 ISSN NO: 2770-4491
May 2026

Evaluation Of The Efficiency Indicators Of Electric Vehicle Heating Technology In Cold Climate Conditions

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Abstract: This article analyzes the problems of energy losses and reduced range during the operation of electric vehicles in cold climates. The indicators are presented, which are aimed at reducing energy consumption and increasing the overall operational efficiency of the vehicle by evaluating the efficiency indicators of electric vehicle battery heating technologies and optimizing them. The amount of energy consumed during battery heating and its impact on the overall energy balance are estimated using mathematical models. Optimal operating modes for the thermal management system of an electric vehicle battery are developed, and an algorithm for controlling the heating process is proposed. The control algorithm is aimed at maintaining the battery temperature at the required level with minimal energy consumption, and its adaptation to real operating conditions is described in detail.

Keywords: Electric vehicle, cold climate, thermal management system, PTC, compressor, energy consumption, solenoid valves, distance, temperature, mathematical model, control algorithm, energy efficiency, thermal loss, internal resistance.

Currently, environmental safety, energy efficiency and carbon emissions reduction are becoming increasingly important in the automotive industry. Therefore, the production and use of electric vehicles worldwide is increasing year by year. According to the International Energy Agency, global electric vehicle sales will exceed 17 million units in 2024, which is more than 20 percent of new car sales.

BYD SONG PLUS CHAMPION helps to obtain experimental results by analyzing the general performance and operating principles of heating systems used in electric vehicle models. In order to create comfort for the driver and passengers in cold climates, electric vehicles have a heating system for the cabin and other devices, which is completely different from the heating system used in vehicles with internal combustion engines.

The decrease in the efficiency of electric vehicles in cold climates is not only due to the decrease in battery capacity, but also to factors such as bringing the battery to optimal operating temperature, heating the cabin, driving speed, road surface conditions and driver's driving style. NREL studies have shown that the efficiency of electric vehicles in cold conditions depends on the battery thermal management system, cabin heating system, speed and driving habits. From this point of view, managing the thermal regime of the battery, reducing the energy consumed for heating and maintaining the driving range is an urgent scientific and practical issue when operating electric vehicles in cold climates.

However, operating electric vehicles in different climatic conditions, especially in cold regions, poses a number of technical and energy challenges. At low temperatures, the electrochemical processes of lithium-ion batteries slow down, the internal resistance increases, and the battery's real usable capacity decreases. In addition, unlike vehicles with internal combustion engines, electric vehicles have limited ability to use excess heat from the engine to heat the cabin, and additional electricity is spent on the HVAC system. A study by the US Department of Energy also found that HVAC system energy consumption in BEV vehicles increases as ambient temperatures decrease.

Electric vehicles use energy-saving electric heating technologies. The general working principle of the heating system used in electric vehicles is shown in Figure 1.

