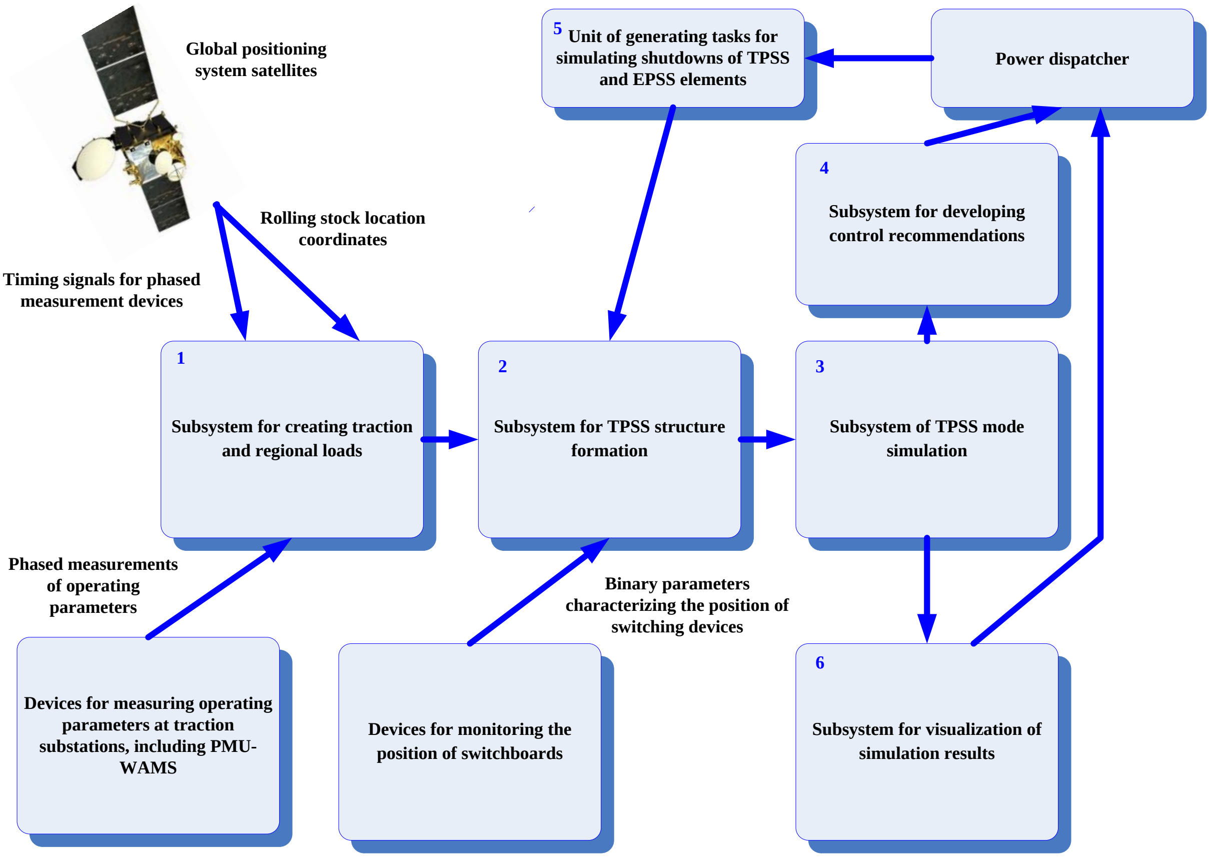

Figure 5 Operational control diagram.

At present time and in the mid-term perspective, real-time information can be accessed only by using the elements of the EPSS that are directly adjacent to the high-voltage busbars of the transformer substation. Therefore, when solving problems of operational control, it is necessary to build an equivalent model of the EPS main network [34].

Figure 5 shows the following main segments of the electrotechnical core of the CPPS:

• assessment of the state using the information received through the channels of the information network of the CPPS;

• prediction of the loads of stationary objects;

• formation of a simplified (equivalent) model of the EPS external network and its operational correction in case of changes in the circuit-mode situation;

• modeling based on train schedules, traction calculations, assessment of the state of the EPSS and prediction of stationary loads;

• construction of the vector of controls.

The goals of implementing the cyber-physical approach are as follows:

• uninterrupted power supply to traction of trains, as well as to important objects of railway transport ensuring the safety of their movement;

• ensuring high quality of electricity on 110-220 kV transformer substation buses, in 25 and 2x25 kV traction networks, as well as in distribution zones;

• minimization of losses of electrical energy in traction power networks and RPS;

• ensuring electromagnetic safety when personnel are exposed to electromagnetic fields generated by traction networks [31];

• efficient control of modes of power traction networks, taking into account train masses, movement sizes and track profiles.

