Development of the theory and methods for calculating the rational operation modes of electric traction equipment of urban electric transport

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Abstract. The article considers the process of converting electrical energy into targeted mechanical motion of electric stock during the implementation of all technological conditions of the production system of urban electric transport. The aim is to confirm the proposed scientific hypothesis that the operation modes of electric traction equipment are formed under the influence of a complexly organized electric thrust process and are the basis of its topological structures. The theoretical study carried out on the basis of the methodological analysis of the theory of electrical equipment, the theory of automatic control and automated electric drive, the theory of electric traction, the theory of motion construction, the systematic approach and the synergistic paradigm resulted in the formulated scientific concept (theoretical system), which identifies the process of electric traction as a system consisting of five levels that are hierarchically related and solve an individual specific task of developing the electric vehicle motion. The obtained theoretical system will allow developing the general theory of electric traction of urban electric transport by improving its methodological foundations and can find practical application when developing methods for calculating its rational modes of operation.

1. Introduction

The development of concepts about the formation of rational modes of operation of traction electric equipment (TEE) of electric rolling stock (ERS), the architecture of interactions with other technical, technological and production processes that characterize the fulfillment of electric traction (ET), helps to solve the actual scientific problem of increasing the efficiency of electric energy system of urban electric transport (UET) [1-3]. The issues concerning the TEE theory associated with the calculation of the technological modes of its work are included in the subject area of the ET theory [4-6]. This allows us to suggest that the improvement of fundamental concepts of the ET formation as a process of converting electrical energy into a targeted mechanical motion of ERS when all technological conditions of the UET production and technical system are fulfilled, can be a methodological basis for the development of the theory and methods for calculating TEE rational operating modes [7-9]. In this regard, the authors for the first time formulated a scientific concept based on a system approach and synergetic methodology of ET interpreting as an open, complexly organized process, the topological basis of a multi-level configuration of which is realization of TEE operation modes as part of an ERS automated electric drive [10-13].
2. Methods of theoretical research

The main idea of the proposed scientific concept (theoretical system) is the interpretation of the ET technological process, the main task of which is the targeted mechanical motion of ERS, which is realized by TEE as part of an automated electric drive, as a set of hierarchically aligned levels (subprocesses). To identify these levels, the theory of “motion building” was used, which was proposed by O.N. Bernstein, the famous biomechanics of the first half of the 20th century [14] and found application in robotics and mechatronics [15]. According to this theory, the realization of controlled motion of objects or systems of various nature, including the technical ones, is carried out through its “construction”. In this case, the motion construction occurs in the general case by 5 levels (“A”, “B”, “C”, “D”, “E’), which are called “levels of motion construction” [14].

On the basis of this theory, the UET ERS levels of motion construction when ET is fulfilled can be identified as follows:

The first level A is a special level of motion construction, at which motion as such is absent, but at the same time there are processes associated with the preparation for motion, i.e. resource support of the process of UET ERS motion.

The second level B is the level of motion construction in the system’s own coordinates (a specific ERS), i.e. spatial, time and force coordination of the TEE mechanical work as part of an automated traction electric drive.

The third level C is the level of motion construction in the surrounding objective space, i.e. spatial, time and force coordination of ERS controlled mechanical motion in terms of the motion route (scheme and profile of the path, etc.).

The fourth level D is the level of motion construction of the system when interacting with objects of the surrounding space, conditioned by the ideas about their qualities and properties of mutual relations (based on objective monitoring of parameters by measurement equipment), i.e. realization of targeted mechanical motion of ERS in the conditions of the transportation process technology (inter-train interval, travel time, etc.)

The fifth level E is the level of motion construction of the system when interacting with objects of the surrounding space, based on acquired knowledge about their qualities and properties of mutual relations, i.e. the implementation of the “idealized” ERS motion, which satisfies the main forecast parameters of the production process task of the UET, formed by the organizational management system.

Levels of motion construction are arranged in accordance with the hierarchy of specific tasks to be solved. At the same time, tasks are solved in parallel, for each level they are continuously formed by the higher level and control the lower level, subject to the conditions of the task of the overall process of mechanical motion of ERS.

The process of ERS motion discussed above can be conditionally represented as the “mechanical” component of the ET process. It is obvious that there is also an “electrical” component that determines the processes of converting electrical energy, forming electrical modes of the TEC, interacting with the energy system, other ERS, etc. These processes also have a clear hierarchical structure and, in the general case, can be represented by 5 levels of construction of the ET system (both in direct and alternating currents) [16]. The real technological process of ET cannot be divided into components, but the conducted analysis allows us to conclude that the main process is also a system of levels connected by hierarchical subordination. At the same time, one of the main conditions for the implementation of the ET process in an open, complex UET system is the exchange of energy $R_E$ (electrical, thermal, mechanical energy, etc.), material $R_M$ (including financial and personnel) and information $R_I$ resources between levels and the external environment [17-19]. When considering the synergetic methodology while describing open complex systems and processes, the definition of “information as measures of Order” is used as opposed to the concept of “entropy as a measure of Chaos” [19]. Under the exchange $R_I$ we will understand any interactions that lead to an “increase in the Order” of the processes and the system as a whole. These can be restrictions, conditions and requirements (“order parameters”) for the processes and phenomena that take place, which are expressed in regulations, instructions, norms, etc.