ISSN NO: 2770-4491
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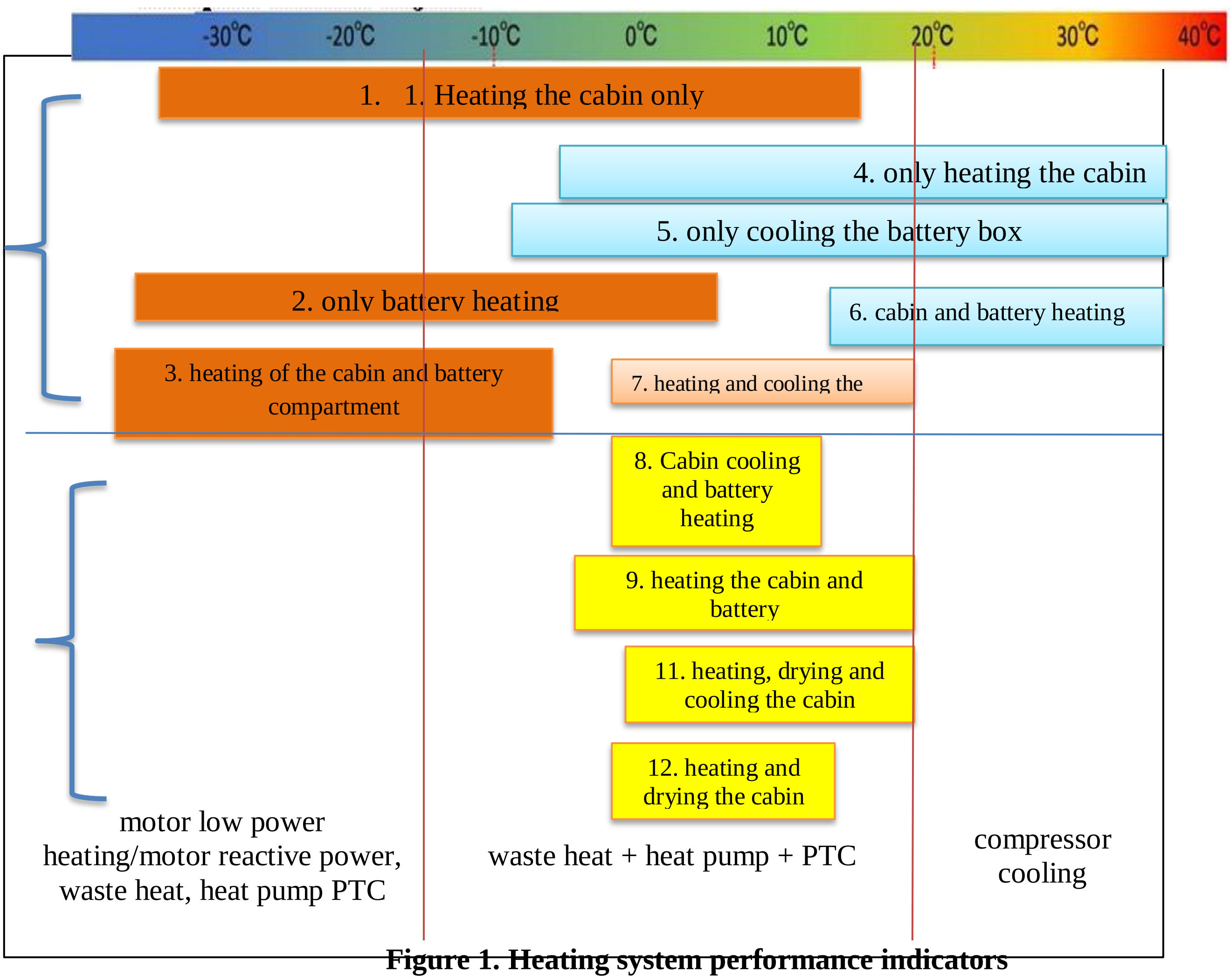

Figure 1. Heating system performance indicators

There are several main purposes of the heating system used in electric vehicles. The function of the electric vehicle interior heating system is to provide a comfortable temperature for the driver and passengers in cold weather, prevent frosting of fiberglass windows, and conserve battery power by consuming minimal electricity. There are several types of heating systems in electric vehicles, and in electric vehicles manufactured by BYD, for example, the BYD SONG PLUS CHAMPION model, the following two main PTC or heat pump (compressor) systems are used (Figure 2).

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Figure 2. PTC heating system used in BYD SONG PLUS CHAMPION model

PTC electric heater is used. This is a heating system based on electrical resistance. The process of this system is that when an electric current passes through the ceramic elements, they heat up and the heating fan moves to distribute warm air into the cabin. The cabin heating system is only shown to work when the outside temperature is +3°C or lower. If the outside temperature is +4°C or higher, no matter how much you increase the climate control temperature, it will distribute cold air into the cabin. The high-voltage PTC system, which is widely used in electric vehicles, also consumes a lot of electricity because it operates entirely on electric energy, which leads to a decrease in battery capacity. [7]

