

# Research on Thermal Management System Integration of Electric Vehicle

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## Abstract

In order to alleviate the endurance anxiety and charging anxiety in the development of electric vehicles, super fast charging and heat pump technologies will be applied to the next generation of vehicle platforms, but they also bring new challenges to the thermal management system. The functional requirements of thermal management systems are increasing, and the complexity of the system and the types and quantities of components are increasing rapidly. Integration has become a solution to simplify the system and reduce costs. The first thing to do is to integrate the physical and functional integration of multiple coolant valves, and integrate the switching of thermal management loop into one valve. Through mechanical integration with other actuators, sensors and heat exchangers in the coolant circuit and refrigeration circuit, the space utilization rate of thermal management system is improved, which provides convenience for the modular design of main engine models. In the future, it will complement the integration of electronic and electrical architecture to achieve a higher degree of drive, control and software integration.

## Keywords

Thermal Management, Integration, Multi-Ports Valve, Modular

## 1. Preface

Global warming and severe air pollution caused by automobile exhaust pose a great threat to human health. When the electricity of pure electric vehicles (PEV) comes from renewable energy sources such as nuclear energy, hydro energy, solar energy and wind energy, the pollution generated will be reduced, and its greenhouse gas emissions are far lower than those of internal combustion engine vehicles (ICEV). PEV is completely driven by secondary batteries (nickel-cadmium, nickel-hydrogen or lithium-ion), which represents the future of the automotive

industry. Another important reason for the development of PEV is the increasingly urgent energy crisis, and the need to adjust the energy consumption pattern. Compared with traditional ICEV, the total energy efficiency of PEV is approximately 60% - 70%, far higher than that of traditional ICEV (only 15% - 18%) [1]. PEV, as a distributed energy storage system, is connected to the smart grid to achieve load balancing, reduce the intermittent impact of renewable energy power generation such as wind energy and tidal energy, and promote the development of related industries. In addition, due to the support of the state and the public, pure electric vehicles also have great development space. Driven by good national policies, the continuous update and improvement of pure electric vehicle technology will vigorously promote the acceptance of pure electric vehicles [2]. Excellent driving performance will boost the consumption of pure electric vehicles, thereby enhancing the development of the new energy vehicle economy and thus promoting the development of the green economy. The research, development and promotion of electric vehicles are of great significance for environmental protection and sustainable development [3].

During the charging and discharging process of the battery, an overly high temperature may cause battery corrosion, decomposition or even explosion, while an overly low temperature may cause battery power and capacity attenuation and a decrease in charging and discharging efficiency [4]. When the electric vehicle is cooling in summer, the compressor is driven by an electric motor, and it is difficult to use the waste heat of the internal combustion engine for heating in winter. Among all the auxiliary systems of electric vehicles, the air-conditioning system has the largest energy consumption, which seriously affects the vehicle's driving range. Currently, the driving range of electric vehicles in cold seasons is severely reduced, which is not conducive to the driving experience. The root cause is that lithium-ion batteries are too sensitive to temperature. Lithium-ion batteries will suffer severe energy loss at temperatures below zero degrees Celsius. Wang *et al.* found that the range attenuation can be as high as 40% in cold weather, requiring larger and more expensive battery packs [5]. Cold engine start-up, slow charging and limited regenerative braking further exacerbate the power loss of electric vehicles. On the other hand, during the charging and discharging process, due to electrochemical reactions and resistance, a large amount of heat is generated inside the battery, which increases the battery temperature. If the temperature is too high, a fire or even an explosion may occur. In addition, when the temperature of the motor drive system is high, its life and efficiency will drop sharply [6]. Therefore, the research and development of an efficient thermal management system to keep the battery, passenger compartment, and motor drive system within an appropriate temperature range is a necessary measure to promote the development of electric vehicles.

