Applying the Heaviside step function to simulate the changes of temperature in automotive batteries

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Abstract. Discharged batteries do not provide the specified voltage in the car's power supply system during parking, which can cause malfunctions of electrical equipment and an increase in the quiescent current in the on-board network, due to incorrect operation of electronic control units responsible for the operation of self-diagnosis systems, anti-theft alarm, multimedia, maintaining a thermal state, etc. Therefore, to ensure a reliable start of the ICE and the proper operation of the electrical equipment of a car at low temperatures, it is required to maintain the battery in a charged state. Vehicle generator is selected taking into account the nominal capacity of the battery, power and operating modes of electrical consumers, which excludes the battery operation with a low level of charge. However, when operating cars in large cities in winter, the battery charge level decreases. Deterioration of the battery charging characteristics, increased power consumption of additional equipment and low speed of movement of cars in the city with frequent stops at intersections are the reasons for the decrease in the efficiency of the battery charge. In such conditions, the battery can be discharged not only by starting the ICE and turning on consumers in the parking lot, but also when the ICE is idling and at low crankshaft speeds while driving on city routes and during rush hours. Considering that the operational characteristics of the battery change significantly with decreasing temperature, studies aimed at establishing and predicting the battery temperature during operation are relevant.

1. Introduction

The aim of the work is to increase the efficiency of vehicle operation by adjusting the frequency of charging the batteries in the winter.

The object of the research is the effect of temperature on the level of charge of car batteries in winter.

The subject of research is the regularities of the formation of the battery charge level, taking into account the change in the ambient temperature and the intensity of the operation of passenger cars.

The current maintenance system does not fully take into account the effect of combinations of conditions and intensity of operation of passenger cars in the city in winter on the formation of the battery charge level. Taking into account the steady trend towards an increase in the power of electric consumers and a wide coverage of the markets for the sale of modern cars with the need for use in zones of temperate and cold climates, studies aimed at developing new methods for maintaining the performance of the battery based on the regularities of the formation of the level of its charge to ensure reliable ICE start-up and proper operation of electrical equipment car in the winter are relevant.
The scientific novelty of the research carried out lies in the establishment of new models of the influence of the ambient air temperature and the intensity of vehicle operation on the battery temperature based on the Heaviside function. The use of the developed simulation model of the formation of the battery charge level, in contrast to the existing ones, makes it possible to more accurately determine the charge level and the battery life between failures when operating cars in the city in the winter, depending on the design and operational factors. The application of the methodology for adjusting the frequency of charging the battery of passenger cars operated in the city in the winter, based on the established models, makes it possible to take into account the complex changes in the ambient temperature and the intensity of operation, which makes it possible to reduce the downtime of equipment and the cost of current repairs when implementing a scheduled preventive maintenance system.

2. Materials and methods
The thermal state of the battery is influenced by many factors, including the processes of transfer of matter in free and porous media, the kinetics of electrochemical reactions, heat transfer and structural mechanics, etc. [22-28]. The regularities of changes in the thermal regime of homogeneous bodies were studied in detail by G.M. Kondratyev [1], who determined the main connections that exist between the rate of cooling, on the one hand, and the physical properties of the body, its shape, size and cooling conditions, on the other. In accordance with the provisions of the theory of regular thermal conditions, the rate of change in the temperature of the battery \( t_c \) can be represented by an equation of the form:

\[
t_c = \Psi \cdot \frac{\alpha \cdot F}{c \cdot \rho \cdot V},
\]

where \( \Psi \) – coefficient of non-uniformity of temperature distribution in the battery;
\( \alpha \) – heat transfer coefficient;
\( F \) – surface area of the battery; m\(^2\);
\( c, \rho \) – heat capacity and density of the battery, respectively;
\( V \) – volume of the battery monoblock, m\(^3\).

In works [1–8] it is indicated that the change in the temperature of the battery is to the greatest extent associated with the effect of the external environment on the area of the side walls of the monoblock battery casing due to blowing. This is due to the fact that the temperature of the lower platform at the place where the battery is installed changes insignificantly, which is due to the limited air access and the low thermal conductivity of the battery case in this part, and above the level of the plates and electrolyte, air cavities are structurally provided for removing gases during overcharging, heat-insulating layer in the upper part of battery monoblocks. Therefore, assuming that the parameters \( \Psi, \alpha, c, \rho \) are constant, and the standard size range of the battery in the range of capacities from 40 to 80 A·h differs exclusively in the length of the monoblock body, the height and width of which are unchanged, when determining the rate of change – temperature drop of the battery. The dependence of the surface area of the battery on the initial capacity was set in the form of the ratio of the battery perimeters, and the change in volume and mass was presented as the ratio of the capacities.