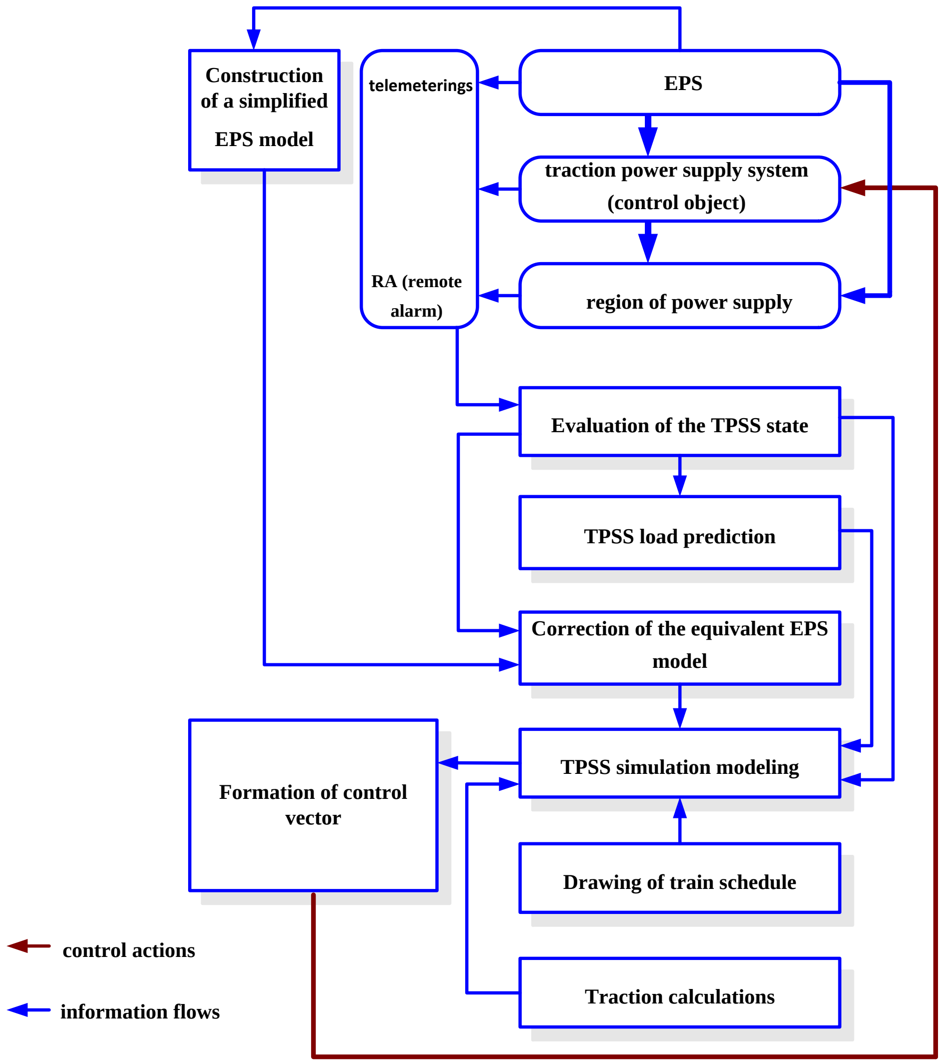

Figure 6 Diagram of operational control of the RPSS.

The special feature of the cyber-physical approach is that the digital models described above are continuously updated through the processing of measuring information coming from the PMU WAMS devices [34] synchronized by signals from global positioning satellites. In addition, satellite technologies [35] are used in drawing of train schedules, which is especially important for high-speed railway lines [36]. Based on measurements, parametric identification of the power elements of the RPSS is periodically carried out [33].

When building the CPPS, the concept of the energy Internet can be used [37], according to which a traction substation and adjacent networks of 25 or 2x25 kV can be considered as energy cells, Figure 7.

