New methodological approach to the development of the theory of electric traction of urban electric transport

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Abstract. The article presents the scientific hypothesis that the modes of operation of electric traction equipment as part of an automated electric drive of the rolling stock of urban electric transport are formed under the influence of a complexly organized technological process of electric traction and are the topological basis of its structure. The aim of the study was to study the process of converting electrical energy into a targeted mechanical movement of rolling stock in the implementation of all technological conditions of the production and technical system of urban electric transport. The theoretical study was carried out on the basis of a methodological analysis of the theory of electrical equipment, the theory of automatic control and an automated electric drive, the theory of electric traction, the theory of motion construction, a systematic approach and a synergistic natural science paradigm. The main result is a formulated scientific concept, which allows to present the process of electric traction as a system consisting of five levels that are in hierarchical relations and solve each specific problem of building the movement of electric transport. The obtained theoretical system will allow developing the general theory of electric traction of urban electric transport by improving the methodological principles of the formation of operating modes of electric traction equipment when implementing the transportation process technology in the production and technical system of urban electric transport.

Introduction

On the modern urban electric transport (UET) for the implementation of controlled mechanical movement is widely used automated traction drive, improving the energy efficiency of which is an important scientific problem, which has important national economic importance. The implementation of the specified operating modes of the electric traction electrical equipment (TEE) that is included in the electric drive is carried out by means of an indirect control system (driver / driver controller) in an automated one, and when using an automated driving system - in automatic modes. In this case, the modes of operation of the TEE, providing for the implementation of electric traction, are interrelated with the modes of movement of electric rolling stock (ERS) [1 - 3].

The general theory of UET electric equipment, based on the methodological principles of the theory of electric machines, the theory of automatic control and automated electric drive and the
theory of electric traction, has many methods for calculating rational modes of operation of the TEE, which practice shows, do not always show a sufficient level of adequacy for UET. Obviously, this is due to the high complexity of the processes that determine the formation of the operation mode of the TEE during the implementation of electric traction in the UET system and the lack of a sufficiently elaborated methodology for their interpretation in the sectoral theory [4, 5]. Against this background, many researchers confirm that experienced, well-trained drivers are able to implement rational modes of operation of the feasibility study, providing ERS modes of movement, saving up to 10% of electricity compared to the resulting map and recommended for execution [6 - 8]. All this determines the relevance of the scientific problem of the development of the theory and methods for calculating rational operating modes for a feasibility study of ERS UET based on the development of a methodology for describing the processes that determine the formation of operating modes of a feasibility study as part of an automated electric drive when implementing the UET technological process.

As mentioned above, the issues of the theory of electrical equipment related to the calculation of the technological modes of its operation as an element of the automated electric drive ERS lie in the subject area of the theory of electric traction. This fact determines the possibility of developing the theory and methods for calculating rational operating modes of traction electrical equipment by improving the basic concepts of the formation of electrical traction as a process of converting electrical energy into a targeted mechanical movement of ERS in the implementation of all technological conditions of the production and technical system of UET. For this, the authors formulated a scientific hypothesis based on a system approach and synergetic methodology on the interpretation of electric traction as an open complexly organized process, the topological basis of a multi-level configuration of which is the implementation of TEE operation modes as part of an automated electric drive [9 - 12]. Such a methodological approach will allow us to develop ideas about the formation of the operating mode of traction electrical equipment, the architecture of interactions with other technical, technological and production processes that characterize the implementation of electric traction, which will help to solve the actual scientific problem of improving the efficiency of the automated traction drive.