When establishing the cooling rate of the battery, it may additionally arise the need to describe forced convection, that is, the effect of wind [5]:

\[
t_{\text{ost}}(V_w) = t_{\text{ostm}} - (t_{\text{ostm}} - t_{\text{ost0}}) \cdot e^{-0.2 \cdot V_w},
\]

where \( t_{\text{ost}} \) – battery cooling rate depending on the wind speed;
\( t_{\text{ostm}} \) – maximum cooling rate of the battery;
\( t_{\text{ost0}} \) – minimum cooling rate of the battery during calm conditions;
\( V_w \) – wind speed, m/s.
Authors in works [2, 3] indicated that when the wind speed increases to 10–12 m/s, the cooling rate of the units reaches a maximum, while its value is 1.5–3 times higher than that during calm. Given the large volume of previously performed experimental studies is devoted to determining the temperature characteristics of automotive components, it was proposed to use the authors’ data when calculating the maximum value of the battery cooling rate. The values of the constants of this equation are determined experimentally, and indicate the change in temperature at the location of the battery installation when exposed to wind.

That was due to the high heat capacity of the battery, the low thermal conductivity of the material of its monoblocks and the slowing down of the stirring rate of the electrolyte at low temperatures, and also due to the relatively short duration of starting the ICE on passenger cars, as a rule, not exceeding 10 s. We estimated it, which is difficult to check in practice the degree of heating of the battery during the passage of discharge and charging currents during the start-up of the ICE at such short time intervals. In accordance with the subject of the study, assuming that during operation after starting the ICE, a trip along the established route follows. It was proposed to take into account the change in the temperature of the battery during discharge during start-up by adjusting the parameters of the model of its warming up depending on the temperature of the engine compartment in the place of its installation [9–27].

3. Findings

The temperature of the engine compartment in the place where the battery is installed is determined by the temperature of the ICE and its components on the one hand, and the temperature of the ambient air and wind speed, on the other. Therefore, to determine it, experimental research is required.

In the process of warming up, the battery temperature tends to achieve a state of thermal equilibrium with the environment. The entire heating process can be broken down into three stages: an irregular stage, a regular stage, and a stationary stage. As shown by the authors in [1–3], due to the high heat capacity of the electrolyte and the low electrical conductivity of the monoblock materials, the battery temperature changes very slowly during the day. Heat from the ICE and its components is not transferred immediately after start-up, but as it warms up, the duration of which under conditions of unsteady traffic in the city takes longer, while the heat release from current-generating processes is also insignificant until the battery warms up and begins to take a large charging current. In this case, the stationary mode is almost completely absent, since the temperature of the electrolyte during the day changes less than the ambient temperature. And the stage of the regular mode begins after a long time due to the regularity of the thermal field of the ICE and the warming up of the engine compartment. Therefore, for the conditions under consideration, with short trips of cars in the city in winter, the irregular mode for the battery heating process dominates and is the main one.

In this regard, we assume that with an irregular heating mode, the temperature of the battery changes linearly over time:

\[
T_{\text{battery}} = T_0 + t_{\text{pr}} \cdot \mu,
\]

where
- \(T_0\) — start temperature of the battery, °C;
- \(t_{\text{pr}}\) — heating factor battery;
- \(\mu\) — warm-up duration, h.

The warm-up coefficient is defined as the ratio of the temperature increment for an irregular process to the duration of this process. With a regular heating mode, the difference between the ambient temperature and the temperature of the battery changes with time exponentially, taking into account the heat release from the current-forming processes considered in the previous section. To describe this process, it is proposed to use the exponential dependence of cooling together with the Heaviside function (Figure 1).
Figure 1. The Heaviside function is a piecewise constant function equal to zero for negative values of the argument and one for positive values.

In this way, the battery cooling process for the conditions under consideration can be characterized by the stage of a regular mode, which occurs after a certain period of time. Its duration is determined by the rate of ordering of the battery temperature field and the duration of cooling of the hood space in the place of its installation to the ambient temperature:

\[
T_{\text{air}} = T_e - (T_e - T_0) e^{-\frac{t - t_0}{m}}.
\]  

(4)

where

\begin{itemize}
  \item $T_0, T_K$ – initial and final temperature of the battery during cooling, °C;
  \item $m$ – cooling rate;
  \item $t$ – duration of the cooling process, h.
  \item $t_0$ – duration of the ordering of the temperature field of the battery, h.
\end{itemize}

For the current ranges of the ambient temperature and cooling time battery, dependence (2) can be represented as a three-dimensional model (Figure 2).

