Operational features of battery-powered electric vehicles in Russia and methods of assessing a state of health of traction batteries

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Abstract. Electric vehicle manufacturers pay particular attention to climatic conditions in the Russian Federation, seeing that chemical reaction rates usually decrease when the environment temperature drops. The analysis of ambient temperature data in the region where electric vehicles will most likely be used aims to select extreme temperatures for calculating powers of a thermostat control system for traction batteries. An electric vehicle simulation model to calculate the power of the thermostat control system for traction batteries is described. An empirical model to assess a state of health of traction batteries is selected. This simulation model adequately reflects thermal processes in a traction battery and can be used for further research.

1. Introduction

Currently, great attention is paid to electric vehicles (EV), and it leads to an increase in the number of such vehicles. The forecasts made by the Directorate-General for Mobility and Transport (DG MOVE) of the European Commission show that the number of electric vehicles will keep increasing and by 2030 the share of light, passenger and commercial electrically powered transport will have reached 31% from the total number of motor vehicles (MV) [1]. Most electric vehicles are not suitable for long-distance routes (between cities), but they are very competitive with ICE vehicles within the same city. The climatic conditions in our country are different and very severe here and there. This work determines the Russian regions where electric vehicles are used and the regions where they will most likely be used. And in these regions, the number of electric vehicles will increase as for using such vehicles there is all the required infrastructure and a fair amount of people. Besides the environment temperature has a significant impact on the performance and energy efficiency of electric vehicles. Therefore, it is necessary to determine design modes (environment temperature curves) and to calculate powers of thermostat control systems (TCS) for electric vehicle traction batteries. Once done, it is possible to determine the average temperature of traction batteries with a simulation model (SM) and to assess its state of health by means of a model-oriented method.

2. Operational features of electric vehicles in the Russian Federation
The increase of hybrid and electric vehicle fleet allows expanding zones for their use, including territories with low temperatures and long winters [1]. According to data of the population density in the Russian Federation [2] (Figure 1) and the climate classification of V.P. Köppen (Figure 2) [3], it can be said that most people live in a humid continental climate with warm summers, in the humid continental climate with hot summers, in the cold semi-arid climate, and the humid subtropical climate. This territory is highlighted with yellow.

Figure 1. Population density in the Russian Federation as of the 1st of January, 2019.

Figure 2. Climate classification in the Russian Federation made by V.P. Köppen.

The main disadvantages of electric vehicles with traction batteries during their using in the Russian Federation consist of a reduction in mileage on a single charge when the temperature drops below zero and an uneven development of charging infrastructure [4]. It is reasonable to use electric vehicles with
a traction battery, first and foremost, in large cities where the charging infrastructure is more
developed. For calculating thermostat control systems, it's necessary to select territories of
metropolises and centres of constituent entities of the Russian Federation. The number of electric
vehicles in these regions will grow, in particular, seeing that there is all the required infrastructure, a
sufficient population density and possibilities to acquire such a type of vehicles. The temperature
drops within 24 hours have been analysed there. These drops are in Figures 3 and 4 [5].

![Figure 3](image3.png)

**Figure 3.** Temperature drop in the city of Krasnoyarsk as of 04.02.2019.

![Figure 4](image4.png)

**Figure 4.** Temperature fluctuation in the city of Astrakhan as of 02.07.2018.

The observation period for the last ten (10) years was not chosen at random as in the last fifty (50)
years the average temperature both in Russia and the whole world had been increasing. It is highly
probable that this trend will continue. See Figures 5 [6] and 6 [7].
Figure 5. Change in the average annual surface temperature.

Figure 6. Globally average combined anomaly of the land-ocean temperature.
3. Assessing the state of health (SOH) of a traction battery

The ability of some LI batteries (LIB) to store energy and to provide specific power is reduced throughout the serviceable life of traction batteries. But the rate of such a change depends on operational conditions of LI batteries. The index of the State of Health (SOH) for LI batteries has been applied for assessing such changes. The State of Health has steadily been reduced both when and without using LI batteries. The reduction in stored energy and power and the increase in resistance are direct indexes for driving range on a single charge. The driving range on a single charge is one of the most important parameters of electric vehicles for consumers. Maintaining optimum temperatures of traction batteries is one of the factors reducing the rate at which the state of health drops [8].

