RESEARCH AND APPLICATION OF HEAT RECOVERY AND AUTOMATION MONITORING SYSTEM FOR NEW ENERGY VEHICLE MOTOR EQUIPMENT

by

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In order to improve the energy efficiency of pure electric vehicles, the author proposes a thermal energy recovery and automation monitoring system for motor equipment based on new energy vehicles. Based on the analysis of the battery thermal management model, a series heat exchange model between the motor and the battery was established. An integrated thermal management system control strategy based on motor waste heat recovery was proposed for electric vehicles in low temperature environments, and simulation and validation were conducted at different environmental temperatures (–10~0 °C). The simulation results show that this configuration can shorten the heating time by 111-343 seconds compared to traditional battery thermal management systems during the heating stage. During the insulation stage, frequent activation of positive temperature coefficient thermistor can be avoided and the battery temperature can be maintained around 20 °C, which is not only conducive to extending the battery life but also reduces the comprehensive energy consumption by 4.39-7.70%. On the other hand, this configuration can reduce the impact of low temperature on comprehensive energy consumption from 9.77-2.07%. It is proved that heat recovery can effectively alleviate the range anxiety caused by ambient temperature.

Key words: *electric vehicles, battery thermal management, motor waste heat, comprehensive energy consumption, range anxiety, integrated thermal management*

Introduction

With the development of social economy, ecological degradation, urban environmental pollution, energy crisis and other issues are becoming increasingly serious. In recent years, fossil energy consumption in the transportation sector has accounted for one-third of the annual consumption [1]. The country and society have formulated strict exhaust emission policies to promote sustainable energy development, which has brought huge challenges to the automotive industry. New energy vehicles, especially electric vehicles, have attracted attention from governments, automotive companies, and universities around the world due to their advantages of zero emissions, high efficiency, and noise free operation. In recent years, with the strong

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support of the country for the development of new energy vehicles, research, and social promotion in related fields have achieved certain results. However, the development of new energy vehicles still faces many problems, among which the problem of vehicle thermal management is currently a problem that needs to be solved [2].

Unlike traditional cars that use internal combustion engines, electric vehicles use lithium batteries or fuel cells to generate electrical energy to drive the motor, converting electrical energy into mechanical energy, which in turn drives the vehicle. Due to the requirements of motor control and rated voltage, electric vehicles have added electronic components such as motor controllers, DC/DC, high voltage junction boxes, and chargers. The optimal operating temperature ranges for motors, motor controllers, and three in one (on-board chargers, high voltage junction boxes, and DC/DC converters) are 10-70 °C, 10-65 °C, and 10-55 °C, respectively. These components will generate a large amount of heat during operation, and if not effectively dissipated, they will generate a lot of heat, it will greatly affect its performance and even its working life. To achieve optimal performance and long lifespan, the operating temperature range of lithium batteries must be maintained between 15-35 °C. When the operating temperature is too low, the internal impedance of the battery will greatly increase, reducing its charging and discharging efficiency, and seriously affecting the battery capacity. For example, when the electric vehicle is operating in the sub zero temperature environment, its range is 60-70% of the normal operation. In addition lithium batteries and electric drive electronic control systems, electric vehicles also have air conditioning and HVAC systems that adjust the temperature in the passenger compartment according to the driver's needs. Therefore, in new energy vehicles, the energy source of the battery pack is not only used to drive the vehicle, but also to maintain temperature management of system components [3]. Excessive energy consumption will affect the range of electric vehicles, this makes the energy efficiency level of the thermal management system extremely important. It can be seen that the current VTMS of new energy vehicles still needs to meet the requirements of high efficiency and low energy consumption. In summary, researching and developing an efficient vehicle thermal management system is beneficial for reducing energy consumption, increasing range, improving safety, reliability, and service life of new energy vehicles. By applying integrated thermal management technology, the air conditioning system, battery thermal management system, and electric drive electronic control system are managed in an integrated manner. The physical architecture of VTMS is improved, and the waste heat generated by various parts of the system can be fully recycled to optimize and improve the performance of VTMS. The physical architecture of VTMS is improved, and the waste heat generated by various parts of the system can be fully recycled to optimize and improve the performance of VTMS. In order to achieve the aforementioned goals, the author, relying on project support, conducted research on the thermal management and control strategies of the electric drive electronic control circuit and battery pack of the new energy vehicle thermal management system. At the same time, an evaluation system for the performance indicators of the vehicle thermal management system was established.