**Methods of theoretical research**

According to the scientific hypothesis expressed, the electric traction process, the main task of which is the purposeful mechanical movement of the ERS, implemented by the TEE as part of an automated traction drive, can generally be represented by a set of hierarchically aligned subprocesses. To describe these subprocesses, it is advisable to use the theory of “building motion” proposed by the famous biomechanics of the first half of the twentieth century. ON. Bernstein [13] and has found application in robotics and mechatronics [14]. In accordance with this theory, the realization of controlled motion of objects or systems of various nature, including biological and technical, is carried out by means of its “construction”. In this case, the construction of motion occurs in the general case by 5 levels (“A”, “B”, “C”, “D”, “E”), which are called “levels of motion construction” [13]. The theory of motion construction determines the mechanisms of motion control and management, which are formed in a special way by levels and have a complex structure. Such a mechanism of “building motion” allows organizing an effective algorithm of “building solutions” in controlling the motion of complex dynamic systems [14].

Based on this theory, the levels of construction of the ERS movement during the implementation of electric thrust can be identified as follows:

- **Level A (Yₐ)** – a special level of building movements, on which movement as such is absent, but at the same time there are processes associated with preparing for movement, i.e. resource support of the ERS process.

- **Level B (Y₈)** – the level of building motions in the system’s own coordinates (specific ERS), i.e. spatial, temporal and power coordination of the mechanical work of the TEE as part of an automated traction electric drive.
Level $C$ ($Y_C$) – the level of building motions in the surrounding objective space, i.e. spatial, temporal and power coordination of the controlled mechanical movement of ERS in terms of the route of movement (plan and profile of the track, length of the stage, etc.).

Level $D$ ($Y_D$) – the level of construction of the system's movements when interacting with objects of the surrounding space, determined by the ideas about their qualities and properties of mutual relations (based on objective monitoring of parameters through measuring tools), i.e. implementation of a targeted mechanical movement of ERS in terms of the technology of the transportation process (schedule, inter-train interval, travel time, etc.)

Level $E$ ($Y_E$) – the level of construction of the movements of the system when interacting with objects of the surrounding space, based on knowledge of their qualities and properties of mutual relations, i.e. implementation of hypothetical (“idealized”) mechanical movements of ERS, satisfying the main forecast parameters of the production process task of the UET, formed by the organizational management system.

Levels of building movement are arranged in accordance with the hierarchy of specific tasks to be solved. In this case, the 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 general process of EPS movement. Thus, the hierarchy of subprocesses, tasks at each level of motion building, entering into interrelationships, form the structure of the process of mechanical movement of ERS.

The process of ERS movement described above can be conditionally represented as the “mechanical” component of the implementation of electric traction. It is obvious that there is also an “electrical” component, which determines the processes of electrical energy conversion, the formation of electrical modes of the TEE, interaction with the environment, the energy system, other ERS, etc. Such processes also have a clear hierarchical structure and, in the general case, can be represented by 5 levels of building an electric thrust system (both on direct and alternating currents) [15].

The analysis of conditionally separated mechanical and electrical components of the electric thrust technological process leads to the conclusion that the main process is also a system of levels related to hierarchical subordination and interconnecting the implementation of various specific tasks that together solve the main problem. The real technological process of electric thrust cannot be unambiguously divided into mechanical and electrical components, but the similarity of their hierarchical structures makes it possible to formulate the main features of the construction of the electric thrust process: multilevel process; hierarchy of levels; parallelism and interconnection of subprocesses; exchange of energy, material and information resources between levels and the external environment.

Taking into account the above-listed features, let us formulate a theoretical system (scientific concept) of the levels of construction of the electric thrust process. For the basis we take the provisions of the theory of the construction of motion, since the main task of electric traction is controlled mechanical movement of ERS. This theoretical system of hierarchy of levels of construction of the process of electric thrust is graphically presented in Figure 1.
The multilevel process of electric traction is determined by the presence in its structure of several levels (subprocesses), each of which solves a specific specific task, which differs from the others, but in combination with others, aimed at solving the main task of the process. Such a subprocess or a group of subprocesses can form one of the levels of the system. So in the structure of the process of electric thrust it is proposed to distinguish 5 levels:

1. **The level of energy supply** ($Y_1$). By analogy with the level of $Y_A$, building motion is decisive for the entire process of electric thrust. At this level, the formation of traction as such does not occur, but the functional readiness of the process to the activity is ensured by ensuring a stable and reliable energy supply of the transportation process.

