Experimental studies of the thermal management system for an electric vehicle in the X-In-The-Loop environment

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Abstract. This article presents the experience of conducting experimental studies of the thermal management system (TMS) intended for the traction electric drive of an electric vehicle, which has each of its wheels driven by an in-wheel motor, in the X-In-the-Loop environment. The paper describes the experimental bench of the thermal management system, which makes it possible to simulate the operating conditions of the high-voltage components of the traction drive of an electric vehicle from the point of view of thermal-hydraulic characteristics. A brief description of the mathematical model used in real-time calculations during both local and collaborative experimental studies is given. The process of collaborative testing of the TMS of high-voltage components of the traction drive of an electric vehicle, in the X-In-the-Loop environment, as well as the results, is demonstrated. A similar approach used in the development of TMS allows increasing the efficiency of the system developed, by optimizing the control algorithm for the executive devices of the TMS, reducing the weight, as well as the overall dimensions of the components, and conducting a detailed analysis of each component. It is also worth noting that the use of collaborative experimental research in the X-In-the-Loop environment will reduce the cost of the experiment, as well as, ultimately, the cost of the product, since with such an approach there is no need for a real test object for each company engaged in the development of one or another electric.

1. Introduction

The thermal management system is one of the important systems of an electric vehicle, which determines the possibilities of its operation, and the possibility of operation at temperatures reaching values significantly below 0 °C. As a rule, the company that develops the car, the company that develops the thermal management system and the companies that develop other components of the car are different companies, often located at great distances from each other. Thus, of great importance is the development of the concept, software, and hardware, which will allow collaborative testing of components, systems and the entire vehicle as a whole with direct participation of specialists who have different specializations.

One possible concept for collaborative testing is a laboratory test method called X-in-the-Loop. More details about this method can be found in articles [1-6]. Within this work, the software and hardware implementation of the test bench for the thermal conditioning system of an electric vehicle equipped with in-wheel motors are shown. An example of physical tests of the developed stand in the X-IN-THE-LOOP environment is given.
2. Methods
To implement the concepts of joint testing X-in-the-Loop in terms of the TMS for the components of the high-voltage system of an electric vehicle, a test bench of the TMS was develop, including a complex mathematical model of the system.

2.1 Thermal management system test bench overview
The test bench was designed to conduct research and calibrations of the thermal management system intended for an electric vehicle with in-wheel motors operation at temperatures from minus 40 °C to plus 50 °C. The design of the test bench allows simulating various loading modes of traction electrical components of a vehicle with the possibility of logging and transferring to a common server. The following parameters are used: hydraulic characteristics of system components, temperature indicators of system components, speed of imitation of the oncoming airflow and the amount of energy spent on the thermal management system. The general view of the bench is shown in Figure 1.

![Figure 1. General view of the test bench: 1 - frame, 2 and 3 - simulators of an electric motor and inverter, 4 - array of fans simulating oncoming air flow, 5 - casing, 6 - power electronics housed with a control system, 7 - heat exchanger, 8 - electric fan, 9 - expansion tank, 10 - three-way valve, 11 - electric pump, 12 - rubber pipes, 13 - differential pressure sensor, 14 - temperature resistances, 15 - transition manifold, 16 - control electronics box.](image-url)

The test bench frame (1) is made of a universal profile and has the following overall dimensions: 2010 x 1410 x 1355. The simulators of electrical components (Figure 2) - the electric motor and inverter - are designed to closely replicate the characteristics of real objects in terms of reproducing...
the temperature characteristics of the coolant on exit from simulated devices. The simulators are equipped with temperature sensors with a short thermal reaction time.

Figure 2. General view of the simulator of electrical components.

The peak heating powers of the simulators are 12.8 kW and 5.2 kW for the electric machine and inverter simulator, respectively. This corresponds to a real electric motor and inverter. The array of fans simulating the incoming air flow (4), combined with the casing (5), allow simulating the speed of the oncoming air flow as a function of the speed of the electric vehicle. The control and power electronics, which are responsible for heating the heating elements and controlling the array of fans, are located in the box (6). The heat exchanger (7) together with the electric fan (8) are designed to remove heat from the coolant of the TMS. The expansion tank (9) is the highest point of the system and performs two functions at once: compensation for changes in the volume of the coolant depending on the temperature and degassing the coolant circulating through the system. The three-way valve (10) is used to cut off the flow of the heating medium passing through the heat exchanger. The investigated TMS includes 4 electric pumps (11), which allow smooth adjustment of the coolant flow rate, over a wide range, at the outlet from the actuators. The components of the system are interconnected in a closed sealed system using rubber pipes (12). The control electronics of the TMS is located in the box (16). The layout of this bench is made taking into account the layout features of a real prototype car.

The test bench includes sensors for measuring liquid flow, presented in this bench by the differential pressure sensors (13) located on the transition manifolds (14), calibrated using turbine flow meters, as well as temperature resistances (14) located at the inputs and outputs of the simulating devices.