The methods for assessing technical condition can be divided into two principle methods, i.e. an experimental method and a model-based one. Experimental methods analyse cumulative parameters of LI batteries which have an impact on the serviceable battery life during its cycle operation to determine the SOH. Model-oriented methods based on models (mathematical models or equivalent circuits) are calibrated during tests and determine the SOH by assessing battery parameters in real-time.

The temperature is one of the main factors that affect reliability. It is compliant with the reliability theory, according to which the operation of any technical device is an irreversible process. Due to different service-induced defects, any external influence (such as electric, magnetic, thermal, mechanic, etc.) causes a response accompanied with an irreversible transition of the entire object into the other limit state (i.e. this relates to deterioration of output parameters or failure). According to thermodynamics, such transition is related to the energy conversion for activating defects, which average dissipation speed is determined by the Arrhenius equation. The time from starting of use to destruction or reaching the other limit state of any technical object must meet the condition [9]:

\[ t = \tau_0 \cdot \exp \left( \frac{1}{k} \sum_{i=1}^{n} \frac{\Delta W_i}{T_i} \right) \]  

\[ \Delta W_i \] is the activation barrier value or energy stored till the destruction of the \( i \) zone. The activation barrier value \( \Delta W_i \) can be different, but for particular appliances the dynamics of the destruction of different zones can vary enormously.

The LI battery with NMC based cathode material is one of the most advanced LI batteries to be used in electric vehicles with a traction battery and has been chosen for research. Based on the performance analysis [10 - 13] and further prior ranking made by experts from MADI (State Technical University), "Innovation Centre KAMAZ" LLC and FSUE "NAMI", State Research Center of the Russian Federation. The following factors have been determined for ranking while choosing traction batteries:

- Coverage of the DOD or SOC range,
- Coverage of the temperature range,
- Coverage of the C-Rate range,
- Cell capacity,
- Accuracy of the chemistry indication for NMC,
- Consideration of a calendar ageing,
- Consideration of resistance;
- Number of cycles for LI battery testing.

The most appropriate work for this purpose is the one made by John Wang, Justin Purewal, Ping Liu, Jocelyn Hicks-Garner etc. [10]. The formula is below:

\[ Q_{loss,\%} = (a \cdot T^2 + b \cdot T + c) \cdot \exp \left[ (d \cdot T + e) \cdot I_{rate} \cdot \frac{A_{thr}}{\theta} + f \cdot I^{0.5} \cdot \exp \left[ -\frac{E_a}{RT} \right] \right], \]  

where \( \tau_0 \) is a scale factor; \( k \) is the Boltzmann constant; \( T_i \) is a temperature of the \( i \) zone; \( \Delta W_i \) is an activation barrier value or energy stored till the destruction of the \( i \) zone. The activation barrier value \( \Delta W_i \) can be different, but for particular appliances the dynamics of the destruction of different zones can vary enormously.
where \( a \left( \text{1}/\text{A·h·K}^2 \right) \), \( b \left( \text{1}/\text{A·h·K} \right) \), \( c \left( \text{1}/\text{A·h} \right) \), \( d \left( \text{1}/\text{K·(C-rate)} \right) \) and \( e \left( \text{1}/\text{(C-rate)} \right) \) are empirical coefficients, \( E_a \) (kJ/mol) is the activation energy, \( R \) is the Boltzmann constant, \( T \) is an operating temperature (K).

4. Simulation modelling of electric vehicles

The simulation model of the electric vehicle straight-line motion (to analyse a virtual use of a traction battery) has been made for assessing the state of health of a traction battery and the environment temperature impact on the electric vehicle with a traction battery. The general appearance of this simulation model is in Figure 7. The simulation model includes five master units. The first one represents a motion speed generation unit, including several motion strategies, such as speeding-up, braking, as well as a motion in different cycles. The second one represents a traction calculation unit based on the vehicle straight-line motion equation [14]:

\[
F_{af} = F_k - F_b - F_{\phi},
\]

where \( F_{af} \) is a force of resistance against the acceleration of sliding and rotating masses of a vehicle; \( F_k \) is a drive force in a contact pattern of traction wheels; \( F_b \) is an air resistance force; \( F_{\phi} \) is a motion resistance force.