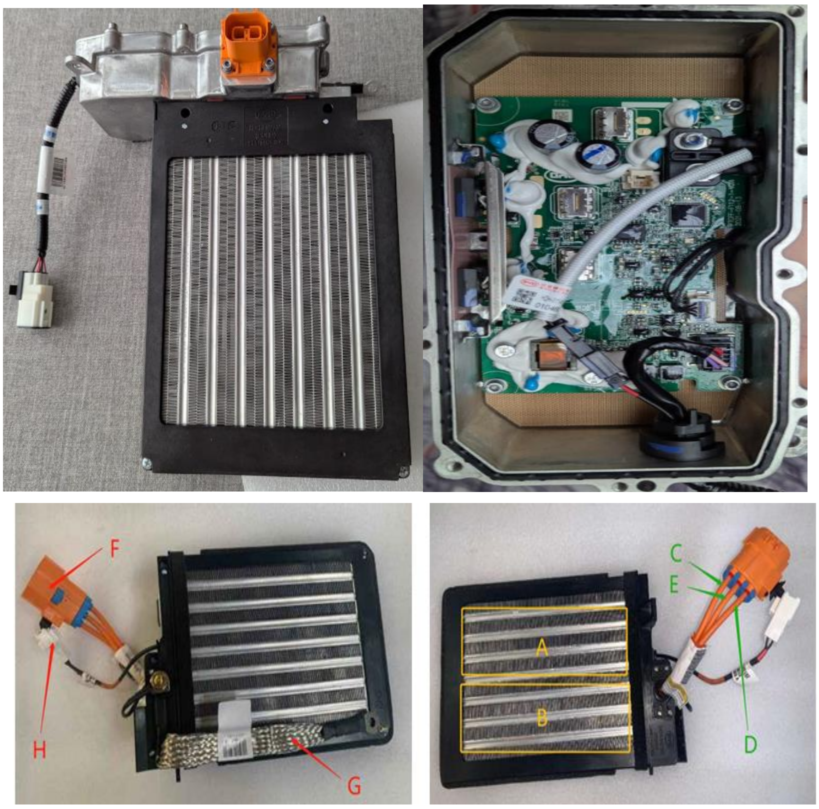

Figure 3. General performance of a high-voltage PTC system

The performance of the high-voltage PTC heating system shown in Figure 3 above is shown in Table 1 below, indicating the individual functions of the devices.

General indicators of the PTC system

Belgilar	Name
A	High-voltage PTC 11
B	High-voltage PTC 2
C	High-voltage PTC 1cable
D	High-voltage PTC 2cable
E	PTC positive cable
F	PTC high-voltage cable connector
G	TC ground wire
H	PTC temperature sensor connector

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As the temperature increases, the PTC element automatically increases its electrical resistance. In this way, the PTC element has the ability to self-regulate and prevent the system from overheating. If the temperature exceeds the norm, the current is limited by the increase in resistance. The heating of the element slows down.

In an electric vehicle, this system is usually integrated into the HVAC (Heating, Ventilation and Air Conditioning) system. Both heating systems used in electric vehicles have advantages and disadvantages, as can be seen in the table below.

Differences between PTC heating and compressor systems used in electric vehicles

№	Type of heating system	Operating principle	System advantages	System disadvantages
1	PTC heater system	Produces heat directly by using electrical resistance.	. It has a simple structure and provides fast cabin heating.	It requires relatively high electrical energy consumption during operation.
2	Heat pump system	Uses a refrigerant cycle to extract heat from the outside environment and transfer it into the vehicle.	It provides higher energy efficiency in the thermal management of the cabin and battery.	ts heating performance may decrease under low-temperature conditions.

PTC is a heating system based on an electrical resistance element with a positive temperature coefficient, and is the most widely used source for heating the cabin air in electric vehicles. The main feature of the PTC element is that its electrical resistance increases as the temperature increases. As a result, it acts as a self-limiting system that automatically limits the temperature. This feature makes the system stable, safe and self-protective. The structure and operating principle of the heating system are different from other heating systems. The PTC heating system used for heating the cabin in electric vehicles is made of a ceramic-based semiconductor material, namely barium titanate. It is coated with metal electrodes on both sides and has the form of a plate. The plates in this heating system are placed on aluminum radiator grilles and serve to direct the air flow.

In the process of operation, the heating system is implemented as follows. The oven is heated by supplying a voltage of 300–400 V from a power source battery or inverter. When the incoming electric current passes through the PTC element, it generates heat as a result of heating, and this hot temperature is transferred to the fan blades installed in the system by directing hot air through the radiator. Another smart system is used in this system, in which the PTC element sharply increases its resistance when the temperature increases, and as a result, heat generation decreases. This process is self-regulating and serves to normalize the cabin temperature.

Therefore, the operation of this system does not require the use of complex thermostat devices. So, PTC heating systems bring a number of advantages to electric vehicles. From a safety point of view, when the temperature of the cabin increases excessively, the element itself reduces its power. One of the most important advantages is that this system quickly heats the cabin by converting electrical energy directly into heat, which also brings special advantages. The maximum speed is a device that can generate heat in 30-60 seconds. Stability can ensure operation, and even with long-term operation, the heat output temperature remains almost unchanged. The flexibility of the heating system determines the possibility of modular installation in various power ranges from 1-5 kW.