## 2. Challenges and Solutions of Electric Vehicles

With the increase in the number of new energy vehicles in possession and the

rising demands for vehicle charging and driving range, long charging time, low charging efficiency, and severe attenuation of driving range in high-and-low-temperature environments have become the main pain points of new energy vehicles. To this end, major automobile manufacturers and scientific researchers have proposed different solutions. They have conducted in-depth research on the evaluation of the driving range of pure electric vehicles in different environments and temperatures, the load characteristics in summer and winter, the improvement of the driving range in high-and-low-temperature conditions, the design and control of the vehicle thermal management system, etc., gradually alleviating the pain points of new energy vehicles in all-climate use.

### **2.1. Range Extension**

With the accelerating pace of electric vehicle upgrades, the ordinary range problem has been basically solved, but the problems of low-temperature and high-speed range need further improvement. To achieve a driving range of 1000 kilometers, GAC AION LX Plus is equipped with NCM ternary lithium-battery packs, NIO ET7 is equipped with semi-solid-state batteries, IM L7 is paired with silicon-doped lithium-compensation batteries, BYD Ocean-X continues to use blade batteries, and Tesla is equipped with Tabless batteries. At the same time, the new pure-electric platform has changed the original structural design. On the premise of considering safety, cost, and vehicle mass, the long-distance driving range can be achieved by changing both the physical structure and the chemical structure of the battery.

### **2.2. Super-Fast Charging**

Charging infrastructure is an important guarantee for the high-quality development of the new energy vehicle industry. During the 13<sup>th</sup> Five-Year Plan period, China's charging infrastructure achieved leapfrog development in terms of technology, standards, and ecology. Currently, fast-charging accounts for 40% of public charging piles in China, and the fast-charging power is generally low, making it difficult to meet the charging demands of the vast majority of users and adapt to the rapid development of the current new energy vehicle industry. To alleviate these difficulties, further enhance the guaranteed ability to charge infrastructure, and continuously strengthen the international competitiveness of China's new energy vehicles, promoting the development of high-power fast-charging will become an important development direction in the current and future period. Since adding charging piles will also bring problems such as construction and maintenance costs, the core of the solution lies in the development of charging technology. The increase in the penetration rate of high-voltage super-charging during 2025-2030 will become the mainstream. For example, NIO's battery-swapping technology and GAC New Energy's super-fast-charging battery. Solutions for achieving super-fast charging include: improving the platform voltage and fast-charging rate performance of the battery at the battery end, making the charging

gun liquid-cooled, enhancing the heat dissipation capacity of the charging pile, and realizing ultra-high-power DC fast-charging.

### 2.3. Heat Pump Technology

Since the PTC, which is a low-temperature heating heat source in the electric vehicle thermal management system, consumes a relatively high amount of energy, resulting in a severe attenuation of the driving range of electric vehicles in a low-temperature environment, various vehicle manufacturers have gradually introduced heat pumps as an efficient heat source in low-temperature environments. They comprehensively consider the temperature control of the motor/electronic control, the temperature control of the power battery, and the air-conditioning of the passenger compartment to construct a more energy-efficient vehicle thermal management system.

## 3. Evolution of Thermal Management System

Compared with traditional electric vehicles, the super-fast charging and heat pump technologies applied in next-generation electric vehicles have brought new functional requirements to the thermal management system. At the same time, some new components also need to be added to meet the complex functional requirements, which directly leads to an increase in cost and the complexity of system integration and control.

### 3.1. Complexity of Thermal Management Function

In the thermal management system of traditional electric vehicles, each component is relatively independent. For example, the motor and power electronics mainly focus on heat dissipation, the battery mainly uses PTC heating or cooler for cooling, and the passenger compartment mainly uses air-conditioning for cooling and PTC for heating. There is basically no heat exchange and thermal coupling among the various systems. However, in order to improve the energy utilization efficiency of next-generation electric vehicles, energy is made to flow as much as possible within the system, increasing the degree of thermal coupling of the system, as shown in **Table 1**.