2.2 Overview of the mathematical model of the system

The mathematical model used for experimental studies of the thermal management system intended for the traction electric drive of an electric vehicle, which has each of its wheels driven by an in-wheel motor, is implemented using the Matlab Simulink computer complex [7, 8], and can be divided into three submodels:

- models of hydraulic processes;
- model of temperature processes;
- model of movement of an electric vehicle.

The hydraulic process model describes the hydraulic movement of fluid through pipelines and other system components. The thermal management system is divided into sections, each of which is one of the basic elements of the hydraulic circuit - elastic, resistance or inertial. The inertial element is
characterized by the transfer of a mass of liquid at a known volumetric flow rate due to the effect of pressure. The elastic element serves to connect at least two pipelines for which the flow rate is known. Resistances are characterized by a known pressure drop across the pipeline section. The resistance of a conventional pipeline is determined depending on the fluid flow according to the well-known formulas [9], while the resistance of the system components (such as the heat exchanger, inverter, electric machine), which have a complex configuration of hydraulic channels, is determined experimentally. The pumps of the thermal management system are also taken into account in this model, and are set as resistances with a positive differential pressure.

The temperature process model describes the process of heat transfer between the components of the system [10]. Convection is accepted as the main type of heat transfer between the multi-mass models. Each component of the system is divided into three masses - the mass of the coolant in the component, the mass of the component itself, and the mass of air that flows over the component.

The motion model of an electric vehicle is used to assess the parameters of the operation of high-voltage components of the traction drive, including in terms of heat energy release [11]. The driving mode of the vehicle is set either by means of a driving cycle, which describes the vehicle speed as a function of time, or in some other similar way. The electric vehicle model used in this work is specified by a single-mass model with a number of assumptions: 1) only the straight-line motion of an electric vehicle is considered; 2) tire slippage relative to the road is not taken into account. 3) The redistribution of the weight of the electric vehicle when performing maneuvers is not taken into account; 4) the radius of the wheel is considered constant and equal to the static radius.

The thermal management system is controlled by the following components: four electric pumps, an electric fan mounted on the radiator casing, and a three-way valve. The operation of these devices is determined using a system control algorithm that implements feedback control of the temperature of the components [12].

2.3 Methodology for Conducting Collaborative Testing in an XIL Environment

One physical test scenario (HIL) is the World Harmonized Light Vehicles Test Cycle (WLTC). The dependence of speed on time, typical of the given cycle, is shown in Figure 3.

![Figure 3. WLTC](image)

To carry out these tests, the test bench was placed in a thermodinamic chamber (Figure 4).
Figure 4. Test bench placed in a thermoclimatic chamber.

The temperature in the thermoclimatic chamber was set by the following series of target values: -40 °C, 0 °C, 30 °C, 50 °C. When conducting local tests that serve to debug the system, the mathematical model of the car's movement described above was used.

When carrying out, together with a company located remotely, physical tests, the vehicle motion model, including wheel motors, was carried out on the basis of a software and hardware complex located on the partner's territory. Information about the speed of the vehicle, the speed of rotation of the wheels, the moment realized on the wheel motors was transmitted in real time to the model, which was implemented on a computer that controlled the actuators of the test bench, and was located on the territory of FSUE "NAMI".

The tests carried out have shown that the TMS of an electric vehicle with four motor-wheels allows maintaining the temperature of the high-voltage components of the traction drive within the specified operating range when operating in a wide temperature range.

3. Results and discussion

This section presents the results of experimental studies of the thermostating system of an electric vehicle, carried out collaborative with a company located remotely. Due to the limited volume of the article, test results are shown only at plus 30 °C.

Figures 5 shows a screen shot taken during the collaborative test. The picture shows the interface of the program in which the software part of the test complex of the partner company was implemented.
Figure 5. Joint Test according to WLTC (1 - graphical representation of the motion of the electric vehicle; 2 - the input information on the temperature of high voltage electric traction drive components obtained from Federal State Unitary Enterprise "NAMI"; 3 – speed of electric vehicle; 4 - braking torque on wheels; 5 - traction torque on the wheels of an electric vehicle)

Fig. 6 shows the results of component temperature, fluid flow and heat output from these tests. It can be noted that the temperature of the components does not exceed 52 °C, which is a safe temperature for high-voltage components of the traction drive of an electric vehicle.
Figure 6. Dependence of the measured parameters on time in WLTC at 30 °C.
4. Conclusion

It should be noted that the developed software and hardware complex for studying the TMS of an electric vehicle in the X-IN-THE-LOOP environment are an indicator that the study of various systems of an electric vehicle can be carried out at one research object.

The approach, which includes a detailed analysis and testing of systems in the XIL environment, will increase the efficiency of the system being developed, reduce the weight and overall dimensions of the components, and conduct a detailed analysis of each component. In addition, conducting collaborative testing in the XIL environment is economically feasible, since there is no need for a real test object in the testing laboratory of each company.

In the case of thermostatic control systems, such an approach will allow creating algorithms for the operation of actuators that provide an energy-efficient mode of operation in the entire variety of operating conditions for electric vehicles.

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