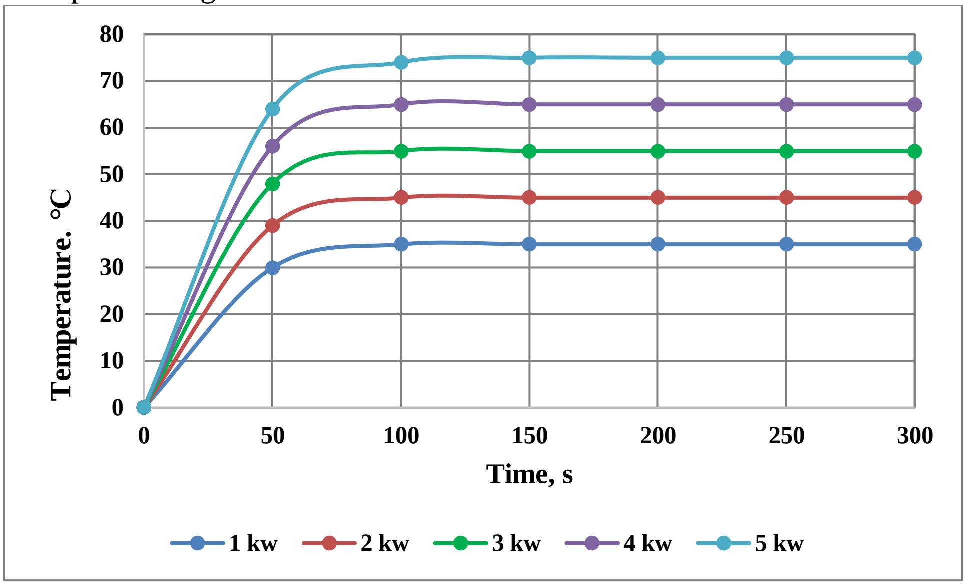

Figure 4. Temperature rise in a heating system as a function of time

The heating system used in these electric vehicles also has its own disadvantages, and eliminating or reducing these disadvantages is the most important and urgent issue of scientific work. The PTC system has some limitations, and their full study and optimization is based on scientific innovation. The biggest disadvantage of this system is its high energy consumption during operation. Since it directly converts electrical energy into heat, it consumes a large amount of electrical energy (COP≈1). As a result of the system's operation, the battery capacity decreases rapidly. For this reason, it reduces the range of the electric vehicle by up to 40% in cold climates. The efficiency of the system does not depend on temperature, and regardless of the outside temperature, the energy consumption process will work without changes when the system is started. The power of the heating system efficiency analysis is expressed by the following formula:

$$Q = U \cdot I = I^{2\cdot} R(T)$$

where:
Q-is the generated thermal power, **W**;
U-is the applied voltage, **V**;
I-is the electric current, **A**;
R(T)-is the resistance at a given temperature, **Ω**.

In the BYD SONG PLUS CHAMPION electric vehicle, which was selected as the object of research, the operation of the PTC heating system ensures hybrid operation of the heat pump and compressor. The operation process is carried out in the following sequences:

- the PTC system is activated when the temperature is below +10°C;
- when the temperature is below 0°C, the PTC element becomes the main heat source;
- when the temperature is +10…+15°C, the system switches to the heat pump compressor.

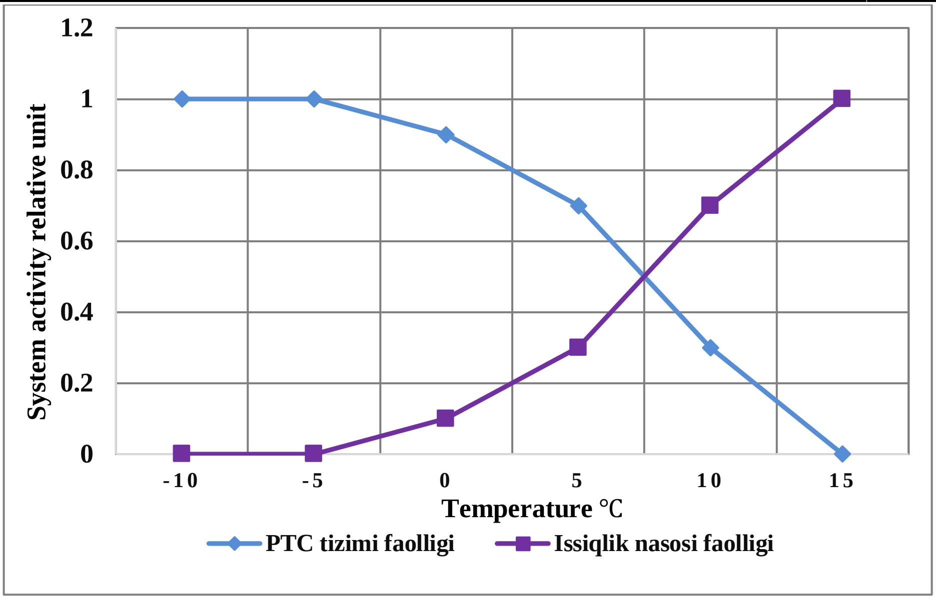

Figure 5. Diagram of the operation mode of the electric vehicle heating system depending on the external temperature.