Thus, we formulate the scientific concept (theoretical system) on construction the ET process in the form of a didactic (from the ancient Greek διδακτικός “explaining”) scheme presented in Figure 1.
The main task of the first level of energy supply ($L_1$) is reliable and stable energy supply of the whole ET process. Obviously, this is provided by the UET traction power supply system associated with the city’s power system, which is a manifestation of the influence of the external environment ($R_E$). The reliability of the traction power supply system is ensured by efficient technical maintenance ($R_M$) and is governed by regulations ($R_I$). We accept that exchanges $R_M, R_I$ occur at all levels of construction of ET and we will not consider them further.

The second level of implementation of the work of electrical equipment ($L_2$) provides ET implementation at the stage of TEE characteristics formation (angular speed of TED shaft rotation $\omega(I)$, TED moment $M(I)$, TED efficiency $\eta_d(I)$, power $P_2(I)$, heating time constant $\tau_\infty(I_D)$, etc.), which are uniquely defined at the design stage and implemented in an automated mode, by indirect control system algorithms.

If ERS is conditionally hang on the ropes and the same control algorithms are used, then the generated traction and braking modes of TEE operation will be identical. That is, at the level $L_2$ a specific problem is solved, which, in the absence of a “master” set $\{\} R_I$ from the level $L_3$ implements the projected modes of ET.

If ERS is set on rails, then an external traction force arises $F_{TR}(\psi_K)$, which in the theory of traction determines the tangential force of traction $F_{Tang}$. Appearing of $F_{TR}$ determines the “transition” to the next level $L_3$, characterized by ERS interaction with the surrounding space and its elements. Interaction with the external environment, sets the conditions (set $\{\} R_I$) for the level $L_2$, (main resistance to motion $\omega_0(v)$, resistance from curves $\omega_c(s)$, resistance from biases $i(s)$, etc), being additional “order parameters” [19].

The third level of ERS controlled motion ($L_3$) forms a controlled mechanical motion of ERS required for motion along a section of the path (with specific characteristics) when exposed to certain external impacts (climatic, weather, etc.). At this level, ET construction algorithms are formed when ERS is moving along individual sections (straight section, with a slope, with a different level of ERS loading etc) or their combinations. It is obvious that for each section, the motion algorithms of TEE and ERS, (level $L_2$), are implemented identically. The level characteristics $L_3$, (ERS traction characteristic $F(v)$, ERS braking characteristic $B(v)$, TEE current versus speed $I(v)$, etc.) are formed taking into account the “order parameters” ($R_I$). The ET managed at level $L_3$ is not yet focused, i.e. implemented in terms of the technology of train work (taking into account the motion time $t_X$, motion interval $\Delta t_{im}$, average running speed $v_{Rav}$, the amount of ERS at the route $n_{ERS}$, speed limitations $v_{lim}$, etc), formed by the set $\{\} R_I$ at the level $L_4$. 

Figure 1. Theoretical system of electric traction process construction $L_1 - L_4$ are levels of the process of electric traction; $R_{M,E,I}$ are exchange of technical maintenance, energy and information resources.

The fourth UET process implementation level ($L_4$) provides the formation of a targeted ET, corresponding to the technological conditions of train work and constructed through the implementation of tasks at the levels $L_1 - L_3$. ET characteristics at the level $L_4$ are the motion curves $v(t), v(s)$, the current consumption curves $i(t), i(s)$, the TED heating curves $\tau(t), ...$ for specific conditions of train operation.

The fifth UET process implementation level ($L_5$) forms ET in accordance with the tasks of the UET production process, which are identified by a set of instructions, regulations, rules, and guidelines, determining the “order parameters” ($R_I$) of the level $L_5$, the average ERS operational speed $v_{oper}$, the specific electrical energy flow rate $A_{sp,rate}$, the rate of passengers carried $W_{sp,rate}$, the amount of traffic $N_{acc,rate}$, and TU...
accidents $N_{acc.rate}$ etc). Such a set $\{\}_{RR}$, formed by a system of the organizational management of an enterprise, as well as by system of levels higher than the UET one (economical, ecological, energy, social, and other systems of the city, region, country) govern the characteristics of ET realization at the level $L_5$, (the specific consumption of electricity for traction $A_{sp}$, the amount of passengers carried $W_{sp}$ etc). The implemented characteristics differ from the “order parameters”, but tend to them, forming the ET process, corresponding to the strategic tasks of the UET production process.

3. Conclusion
Thus, the authors theoretically substantiated that ET is a complex multi-level process, which is based on the conversion of electrical energy into mechanical motion of ERS according to the technology of the transportation process of the UET production and technical system. The implementation of the process of ET, or according to the authors’ definition - its construction, takes place along hierarchically aligned levels, each of which solves a specific task. Each level, being in the hierarchical subordination of the superior one and receiving from it and from the “external environment” conditions for solving its own task, forms the implementation conditions for the lower level. Moreover, each subordinate level forms the basis for the implementation of a subprocess of a higher level. Due to this, continuous interaction between levels and the external environment is realized, which is expressed in the flows of energy, material and information resources, which, according to the modern synergetic world outlook, is an indispensable condition for the existence of complex dynamic systems and processes.

Methodologically important is the confirmation that the modes of TEE operation are the basis of the ET process, because they are formed at the level $L_2$, which implements the conversion of electrical energy into mechanical energy, which, in accordance with the proposed theoretical system (Figure 1), is the base of the construction of the remaining levels determining the UET production process technology.

The theoretical studies presented in this paper allow developing the theory and methods for calculating rational modes of operation of the UET TEE, as well as improving the methodological basis for training transport industry specialists in the light of modern system-synergetic ideas [20], which together will contribute to solving an important scientific and topical practical problem of improving energy efficiency of the UET system.

4. References
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