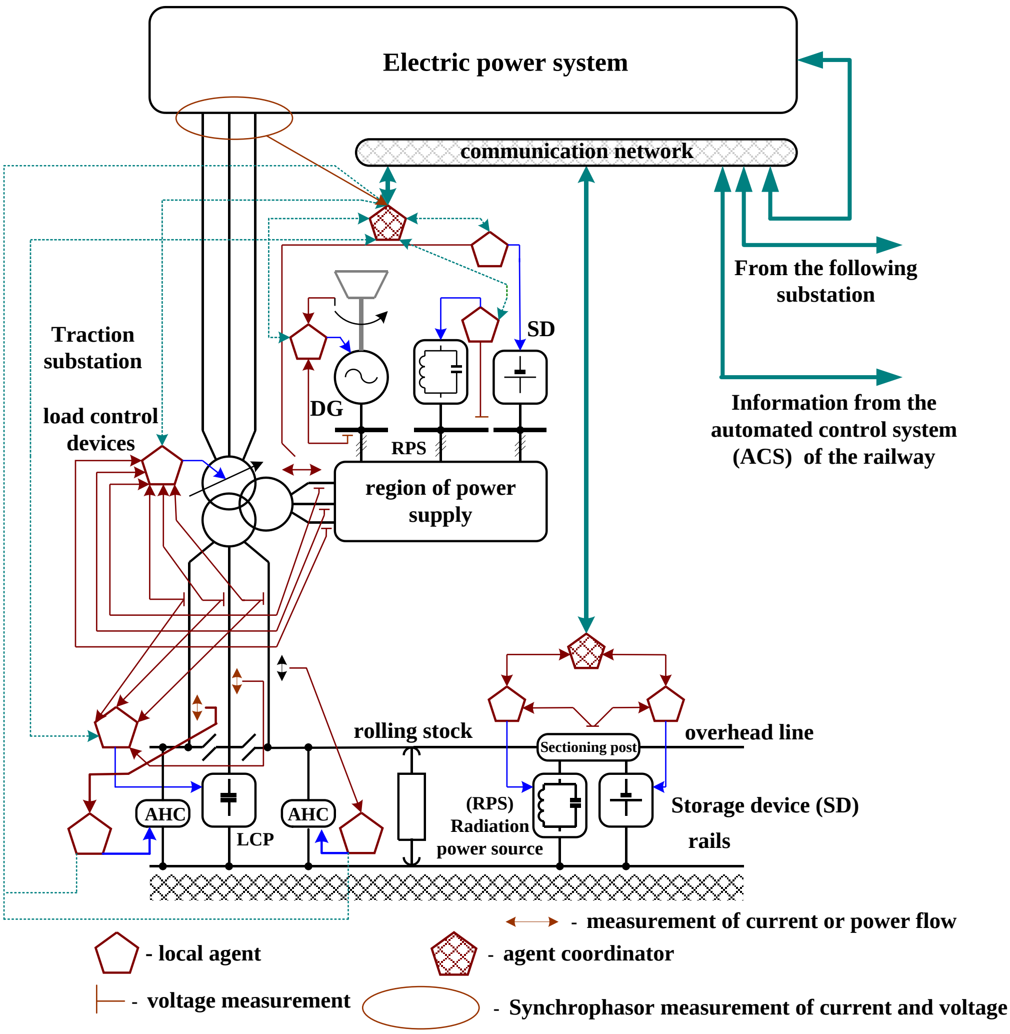

Figure 7 Diagram of the CPPS energy cell: DG – distributed generation; AHC – active harmonic conditioners; LCP – longitudinal compensation plants.

Apart from the standard equipment of transformer substations and traction stations, these cells may include the following active elements of the smart grid: active harmonic conditioners (AHC); controlled reactive power sources (RPS); longitudinal compensation plants (LCP); energy storage devices (ESD); distributed generation (DG) plants; load control devices (LCD) for transformation coefficients of traction transformers. To control energy cells, multi-agent technologies can be used [29].

4. EXAMPLES OF MODELING CPPS

The limited size of the paper does not allow us to give detailed examples of modeling CPPS on the basis of technologies presented above [28–34]. Therefore, below are examples of modeling the modes and conditions of electromagnetic safety, performed in Fazonord [28]. We studied the RPSS which diagram is shown in Figure 8.

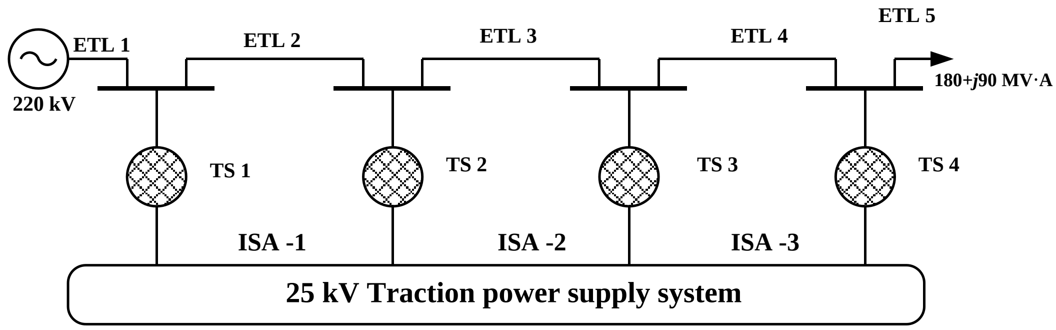

Figure 8 The RPSS diagram: ISA – intersubstation area; TS – traction substation; ETL – electric transmission line.