Literature review

Battery electric vehicle originated in Europe in 1873. The earliest car in the world was electric vehicles. But later, with the emergence of Internal combustion locomotive and the limitations of batteries, motors and driving modes of electric vehicles, the development of electric vehicles fell far behind Internal combustion locomotive, the oil development in the Middle East in the 20th century led to a decrease in the development speed of electric vehicles. However, it was not until the oil crisis in the Middle East in the 1970's that people gained a new understanding of the importance of electric vehicle development for the country, and the development of electric vehicles reached a new wave. In the 1990's, due to environmental pollution, resource depletion and other factors, developed countries such as Europe and the USA set off a third boom in the development of electric vehicles, and regarded the development of electric vehicles as a solution the aforementioned series of problems. In the 1980's, the rapid development of science and technology in various disciplines, as well as the development of modern electronics, internet technology, and new polymer materials, made electric vehicles once again the mainstream of the automotive industry. On the basis of studying existing mature technologies and solutions, combined with the characteristics of visualization equipment for underwater operations, Mansur *et al*. [4] proposed a set of motion attitude stability analysis theory suitable for underwater platforms. Combining various control theories, the motion control equations of underwater robots were established, and the optimal control method was designed. Pan *et al*. [5] have constructed a GIS based safety evaluation system for interval tunnel entrances, providing a reference for the safety evaluation of interval tunnel entrances. The determination of construction and support parameters in tunnel engineering is deeply influenced by the stress conditions of tunnel engineering. Cai and Mao [6] designed an intelligent monitoring system for the operating parameters and environment of converter transformers. Expanded current monitoring methods and further integrated key operating parameters and environmental monitoring information of converter transformers.

At present, there are many research directions for electric vehicles, mainly including motor drive technology, motor control strategy issues, charging power and efficiency issues, and vehicle control strategy issues. Among these issues, the selection of driving motors, the selection of operating ranges for driving motors, the achievement of high performance indicators, the achievement of maximum braking energy recovery efficiency, and the formulation of vehicle control strategies are key issues faced by the current development of electric vehicles.

Integrated thermal management of electric vehicles based on motor waste heat recovery

Integrated thermal management system configuration

The integrated thermal management system proposed by the author is shown in fig. 1. The motor thermal management system and battery thermal management system achieve heat exchange through Valves 1 and 3, while the air conditioning and battery achieve heat exchange

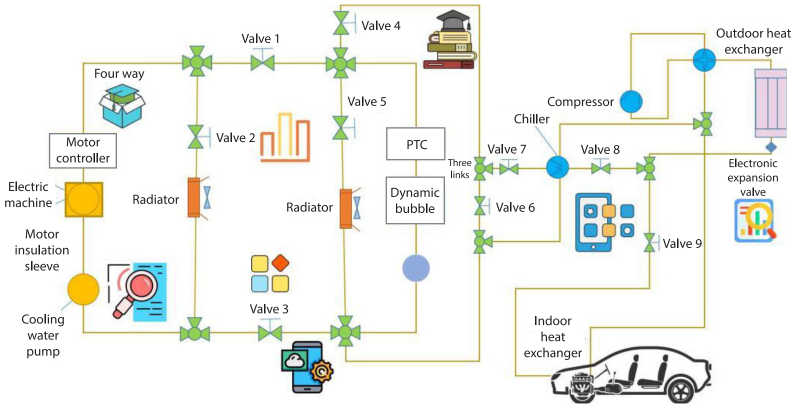

Figure 1. Structure of electric vehicle integrated thermal management system

through Valves 6 and 7. The external insulation material of the motor is wrapped to fully utilize the residual heat of the motor. According to the different states of the valve, the battery thermal management system can be divided into four working modes. The valve state is composed of eight binary digits, with the 1-7 digits representing valves 1-7 from left to right, the 8th bit is the positive temperature coefficient (PTC) opening signal, where Valvea 1 and 3 are disconnected, which is the traditional parallel configuration mode.