This unit determines the required rotation moment and speed on an electric motor shaft. The third one represents a traction electric motor unit. This unit, serves for entry of such electric motor parameters as peak and long moments versus a rotor speed and a performance factor of an electric vehicle versus a rotation speed moment and a DC voltage in a traction inventor. The fourth one represents a unit to calculate electrical specifications, electric output and energy spent for driving. The fifth one represents a traction battery unit and includes charge and discharge current limitations, voltage decrease with a battery power reduction, heat power produced while charging and discharging, as well as power necessary to dissipate heat. The vehicle traction dynamics takes into account motor torque limitations and battery current and voltage limitations.

![Figure 7. General appearance of the simulation model.](image_url)
The simulation model has been created for a vehicle with a gross mass of 4 tons. The standard electric motor has a rated power of 80 kW and a peak power of 160 kW. The traction battery includes a Li battery with an NMC active cathode material. Its rated voltage makes up to 666 V, and its capacity is equal to 100 A·h. To determine the power of the thermostat control system for traction batteries there have been made several calculations, taking into account an urban bus route within 24 hours and with a mileage of 200 km. The top graph in Figure 8 shows a vehicle speed depending on time. The central graph in the same Figure shows charge and discharge currents of a battery unit, as well as peak and long-term current limitations. The lower curve shows the SOC curve for the traction battery throughout a day. Based on the data, it is clear that charge and discharge currents do not reach peak current limitations, and the SOC does not fall below 25%.

Figure 8. Results of the calculations made according to the daytime mileage.

In the chosen region (city of Astrakhan in Figure 4) a daytime mileage at the extremely high temperature has been calculated to determine cooling powers of the thermostat control system for traction batteries. These calculations have been realised with different cooling powers from 100 to 1000 W with the step of 100 W. The results of the calculations (Figure 9) show that the cooling power of 600 W is sufficient for providing a battery unit performance in the optimal temperature range from +10 to +35 °C [8].

For the day with the lowest temperature in the city of Krasnoyarsk, have been made the same calculations at different heating powers from 1000 W to 3000 W with the step of 200 W to determine heating powers of the thermostat control system for traction batteries. Based on these calculations (Figure 10), it could be concluded that the heating power of 2000 W can provide the battery with the temperature not below +10 °C.

Figure 11 shows a change in the temperature at the altitude of 2 meters above the ground for the cities: Moscow, Astrakhan and Krasnoyarsk [15]. Under such conditions, the average temperature for the traction battery within a year is the following: for the city of Moscow it is 24.28 °C, for the city of Astrakhan it is 25.58 °C, for the city of Krasnoyarsk it is 24.15 °C.
Figure 9. Dependence of cooling powers of the thermostat control system on the environment temperature.

Figure 10. Dependence of the heating powers on temperatures.

Figure 11. Change in the ambient temperature within a year in Russian cities.
In its standards, the USCAR indicates that it is appropriate and safe to use the traction battery until its capacity reduces by 20% from the initial value [16] and the internal resistance increases twice [17]. Figure 12 shows curves of loss in power under various service conditions in different cities. With these powers of the thermostat control system and a traction battery design, the capacity will go down to 80% after 4009 cycles while using in the city of Astrakhan, after 4128 cycles while using in the city of Krasnoyarsk, and after 4104 cycles while using in the city of Moscow. The variation between these values is less than 3%. This suggests that the heating and cooling powers of the thermostat control system are sufficient for using the battery under these conditions. This value can be named one of the most important values in the thermostat control system design. The traction battery will serve for three (3) years till its replacement while using the electric vehicle within total 345 days a year if the minimal state of charge per cycle is not less than 25% [18-20].

Figure 12. Loss of power while using in different cities of the Russian Federation.

5. Conclusion
Several works in this field have been studied to assess the SOH, and for this purpose the most suitable method has been determined by applying a priori ranking method. The rating conditions have been determined, and the curves of a change in extreme temperatures for the last ten (10) years have been selected. These data are initial for the simulation model.

The designed simulation model of the electric vehicle is a work tool to determine specifications of the traction battery (currents, state of charge, state of health, temperatures of a LI battery etc.), as well as to calculate auxiliary systems of the electric vehicle, including the thermostat control system. The calculation for loss in power indicates that values of loss in power vary from each other insignificantly (less than 3%) while using in Russian cities (where electric vehicles will most likely be developed). This suggests that the ambient temperature has no significant impact on loss in power due to the active thermostat control system.

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