We simulated the movement of nine trains weighing 4084 tons in an odd direction (Figure 9a). The current profiles of the train are shown in Figure 9b. It was assumed that an adjustable RPS was installed on the buses of the 220 kV traction substation 4; the RPS ensured stabilization of line voltages at 216 kV. The simulation results are illustrated by Figures 10–13. Negative values of active power in Figure 10b correspond to regenerative braking modes with the return of electrical power to the network.

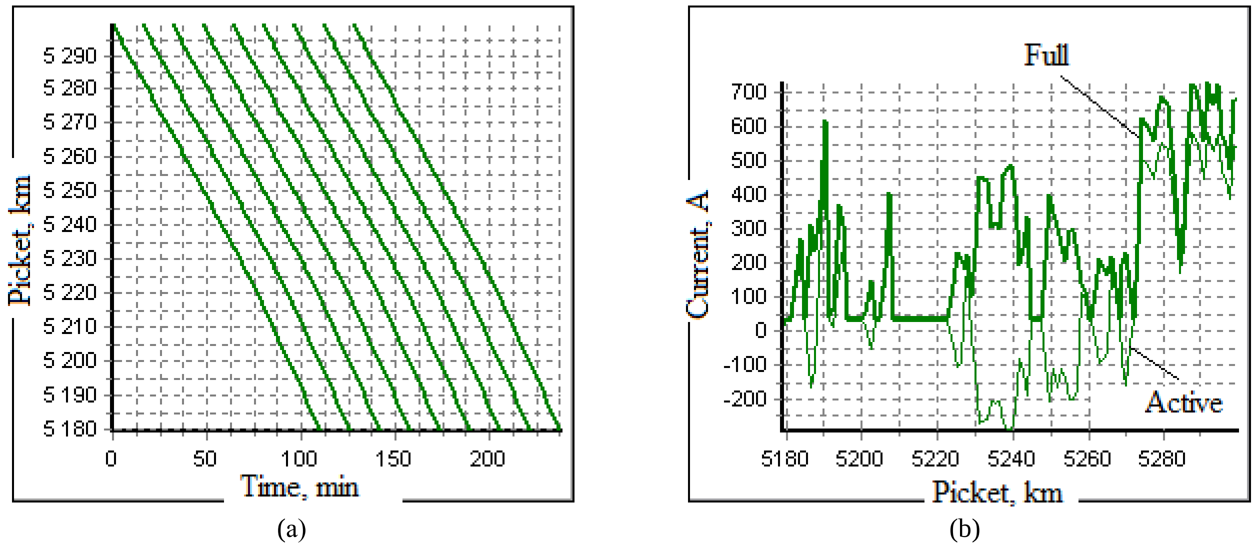

Figure 9 Schedule (a) and current profile of an odd train weighing 4084 t (b).

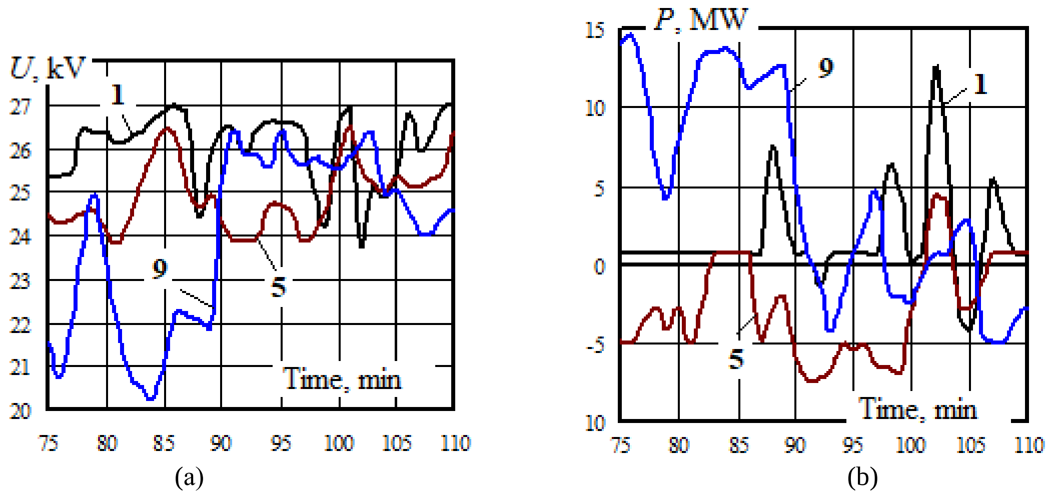

Figure 10 Voltages on current collectors of electric locomotives (a) and active powers consumed (generated) by electric locomotives (b): digits indicate train numbers.