   Energy supply is determined by the methods, methods and means of receiving, converting and distributing energy in the traction power supply system, its technological level, availability of power reserve, material support, as well as the qualifications of service personnel.

2. **The level of implementation of the work of electrical equipment** ($Y_2$). By analogy with the level of hydrocarbons $Y_B$, at this level is considered a subprocess implemented in the system limited by the object’s own coordinates (in this case in the ERS system), without taking into account the action of external forces that change the pulse (amount of motion) of the object (but subject to the exchange of energy, matter and substance with the external environment - heating and cooling of the TEE, electromagnetic interactions, changes in humidity, etc.). It is conditionally possible to imagine that the EPS is suspended on cables over rails and, consequently, there are no tangential traction forces or resistance forces to movement external to the ERS. In this case, the electric thrust generated by the TEE, is implemented as a torque applied to the wheel pair or wheel.

   The subprocess of this level is characterized by certain algorithms for the operation of the TEE and an indirect control system, which are determined by the passport electrical and electromechanical characteristics of their constituent elements. These algorithms are formed at the stage of designing the EPS and uniquely determine the implemented modes of operation, i.e. under identical external conditions, the EPS implements identical characteristics. This is a feature of this level, which consists
in the fact that the algorithms for creating electric thrust are unchanged and are determined at the
design stage by using a TEC with certain characteristics. Changing the algorithms for the
implementation of electric traction requires changing the characteristics of individual elements of the
traction drive system.

3. The level of controlled movement of ERS (Y₃). At this level, by analogy with Yₑ level, a
subprocess of interaction of the ERS with the surrounding space and its elements is formed. So when
the wheelset interacts with the elements of the path, a tangential traction force Fₑ, external to the EPS,
arises, leading to movement, and the electrical and electromechanical characteristics of the electrical
equipment form the ERS traction characteristic. The created Fₑ is controlled, which allows to realize
the controlled movement of the ERS. ERS control is carried out either by the driver or by the
automatic driving system. Different parameters of the surrounding space, expressed in the physical
characteristics of the plan and profile of the track, climatic and weather conditions, voltage at the
current collector, etc., determine the various implementations of electric traction.

The difference of this level from the next one is that in this case electric thrust, and, therefore,
controlled movement is not yet “targeted”, i.e. realizing some goal, in particular - to transport
passengers from one point to another, following in the schedule, while the driver's qualifications at this
level are not taken into account.

4. The level of implementation of the technological process UET (Y₄). At this level, by analogy
with the level of Yᵦ, a subprocess of interaction of EPS with the surrounding space and its elements is
formed taking into account their specific properties and characteristics, for example, the
implementation of the required travel speed on the stretch taking into account the movement schedule,
ensuring speed limits on individual sections, etc. The movement is no longer just “controlled”, but
“targeted”, i.e. aimed at achieving a specific goal - ensuring the transportation of passengers along the
route network in accordance with the technology of the transportation process of the UET and the
quality requirements of train work. At this level, electric traction depends on the level of professional
qualifications of the driver or the ERS driver.

5. The level of implementation of the production process UET (Y₅). This level of the electric
thrust construction system is abstract and corresponds to the Yₑ level in the theory of motion
construction. Its abstractness is associated with the formation of an "idealized" process of electric
traction, which lower levels tend to realize. Conventionally, at this level, a “program is built up”,
according to which the electric thrust process is to be implemented, in accordance with the predicted
“idealized” process, which continuously controls this process and predetermines it (for example, the
predicted level of electricity consumption, passenger traffic, etc.). This subprocess lined up with the
strategy of the production process of the transport production UET.

The hierarchy of the electric traction process is determined by the fact that the subprocesses of the
lower levels are part of the subprocesses of higher levels (see. Fig. 1). Processes of higher levels
“subordinate” to themselves subprocesses of lower ones — they set the parameters and conditions for
their implementation of Rᵦ. In this case, the higher the level of the system, the more complex the task
of implementing electric traction in the UET system, it solves.