The operating power of the PTC heating system in the BYD SONG PLUS CHAMPION electric car is usually around 3–5 kW, which allows you to increase the temperature of the electric car interior by 20–22°C within 10 minutes.

One of the biggest drawbacks of the heating system used in electric cars is its high energy consumption, which leads to low efficiency. For example, since the PTC heater directly converts electrical energy into heat, only 1 kWh of heat is obtained from 1 kWh of electricity. At the same time, the heat pump compressor loses its efficiency when the temperature is below –10°C in cold weather, as a result of which the car operates only in PTC mode. The negative effect of this is that the driving range in cold climates is reduced by 30–40%.

The main reason for the rapid decrease in battery power in the BYD SONG PLUS CHAMPION electric car in cold climates is that the heating system receives electricity directly from the battery. If the outside temperature is around -20°C, the heating system alone can consume 4-6 kWh of energy per hour. This results in a decrease in the battery's power reserve. This limits the long-distance travel of electric cars in cold climates.

There are problems in the maintenance and repair of the heating system used in electric cars, and the PTC system heaters require repair using special equipment in heat pump compressor service centers. Measures to eliminate these shortcomings and simplify them require system study and scientific.

Analysis of problems and consequences that arise in the heating system

№	Type of disadvantage	Cause	Result
1	High energy consumption	The PTC heating system operates with **COP = 1**.	The driving range of electric vehicles decreases.
2	Reduced efficiency in cold climate conditions	The operating performance of the heat pump decreases under cold climate conditions.	Delays occur during the heating process.
3	Increase in battery load	The heating system consumes energy directly from the battery.	The battery state of charge decreases more rapidly.
4	Complex design structure	The system consists of multiple hybrid components.	The initial cost and maintenance expenses

			of the system are high.

It was considered that there are a number of specific shortcomings in the heating system of BYD SONG PLUS CHAMPION electric vehicles. Therefore, by analyzing them, it is possible to achieve efficiency in carrying out scientific and practical work, analyzing and developing recommendations. Although the combined heating systems of the PTC heating system and thermal control systems used in such modern models serve effectively, it is possible to achieve the desired result by increasing the useful coefficient of this system and reducing costs. In developing measures to improve energy efficiency, it is necessary to adjust the power in real time using an intelligent control algorithm.

The general structure and performance of the thermal control system are also one of the most basic devices for electric vehicles. The thermal control system, which is widely used in electric vehicles, has very wide capabilities and high performance. This module mainly controls the electric vehicle batteries and the heating system and cooling circuits of the passenger compartment through valves (solenoid valves). It also performs the function of diverting the heating and cooling flows in the desired direction.

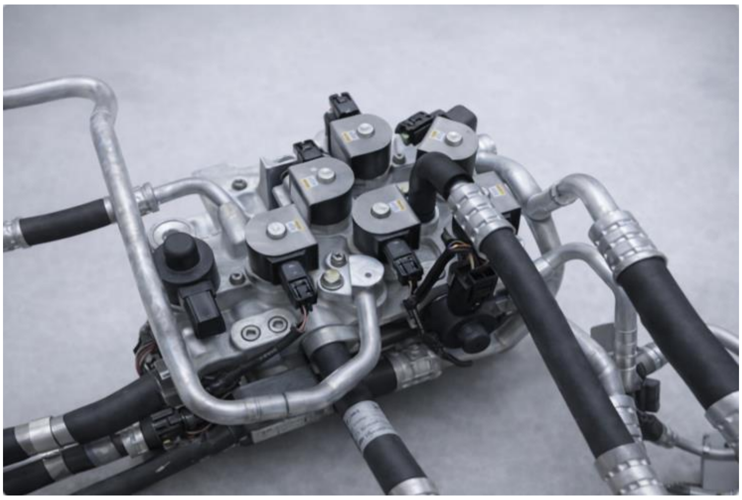

Figure 6. General view of the thermal management module

This central control module combines nine solenoid valves (six switching valves and three expansion valves) and connects the compressor, condenser, HVAC system, and battery via 10 refrigerant pipes. This makes it an energy controller that controls the heat flow throughout the entire electric vehicle. The electric motor and inverter are cooled by a special fluid circuit. The thermal management of the HVAC and battery is directly controlled by the refrigerant flow. This system allows for eight different operating modes. This system covers various combinations of HVAC and battery heating and cooling. As a result, it ensures efficient energy distribution in a wide temperature range from -30°C to 50°C [9].