Mode 1 represents the circulation between the motor and the battery, using the residual heat of the motor to heat the battery. The PTC is turned on heat the battery. Mode 2 is the motor circulates with the battery, using the residual heat of the motor to heat the battery, and the PTC is turned off. Mode 3 is the indicates that the battery operates in a small cycle, and neither the motor nor the PTC heats the battery, and Mode 4 indicates that the battery operates in a large cycle, and the heat from the battery is dissipated through the heat sink [7].

Battery thermal management model

At present, lithium-ion batteries are mainly used as power batteries, and their heat exchange model is:

$$Q_{\mathrm{a-w}} + Q_{\mathrm{x-w}} + Q_{\mathrm{b-w}} = C_{\mathrm{w}} \times m_{\mathrm{w}} \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} \tag{1}$$

where $Q_{\text{a-w}}$ is the convective heat transfer power between the ambient temperature and the coolant, $Q_{\text{x-w}}$ – the heat transfer power of the motor, radiator, and PTC to the coolant, $Q_{\text{b-w}}$ – the heat exchange power of the battery pack to the coolant, C_{w} – the specific heat capacity of the coolant, m_{w} – the quality of the coolant, and T_{w} – the coolant temperature.

$$C_{\mathrm{w}} \times m_{\mathrm{w}} \times \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} = h_1 \times \left(T_{\mathrm{w}} - T_{\mathrm{a}}\right) + Q_{\mathrm{P,R-w}} + Q_{\mathrm{m-w}} + f\left(q_{\mathrm{cell}}, h_2, T_{\mathrm{b}}, T_{\mathrm{w}}\right) \tag{2}$$

where h_1 is the heat transfer coefficient between the ambient temperature and the coolant, h_2 – the heat transfer coefficient between the coolant and the battery pack, T_{b} – the temperature of the power battery, T_{a} – the ambient temperature, $Q_{\text{P, R-w}}$ – the heat transfer power of the battery radiator or PTC to the coolant, Q_{cell} – the heat generation rate of the lithium-ion battery, and $Q_{\mathrm{m-w}}$ – the heat transfer power of the motor to the coolant.

Control strategy for integrated thermal management system in low temperature environment

According to the conservation of energy, the temperature change of a battery depends on the changes in external heating, the total power of self heating, the total power of heat dissipation such as battery thermal radiation and thermal convection. Specifically, the correlation equations for battery temperature, coolant temperature, ambient temperature, and solenoid valve signal are:

$$x_1 Q_{\mathrm{P,R-w}} + x_2 Q_{\mathrm{m-w}} + h_1\left(T_{\mathrm{w}} - T_{\mathrm{a}}\right) + f\left(q_{\mathrm{cell}}, h_2, T_{\mathrm{b}}, T_{\mathrm{w}}\right) = C_{\mathrm{w}} \times m_{\mathrm{w}} \times \frac{\mathrm{d}\left[r\left(T_{\mathrm{b}}\right)\right]}{\mathrm{d}t} \tag{3}$$

$$\text{Among}: x_j = \begin{cases} 1\left(\text{working mode on}\right) \\ 0\left(\text{work mode off}\right) \end{cases}, \; j = 1, 2, ... \tag{4}$$

When a certain working mode signal is 0, all solenoid valves in this working mode have a 0 signal, and the effective cooling (heating) power of the relevant circulating circuit coolant on the battery pack is 0, indicating that this circulating circuit has no effect on the temperature of the battery pack. The temperature of the battery pack depends on the other circulating circuits with a working mode signal of 1.