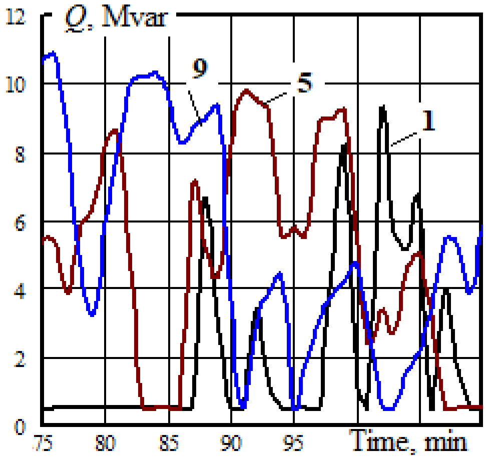

Figure 11 Reactive power consumed by electric locomotives.

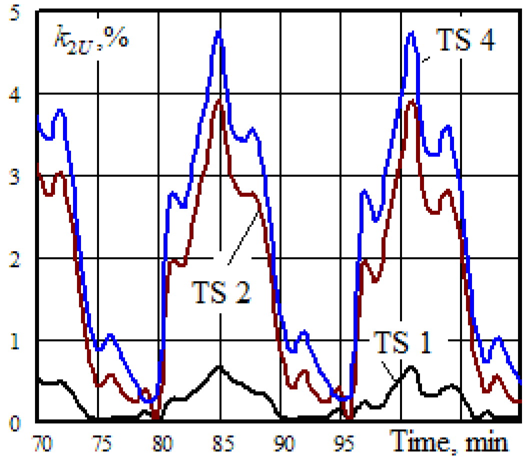

Figure 12 Return sequence asymmetry coefficients on buses of the 220 kV TS.

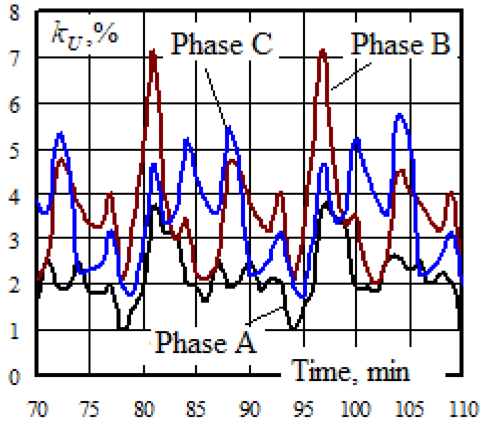

Figure 13 Total harmonic coefficients on buses of the 220 kV TS 3.

The simulation results draw us to the following conclusions:

1. In the considered simulation interval, we can observe a voltage drop on the pantograph of train No. 9 below the allowable limit of 21 kV, which requires mode correction. For example, it can be done by switching on a controlled RPS on the 27.5 kV buses of traction substations or putting into operation the LCP devices. In addition, it is possible to increase voltage on the current collectors by changing the setting of the RPS installed on the 220 kV buses of the traction substation 4 provided that it has a power reserve.

2. Asymmetry coefficients on buses of the 220 kV traction substation 2 and traction substation 4 go beyond the normally allowable limit of 2 %. If the excess time exceeds 5 %, then it is necessary to turn on symmetrization devices [30].

3. Coefficients of harmonics on buses of the 220 kV traction substation also go beyond the allowable limits, which requires the inclusion of active harmonic conditioners [29, 30].

5. CONCLUSIONS

Methods for determining the modes of cyber-physical power supply systems for AC railways are proposed. Based on the results of computer modeling, it was shown that effective computer models for solving these problems can be implemented on the basis of methods developed for modeling EPS and RPSS in phase coordinates.

AUTHORS' CONTRIBUTIONS

Conceptualization: Y.B., A.K. and K.S.; methodology: Y.B. and A.K.; software: Y.B.; validation: Y.B., A.K. and K.S.; formal analysis: Y.B. and A.K.; investigation: Y.B., A.K. and K.S.; resources: K.S.; data curation: A.K.; writing original draft preparation: Y.B.; writing review and editing: Y.B., A.K. and K.S.; visualization: Y.B.; supervision: K.S.; project administration: Y.B. and A.K. All authors have read and agreed to the published version of the manuscript.

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