A simulation model of a traction network taking into account the variable resistance of the contact line and a given power profile of the electric vehicle in MatLAB Simulink

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Abstract. The article describes an approach to the development of a simulation model of an electric transport traction network, taking into account the change in the resistance of the contact wire when the vehicle is moving. The advantage of the model is that it is executed using the building blocks of Simulink, visually reflects the topology of the traction network, and can be used for modeling both trolleybus and rail transport networks. As the initial data for the model, both standardized drive cycles and experimentally obtained modes of vehicle motion can be used.

1. Introduction

Despite the active development of autonomous electric vehicles, interest in electric transport systems powered by a traction network is not waning in the scientific community. In this area of scientific knowledge, it is possible to single out the direction of research aimed to reduce energy losses in the elements of the traction network. These works often consider various technical solutions aimed to reduce power losses in the elements of the traction power supply system. At the same time, the efficiency of the proposed solutions is preliminary estimated using various models, and after that experimental studies are already carried out.

The analysis of modern publications in the field of modeling of electric transport traction networks made it possible to distinguish two main groups of methods that underlie the development of models. The first group of methods is characterized by the use of standard software packages for modeling, primarily MatLAB [1-4]. Such models are built on the use of standard blocks of MatLAB libraries, which makes them possible to reproduce by other researchers. Moreover, these models allow getting visual results. The disadvantages of these models include, for example, the impossibility of taking into account changes in the parameters of the traction network when the rolling stock is moving or its stepwise change. In addition, when modeling the power consumer (rolling stock) itself, the assumption is often used that its characteristics do not depend on the real value of the voltage in the traction network.

The second group of modeling methods is based on researchers own development of programs for calculating complex nonlinear differential equations describing the operation of the traction power supply system [5-9]. These methods are characterized by the ability to analyze complex topologies of the traction network with a variable value of the number of rolling stock units, as well as the ability to...
take into account the modes of regenerative braking. As a rule, these methods [7-9] imply the construction of a network graph in a dynamic mode with subsequent iterative calculation of the electrical characteristics of the system. The rolling stock is modeled by a current source [4, 7] or a power source (consumer) [9]. The main difference between these methods is in the methods of numerical solution of systems of complex nonlinear equations. It should be noted that there is not always a description of the method for obtaining the initial data for modeling, which does not allow assessing the degree of compliance of the considered driving modes with real conditions. The last remark is especially important in the study of ground urban electric transport systems, characterized by significant load fluctuations that are difficult to predict.

The purpose of this work is to create a simulation model of a traction network in the MatLAB which has the following features:

• Taking into account the change of the resistance of the contact wire during the movement of the vehicle;
• Consideration of nonlinearity of characteristics of traction substations;
• Consideration of the possibility of regenerative braking;
• Possibility of using energy storage devices in the traction power supply system or on rolling stock;
• Taking into account the real modes of movement of rolling stock on the line.

2. The model structure and description of its elements
In this work, the blocks of the SimPowerSystems library are used to model the traction network. The main elements of the model are:

• Rolling stock;
• Traction substation;
• Traction network (contact network and feeding lines);
• Control system (rolling stock and variable resistance of the contact wire).

2.1. Rolling stock model
As a rule, simulations are carried out to determine the effectiveness of certain developments by comparing systems before and after changes. In these cases, it is necessary to provide some conditional basis, something that should remain constant, despite the changes introduced. When modeling transport systems, this basis, according to the authors, should be transport work, i.e. the effectiveness of any decisions should be evaluated with the same amount of transport work. This requirement in the model is achieved by maintaining the motion mode.

The literature describes several approaches to building a rolling stock model. For example, an electrical machine block and a power converter can be used. Such a model requires an additional speed regulator unit to set the required motion mode and makes it possible to study processes not only on a large, but also on a small time scale, for example, transient processes and the quality of regulation in a traction power drive. However, for the case under consideration, it is advisable to simplify the model, since, as shown above, the main requirement in modeling rolling stock is to preserve the volume of transport work.

As the initial information for the model, a certain given drive cycle is considered, i.e. dependence of the speed of the rolling stock on time $V(t)$. Based on this dependence and the main characteristics of the rolling stock, it is possible to determine the required electric power consumed by the rolling stock in traction mode ($P_{EL_{-TR}}$) and generated in braking mode ($P_{EL_{-BR}}$):

$$P_{EL_{-TR}}(t) = m \cdot (1 + \gamma) \cdot \frac{dV(t)}{dt} + W_0(t) \cdot \frac{V(t)}{\eta_{TR}}$$

$$P_{EL_{-BR}}(t) = m \cdot (1 + \gamma) \cdot \frac{dV(t)}{dt} - W_0(t) \cdot V(t) \cdot \eta_{BR}$$

(1)
where \( m \) is the mass of the rolling stock, \( m\cdot(1+\gamma) \) is the equivalent mass of the rolling stock taking into account the inertia of the rotating parts, \( W_0(t) = m\cdot(12 + 0.004\cdot V(t)^2) \) is the movement resistance force of the rolling stock. \( \eta_{TR} \cdot \eta_{BR} \) is, respectively, the efficiency of the rolling stock in the traction and braking modes (takes into account energy losses when converting mechanical energy into electrical energy and vice versa).

The rolling stock in the power circuit of the model is represented by a controlled current source, the current reference is determined using a PID controller tuned to minimize the difference between the specified power, determined by (1), and the calculated power, determined as the product of the actual value of the rolling stock current and voltage on its pantograph. To control and evaluate the calculation error, the model provides for the display of the difference between the specified powers \( dP \) (Figure 1).