The integrated thermal management system needs to switch modes based on environmental temperature, coolant temperature in the circulating circuit of various operating components, and other states, control the temperature of the power battery around 25 °C. The T_{bat} is the battery temperature, and when in a low temperature environment, the battery enters operating Mode 1. When $T_{\mathrm{bat}} \geq 15$ °C, enter working Mode 2. At this point, PTC is turned off. Due to the thermal radiation and convective heat dissipation of the battery, the temperature of the battery may decrease. If $T_{\mathrm{bat}} < 13$ °C, return to working Mode 1. When $T_{\mathrm{bat}} \geq 26$ °C, enter working Mode 3. At this point, neither the PTC nor the motor waste heat heats the battery, and the battery temperature may decrease. If $T_{\mathrm{bat}} < 25$ °C, return to working Mode 2. If $T_{\mathrm{bat}} \geq 30$ °C, enter working Mode 4. It should be noted that the temperature thresholds of 13 °C, 15 °C, 25 °C, 26 °C, and 30 °C in the previous strategy can be adjusted according to actual needs. The author only selected based on experience without optimization.

Hardware design of automatic monitoring system for heat recovery

The main purpose of the automatic monitoring system is to achieve real-time monitoring of the entire thermal energy recovery and utilization system and to protect the equipment. The automatic monitoring system can also be divided into two subsystems, namely the new energy vehicle automatic monitoring subsystem and the constant temperature and pressure water supply subsystem. Based on the flowchart of the thermal energy recovery system in section *Integratet thermal menagement of electric vehicles based on motor waste heat recovery* and the heat exchanger in the thermal energy recovery and utilization system as the boundary, a thermal energy recovery monitoring system is composed of new energy vehicles, thermal energy recovery control pump sets, cooling water pumps, and condensationwers. The underground insulation water tank, circulating heating water pump, and variable frequency constant pressure water supply unit form a thermal energy utilization monitoring system.The main hardware structure of the automatic monitoring system consists of a PLC controller and its extension module, on-site human-machine interface, Ethernet switch, centrifugal new energy vehicle control cabinet, high voltage distribution cabinet, and various sensors. It includes two automatic monitoring systems, one is the new energy vehicle automatic monitoring system with S7-1200 1215C as the core, and the other is the constant temperature and pressure automatic monitoring system with S7-200 224CN as the core, using S7-1200 1215C as the local station (customer station) and S7-200 224CN as the remote station (service station), communication between the two control cabinets is achieved through a switch.

As the main monitoring system, the monitoring system needs to monitor the operating status of the entire system. The constant temperature and pressure water supply system, as a subsystem, ensures the supply conditions for the system to recover hot water and maintain the supplied hot water within a certain temperature and pressure range. The automatic monitoring system has two control methods, local control and remote control. Local control is achieved through a touch screen (HMI), connecting the PLC to the HMI, displaying the data monitored by the PLC through the HMI, and manually changing the operating status of the new energy vehicle system and querying vehicle operating data through the HMI. Remote control also has the aforementioned local control function, which is connected to a personal computer through Ethernet and Ethernet switches to monitor the operation of new energy vehicle groups. The automatic monitoring system needs to monitor two subsystems, one is to monitor the body data in the heat recovery system and the parameters of each part of the heat recovery system, the other is to monitor and process the parameters of each part of the constant pressure and temperature system in the heat utilization system. The main functions of the monitoring system include data processing of sensor monitoring quantities, reasonable identification of monitoring parameters, identification and action protection of fault shutdown measures, adjustment of intake valves for centrifugal new energy vehicles, switching of backup equipment for fault systems, loading and unloading of hysteresis control for screw type new energy vehicles, constant temperature and pressure water supply, and human-machine interface control of new energy vehicle groups and display of actual values of various parameters.

In this system, the main parameters that need to be monitored are:

- Temperature parameters [°C], new energy vehicle inlet and outlet temperature, motor stator temperature.
- Pressure parameters [MPa], include pipe-line pressure, new energy vehicle inlet and outlet pressure, air bag pressure, and air filter pressure difference.
- Bearing vibration parameters [μm], Motor 1 vibration, Motor 2 vibration, and Motor 3 vibration.
- Other parameters include high voltage cabinet voltage [kV], high voltage cabinet current [A], and valve opening [%]. Monitoring temperature parameters, pressure parameters, bearing vibration parameters, voltage, current and other parameters to determine whether new energy vehicles are operating under normal operating conditions plays an important role and significance in the protection and maintenance of new energy vehicle systems.