The main task of the thermal management system is to ensure the proper temperature of the high-voltage battery, which is the energy source in electric vehicles, since its efficiency and safety largely depend on the temperature regime.

If the battery temperature is higher than normal, the power decreases, which negatively affects the rapid failure of the battery and its safety. If the battery temperature is low, the internal resistance increases and the charge acceptance capacity decreases, which negatively affects the range of the electric vehicle.

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Figure 7. Location of thermal management system pipelines

In the thermal control module shown in Figure 7, the main function of the metal pipes and hoses is to ensure the movement of the heater and coolant flow. The black cylindrical square elements are electromagnetic (solenoid) valves, which provide the flow direction and the connection and disconnection of the circuits based on the signal from the electronic control unit.

Low-temperature charging mode: When charging in a low-temperature environment, the battery pack is directly heated by the heat pump air conditioning compressor and the high-voltage system to maintain the battery in the best state of charge and shorten the charging time.

Low-temperature control mode: During low-temperature control, the battery pack is directly heated by the heat pump air conditioning compressor and the high-voltage system to maintain the battery in the best state of discharge and improve the power performance of the electric vehicle at low temperatures.

There are valves for the condenser, which is a heat transfer element. The main function of the condenser is to connect the current to this heat exchange point. The electromagnetic valves (solenoids) used in this system have fast control and are controlled by the ECU (Electronic Control Unit) in the system's on/off or step PWM (Pulse Width Modulation) electrical signal control mode. As a result, the resulting refrigerant flow performs the function of intelligent automatic redistribution.

The main parameters of the selected existing mathematical model are the battery state (Tb), the real ambient temperature (Ta), the heat flow (Q), the battery heat capacity (Cb), and the open-closed state of the valve (ON/OFF discrete). A mathematical model based on reducing the energy required to heat an electric vehicle battery in cold climates In order to achieve good lighting efficiency in electric vehicles, it is necessary to maintain the heat balance of the battery at a constant temperature. Therefore, it is advisable to use the formula given below.

The main equation of the existing mathematical model:

$$C_b \frac{dT_b}{dt} = Q_{gen} + Q_{heat} - hA(T_b - T_a)$$

here:
dT_b **-** is the thermal capacity of the battery, **J/°C**;
Q_{gen} - is the heat generated inside the battery, **W**;
Q_{heat} - is the thermal power supplied by the heating system, **W**.

$$Q_{heat}(t) = u_v(t) Q_{max}$$

$$u_v(t) = f(T_b\,,\, T_a, SOC, \tau_{open}, \tau_{close})$$

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here:
SOC - battery charge level;
τ_{open} - valve open time (s);
τ_{close} - valve closed time (s).

$$C_b \frac{dT_b}{dt} = Q_{gen} + u(t)Q_{max} - hA(T_b - T_a)$$

$$J = \int_0^{t_f} [\alpha E_{heat}(t) + \beta(T_b - T_{ref})^2]dt \to min$$

In a discreet manner:

$$J = \sum_{i=1}^{n} \alpha\, u_{v,i}\, Q_{max}\Delta t + \beta(T_{b,i} - T_{ref})^2 \to min$$

here:
α - weighting coefficient given to energy consumption;
β - weighting coefficient given to temperature deviation.

Thus, the model simultaneously fulfills the following two goals:
1. Reduces the energy consumed for heating the battery, which increases the range;
2. Maintains the temperature, which is important for the battery in cold climates, ensuring its stability.

In conclusion, it should be emphasized that one of the main problems in the operation of electric vehicles in cold climates is energy losses associated with a decrease in battery temperature. At low temperatures, the internal resistance of the battery increases, as a result of which energy consumption increases and the range of the electric vehicle is significantly reduced. During the conducted research, the effect of the battery heating process on the energy balance was assessed based on mathematical models and opportunities for reducing the amount of energy consumed for heating were identified. The developed optimal control algorithm approach serves to minimize excess energy consumption while maintaining the battery temperature in the required range. The results confirm that effectively managing the heating system can improve the overall energy efficiency of an electric vehicle and increase its range.

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