![Figure 1. Determination of the rolling stock current by the required power.](image)

2.2. Traction network model

The minimum set of traction network elements includes a traction substation, supply lines, which are resistances, and a contact network, which is a variable resistance depending on the position of the rolling stock on the section. The value of the resistance of the contact network at any time for a trolleybus moving away from the traction substation is determined by the expression:

\[
R_{CW}(t) = 2\cdot r_{CW} \cdot L(t) = 2\cdot r_{CW} \cdot \left( L_0 + \int_0^t V(t)dt \right),
\]

where \( L_0 \) is the initial coordinate of the rolling stock, \( r_{CW} \) is the specific resistance of the contact wire, reduced to a unit of length, Ohm/km.

When the rolling stock moves to the traction substation, in expression (2) in front of the integral it is necessary to replace the “+” sign with “-”. When simulating systems with two-sided power supply, it is necessary to additionally determine the resistance of the contact wire of both network arms. Provided that the rolling stock moves from substation 1 to substation 2, the resistances of the contact network will be determined:
where $L_{SEC}$ is the length of the overhead contact section.

In the Simulink, when using the SimPowerSystems library, it is not possible to simulate variable resistance, therefore the authors propose to replace the resistance with a controlled voltage source directed against the flow of the train current with the value:

$$\Delta U_{CW}(t) = I_{RS}(t) \cdot R_{CW}(t),$$  \hspace{1cm} (4)

where $I_{RS}$ is the rolling stock current.

The calculation of the voltage drop ($V_{\text{drop}}$) from the resistance of the contact wire in the traction network model is shown in Figure 2.

![Figure 2](image)

**Figure 2**. Calculation of the voltage drop from the resistance of the contact wire.

The general view of the model for the case of a one-sided power supply circuit and one rolling stock per section is shown in Figure 3. The "ERS Current Estimation" block is a block for determining the vehicle current: its contents are shown in Figure 1. The "Energy Counter" block is a connection of an ammeter, a voltmeter and an integrator to determine the energy consumption from the traction substation. The designation and interpretation of the main elements of the model is presented in table 1.

| Designation   | Appointment                                                                 |
|---------------|-----------------------------------------------------------------------------|
| $V_{\text{kmph}}$ | Rolling stock speed (km/h)                                                  |
| $U_{\text{eps}}, I_{\text{eps}}$ | Accordingly, the voltage on the current collector of the rolling stock (V) and the current of the rolling stock (A) |
| $R_{FL}$      | Feeding line resistance (Ohm)                                               |
| $R_{KS}$      | Contact wire resistance (Ohm)                                               |
| $U_{tp \_xx}$ | Open circuit voltage of traction substation (V)                             |
| $I_{tp1}, U_{tp1}$ | Accordingly, the current of the traction substation (A) and the voltage on the buses of the traction substation (V) |
| $P, dP$       | Accordingly, the actual power consumed by the rolling stock (kW) and the error in calculating the power (W) |
| $TS_{\text{energy}}$ | Energy consumed from traction substation (J)                              |
| $ERS_{\text{energy}}$ | Energy consumed by rolling stock (J)                                      |
3. Discussion of simulation results

In this paper as a starting motion cycle adopted cycle NewYorkBus model ADVISOR [10]. This cycle is characterized by rather low values of both current and average speed, which is typical for movement within the city in a traffic flow. The results of the model experiment are shown in Figure 4. The experiment was carried out with the following parameters of the elements of the traction power supply system: the resistivity of the contact wire is 0.18 Ohm/km, the idle voltage of the traction substation is 600 V.

![Figure 3. General view of the model of a traction power supply system with one-sided power supply and one rolling stock per section](image)

![Figure 4. Model experiment results](image)

The energy consumption for the movement of the rolling stock (when measured on the pantograph) was 6.606 MJ, and the energy consumption for the buses of the traction substation was 7.036 MJ. Thus, the losses in the elements of the traction network amounted to 6.11%. We can also see the change in the total resistance of the catenary from 0 to 0.36 Ohm at the end of the section 1 km long. It is also seen that as the rolling stock moves away from the beginning of the section, an increase in
voltage drops associated with changes in the traction current and an increase in the ohmic resistance of the network is observed.

4. Conclusion
The paper describes the approach to create a simulation model of a traction network taking into account the variable resistance of the contact wire in the MatLAB Simulink. The approach to rolling stock modeling based on the drive cycle is also shown. The paper showed the simulation of a one-sided power supply system is carried out and the possibility of studying a system with a double-sided power supply and several rolling stocks per section.

References
[1] Zakaryukin V et al. International Scientific Conference Energy Management of Municipal Transportation Facilities and Transport EMMFT 2017, Advances in Intelligent Systems and Computing vol. 692, pp. 91-99.
[2] Zhang Y.W. et al. 2011 The International Conference on Advanced Power System Automation and Protection, pp. 946-950, doi: 10.1109/APAP.2011.6180727.
[3] Lui H et al. Proceedings of the 4th International Conference on Electrical and Information Technologies for Rail Transportation (EITRT) 2019, Lecture Notes in Electrical Engineering 638, 623-634.
[4] Fang M et al. IOP Conf. Series: Journal of Physics: Conf. Series 1087 (2018), doi:10.1088/1742-6596/1087/4/042058
[5] Grechishnikov V A 2010 Russian Electrical Engineering 81(5) 246–249
[6] Song Y et al. 2019 Proceedings of the 4th International Conference on Electrical and Information Technologies for Rail Transportation (EITRT), 585-592.
[7] Bosyi D et al. 2017 Transport Problems 12(3) 5-19.
[8] Cherepanov A. et al. 2018 MATEC Web of Conferences 216 02006 doi: 10.1051/matecconf/201821602006
[9] Jing S et al. 2018 Mathematical Problems in Engineering, 3084184.
[10] Zhang Z Z 2013 Applied Mechanics and Materials 416-417 735-738