Simulation analysis

In order to verify the performance of the integrated thermal management system and comprehensively reflect the adaptability of the structure to the environment, the author established a simulation model for the integrated thermal management system of electric vehicles in AMESim, compare and simulate the integrated thermal management system with traditional battery thermal management system under different environmental temperatures. The control strategy of the traditional battery thermal management system is similar to the integrated thermal management system in the text, in that only the battery operating Modes 1, 3, 4, and only PTC heating in battery working Mode 1, when $T_{\text{bat}} \geq 15$ °C, enter work Mode 3. At this point, PTC is turned off and the battery temperature may decrease. If $T_{\text{bat}} \leq 13$ °C, it will return to working Mode 2. When $T_{\text{bat}} \geq 30$ °C, enter working Mode 4 and the battery dissipates heat. The simulation environment temperatures are set to –10 °C, –5 °C, and 0 °C, respectively, and the simulation conditions are 10 CLTC (Chinese cycle conditions) [8].

The battery temperature is shown in figs. 2 and 3. Obviously, there are two-stages in the figures. One-stage is when the battery temperature rises rapidly, and the other stage is when the battery temperature slowly rises and ultimately maintains at a certain temperature. For the convenience of description, Configuration A in the figures represents an integrated thermal management system, while Configuration B represents a traditional battery thermal management system.

In figs. 2 and 3, the battery temperature is first heated from the ambient temperature to 15 °C, which is defined as the battery heating stage. After the heating stage ends until the battery temperature exceeds 30 °C, this stage is defined as the battery insulation stage. The battery temperature diagram and PTC switch signal during the heating stage are shown in figs. 4 and 5. The starting point of the heating is the ambient temperature, and the ending point of the heating is 15 °C (*i.e.* the first shutdown point of the PTC switch signal in the strategy). The solid line

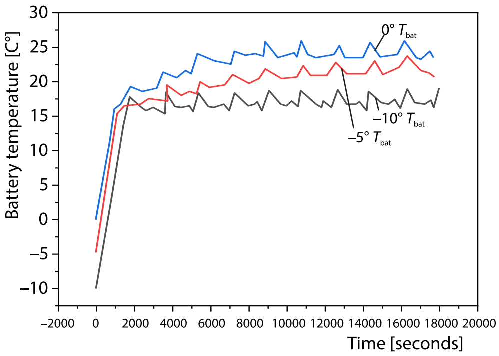

Figure 2. Battery temperature of the integrated thermal management system

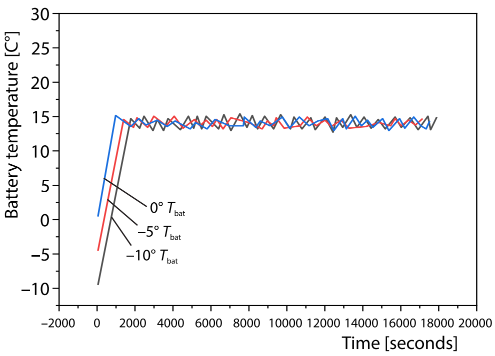

Figure 3. Battery temperature of the traditional battery thermal management system

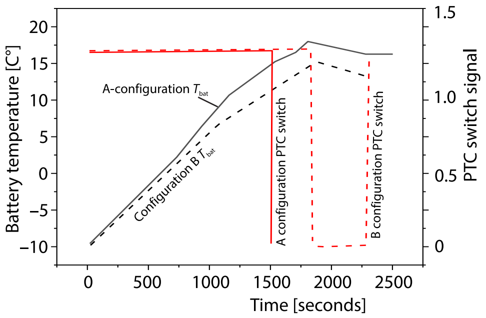

Figure 4. The –10 °C battery temperature and PTC switch in the heating stage

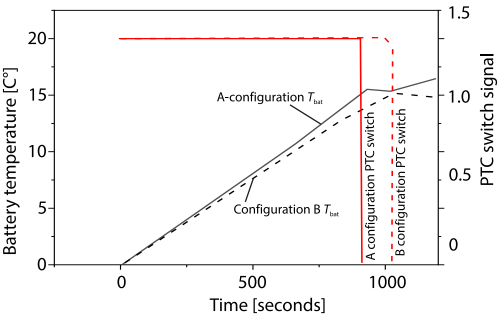

Figure 5. The 0 °C battery temperature and PTC switch in the heating stage

represents the integrated thermal management system, the dashed line represents the traditional battery thermal management system, the black line represents the battery temperature, and the red line represents the PTC switch signal.