So, for example, the subprocess of the controlled movement of ERS (Y₃) includes in its
composition the subprocess of realization of the work of the electric equipment (Yₑ) and at the same
time is part of the subprocess (Y₄) determined by the technology of the transportation process. At the
same time, all these subprocesses include a subprocess of receiving, converting and distributing the
energy consumed by the EPS (power supply subprocess - Y₁), which does not form a movement, but
which provides electrical traction for the whole process, and also obey the subprocess of implementing
the transport production process strategy (Y₅). This subprocess is the highest in this hierarchical
system, since determines the requirements and conditions for the implementation of all previous
subprocesses.

The parallelism of the subprocesses occurring at each level is due to the mechanism for the
implementation of electric traction and the vertical hierarchy of system levels. Levels of a higher order
form their subprocesses not at the end of the subprocess of the lower level of the system, but at the
time of its implementation with continuous interaction, which determines the interconnection of subprocesses. At the same time, the implementation of their specific task is built by the higher level on the basis of the task of the lower level, fully defining the conditions and parameters of its implementation (Figure 1).

Thus, the controlled movement of ERS (Y₃) on an elementary section of the path (with certain parameters) is built on the basis of the implementation level of the operation of the EPS electric equipment (Y₂), which generates algorithms and modes of operation of the automated EPS electric traction drive (climatic conditions and weather conditions, etc.) in which the subprocess Y₃ is built. When executing the EPS technology (Y₄), the movement along the route network while maintaining the driving speed and the inter-train interval in difficult traffic conditions is implemented based on the subprocess of the EPS controlled movement level in the elementary segment, which is formed taking into account the EPS operation conditions. Similarly, the construction of motion for all levels.

The exchange of energy, material and information resources between the levels and the external environment is one of the main conditions for the implementation of the electric traction process in an open complex UET system [16, 17]. Obviously, this condition is strictly implemented only in the general case, and in real conditions, as a rule, only some interactions are obvious. So, for example, energy exchanges (electrical, thermal, mechanical energy, etc.), as well as material resources (including financial and personnel) are obvious [18]. In describing open complex systems, the definition of “information as measures of Order” is used in the synergetic methodology, as opposed to the notion of entropy as a measure of Chaos [19]. By the exchange of information resources, we will understand any interaction leading to the “increased Order” of processes and the system as a whole. It can be various restrictions, conditions and requirements for the parameters of the processes and phenomena (different for each level (subprocess)), expressed also in the regulations, instructions, norms, etc. all that limits (“orders”) the numerous multitude (“Chaos”) of the options for the implementation of a process or its structure. Conventionally, the structural diagram of the exchange of energy \( R_E \), material \( R_M \) and information \( R_I \) resources between the levels of building electric traction and the external environment is shown in Figure 1.

Conclusion

The theory of electrical equipment requires the development of ideas about the traction process, because It is the modes of operation of the feasibility study that unambiguously determine the modes of movement of the ERS, and electric traction is the point of application for managing the production and technical process of the UET, which is not only a scientific, but also an important practical problem.

In the course of a theoretical study based on the proposed hypothesis, the authors formulated a scientific concept representing a technological process of electric traction, the main task of which is to transform the electrical energy of a source into a targeted mechanical movement of ERS, a set of hierarchically aligned subprocesses, each of which is in the hierarchical subordination of a higher level process and forming the conditions for the implementation of the subprocess of the subordinate, decides on a specific the task of building the movement.

The presented theoretical system will make it possible to develop the general theory of UET electrical equipment by improving the methodological principles of the principles of forming the TEE operation modes when implementing the technology of the transportation process in the UET production and technical system. The identified structural and functional relationships of the implementation process of the feasibility study, which characterize the interaction architecture with other technical, technological and production processes ensuring the implementation of electric traction, will allow determining rational modes and methods of controlling automated traction electric drive, which will solve the problem of increasing energy efficiency in the UET system.

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