Figure 2. Changes in battery temperature depending on the ambient temperature and the duration of cooling.
Combining the influence of the battery capacity and wind speed, the model of the change in the cooling rate of the battery when it is installed under the hood can be represented as follows:

\[ t_R(C_{20}, V_w) = t_R(V_w) \left( \frac{C_0}{C_{20}} \right) \left[ w + l \right] \]

where \( t_R \) – cooling rate of the battery;
\( t_R(V_w) \) – function of the dependence of the cooling rate of the battery on the wind speed when the battery is installed under the hood;
\( C_0 \) – initial battery capacity, A·h;
\( C_{20} \) – alternative battery capacity, A·h;
\( w, l \) – width and length of the wall of the battery monoblock, respectively, m.

To test the results obtained there was modeling of the charge level of a Hyundai Solaris car in a representative place of cold climate Salekhard. The specific features of car operation in this region were additionally taken into account. The area of Salekhard is relatively small and does not exceed 30 km², in comparison with the cities of Tyumen and Moscow, the area of which is more than 230 km² and 2500 km², respectively. The average duration of one trip in the city rarely lasts more than 0.4 hours, however, in the absence of autonomous pre-heaters, heaters and other ICE heating systems on the car, in winter, when the car is stored without a garage. The warm-up time before driving increases to 0.5 hour and more, due to low temperatures and strong winds, the speed of which in this region exceeds 10 m/s. Thus, with warming up, the average duration of one trip will be 0.9 hours. Taking into account the large fluctuations in average daily temperatures, the values of which reach minus 40 °C, in order to prevent freezing of the battery electrolyte under such conditions, it is proposed to raise the threshold value of the minimum level of charge from 30% to 40% (Figure 3).

**Figure 3.** Modeling of the battery SoC and temperature by operation in the period from November to March in the cold climate region: SoC – battery state of charge, %; \( T_{\text{battery}} \) – battery temperature, °C; \( T_{\text{air}} \) – ambient temperature, °C

The simulation results indicate that under such operating modes in the climatic conditions of Salekhard, the battery charge level rapidly decreases with the onset of December and reaches a threshold value in the middle of the month. To maintain the battery in an efficient condition during daily use, it is necessary to regularly warm up and charge it at intervals of 5 days for two months. The main reason for such a sharp deterioration in the charging conditions of the battery is a decrease in the
average daily air temperature to minus 20 °C in December and a further decrease to minus 27 °C in February, while simultaneously exposed to a strong wind with an average daily speed of more than 3 m/s. As measures to improve the charge and reduce the cost of battery maintenance during such operation, it is proposed to increase the warm-up time before the trip by 0.4 hours, which will reduce the number of additional charges 2–3 times. In addition, when operating a car in this region, it is recommended to give preference to the battery of the maximum possible capacity provided by the manufacturer for installation on this car. This will reduce the number of services, depending on the mode of use without increasing the warm-up time. Hence, using the example of the car, the influence of various climatic conditions and operating modes in the city on the formation of the battery charge level in the winter is demonstrated.

4. Conclusion
In this way, the influence of various climatic conditions and operating modes in the city on the formation of the battery charge level in the winter period has been demonstrated. With the help of the developed model, it is possible to study the process of changing the average unit cost of operating a car when changing various input characteristics. This information can be useful in determining the methods of ensuring the operability of battery in cold climatic conditions and making decisions about the moments of carrying out and the content of the list of technical impacts depending on the adopted maintenance system, as well as the conditions and intensity of operation. After determining the unit costs according to the simulation model, the optimal frequency of battery charging is established and the difference between the total unit costs is calculated.

The simulation model provides for the possibility of changing the initial data not only for the car and climatic conditions, but also for the movement parameters in accordance with the selected driving cycle or a given typical route. Therefore, the application of the technique is not limited to a specific car model, fixed driving conditions and a specific climatic region. With known initial data, the technique can also be used for other cars operated at low temperatures in cities with different population sizes, taking into account the peculiarities of traffic organization, average flow rate, average daily mileage and other indicators of conditions and intensity of operation.

A change in the battery charge level affects the total costs, consisting of the cost of charging the battery, the costs arising in the event of a failed start of the car's ICE, and the cost of purchasing new batteries. The economic effect from the use of research results is achieved by changing the frequency of the battery charge, which reduces downtime in current repairs, reduces the cost of purchasing new batteries and increases the reliability of the ICE winter start-up.

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