From the battery temperature curve during the heating stage, it can be seen that the A configuration battery temperature represented by the thin solid line is always above the B configuration battery temperature represented by the thin dashed line, indicating that the slope of the integrated thermal management system battery temperature rise curve is higher than that of traditional battery thermal management systems. From the PTC switch signal line, it can be seen that compared to traditional battery thermal management systems, the integrated thermal management system switches off PTC earlier (*i.e.* the battery temperature reaches 15 °C faster). Under different low temperature environments (–10~0 °C), compared to traditional battery thermal management systems, the integrated thermal management system reduces the heating stage time by 343 seconds, 250 seconds, and 111 seconds, respectively.

An integrated thermal management system can maintain the battery temperature at around 25 °C. According to the traditional battery thermal management system strategy, the traditional battery thermal management system can only maintain the battery temperature at around 14 °C. However, due to the influence of working conditions and environmental temperature, the average temperature during the battery insulation stage of the integrated thermal management system did not reach 25 °C.

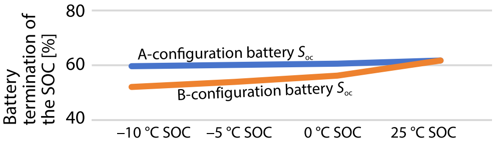

Figure 6. Battery termination SOC

The battery temperature and PTC activation time in low temperature environments directly affect the changes in battery SOC, thereby affecting the range of electric vehicles. In order to analyze the energy consumption differences between integrated thermal management systems and traditional battery thermal management systems in low temperature environments, as well as the impact of different environmental temperatures on the range of electric vehicles, the author simulated the termination of SOC for different configurations under established operating conditions in low temperature environments (–10~0 °C) and room temperature environments (25 °C), as shown in fig. 6. The difference in SOC termination between different low temperature environments and room temperature environments is shown in tab. 1.

Table 1. Difference between low temperature and 25 °C battery termination SOC

Ambient temperature	–10 °C	–5 °C	0 °C
Configuration A	2 .07	1 .40	1 .26
B configuration	8 .77	7 .62	5 .54

From fig. 6, it can be seen that the integrated thermal management system has different degrees of reduction in comprehensive energy consumption compared to traditional battery thermal management systems in different low temperature environments. The economic efficiency can be improved by 7.70%, 6.12%, and 4.39% under –10 °C, –5 °C, and 0 °C environments, respectively [9, 10]. From tab. 1, it can be seen that the termination SOC of traditional battery thermal management systems in different low temperature environments is reduced by a maximum of 8.77% compared to room temperature environments. Benefiting from the full utilization of motor waste heat, the termination SOC of integrated thermal management systems in different low temperature environments is reduced by no more than 2.07% compared to room temperature environments. It can be seen that the integrated thermal management system greatly weakens the impact of ambient temperature on driving range, and can effectively alleviate range anxiety.

Conclusion

In order to improve the endurance mileage and the new energy vehicle problem of *range anxiety* of electric vehicles, the author proposes an integrated thermal management system for electric steam new energy vehicles based on motor waste heat recovery, which can meet the needs of new energy vehicles for battery heating and insulation by using the serial and parallel switching of the thermal management system of motor and battery new energy vehicles under low temperature environment. The simulation results of new energy vehicles in different low temperature environments (–10~0 °C) show that the integrated thermal management system can shorten the heating time of the new energy vehicle's heating system by 111~343 seconds compared to the traditional battery heat pipe system during the heating stage, and can reach the target temperature of the new energy vehicle faster. During the insulation phase, the integrated thermal management system can maintain the battery temperature near 20 °C through the residual heat of the electric new energy vehicle engine, which is not only closer to the temperature range of the new energy vehicle battery, but also avoids frequent starting of the PTC heater.

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