While the functional requirements are increasing, the scenarios of using multiple functions simultaneously are also increasing. This requires that multiple heat exchange loops need to cooperate with each other to achieve the purpose of heat transfer, as shown in **Table 2**.

### 3.2. Diversification of Thermal Management Components

Compared with traditional fuel vehicles, electric vehicles have the advantages of zero-emission and low-noise. However, the performance, safety, and lifespan of electric vehicles largely depend on the thermal management system. The thermal management system not only has to ensure that the battery operates within an appropriate temperature range but also needs to conduct effective thermal control

**Table 1.** Thermal management requirements.

|  | Motors and electronic controls  | Battery pack  | Crew compartment  |
|--|---|---|---|
| Conventional electric vehicles           | Radiator heat dissipation.  | Radiator heat dissipation.<br>Air conditioning refrigeration.<br>PTC heating.   | Air conditioning refrigeration.<br>PTC heating.                       |
| The next generation of electric vehicles | Radiator heat dissipation.<br>Waste heat recovery.<br>Oil cooling and heat dissipation. | Radiator heat dissipation.<br>Air conditioning refrigeration.<br>PTC heating.<br>Motor heating.<br>Heat pump heating. | Air conditioning refrigeration.<br>PTC heating.<br>Heat pump heating. |

**Table 2.** Combined thermal management functions.

| Scenario                                   | Motor and Electronic Control | Battery Pack              | Passenger Compartment    |
|--|------------------------------|---------------------------|--------------------------|
| Low—Temperature Heating/Charging           | Waste Heat Recovery          | Heat Pump Heating         | Heat Pump Heating        |
| Extremely Low—Temperature Heating/Charging | Radiator Heat Dissipation    | PTC Heating               | PTC Heating              |
| Normal—Temperature Heating                 | Waste Heat Recovery          | /                         | Heat Pump Heating        |
| Normal—Temperature Slow Charging/Driving   | Radiator Heat Dissipation    | Radiator Heat Dissipation | /                        |
| Normal—Temperature Fast Charging           | Radiator Heat Dissipation    | Air-conditioning Cooling  | /                        |
| Normal—Temperature Cooling                 | Radiator Heat Dissipation    | Radiator Heat Dissipation | Air-conditioning Cooling |
| High—Temperature Charging                  | Radiator Heat Dissipation    | Air-conditioning Cooling  | /                        |
| High—Temperature Cooling                   | Radiator Heat Dissipation    | Radiator Heat Dissipation | Air-conditioning Cooling |

over key components such as motors and electronic control units, while ensuring the comfort of the cockpit. Therefore, in-depth research on the evolution of the thermal management system of electric vehicles is of great significance for improving the overall performance of electric vehicles.

### 3.2.1. Improvement of Battery Thermal Management

With the increase in battery energy density and power demand, liquid-cooling technology has been gradually applied to battery thermal management. A liquid-cooling system usually consists of coolant pipes, pumps, heat exchangers, etc. The coolant circulates in the pipes, taking away the heat generated by the battery, and transfers the heat to the external environment through the heat exchanger. For example, some mainstream electric vehicle manufacturers have designed complex coolant channels inside the battery module, enabling more effective control of battery temperature. The advantage of liquid cooling lies in its high thermal conductivity and specific heat capacity, enabling efficient heat dissipation. It can better ensure the uniformity of temperature within the battery pack and improve the safety and lifespan of the battery. However, the liquid-cooling system also faces

some challenges. For example, coolant leakage may lead to safety issues such as battery short-circuit. In addition, the complexity of the liquid-cooling system increases the cost and maintenance difficulty.

### **3.2.2. Upgrade of Thermal Management for Motors and Electronic Control Units**

To cope with the heat dissipation requirements of high-power motors, liquid-cooled motor technology has been developed. A liquid-cooled motor has coolant channels set inside the motor to timely take away the heat generated during the motor's operation. This way can effectively control the motor temperature, improving the power density and reliability of the motor. For example, the drive motors of some high-performance electric vehicles adopt oil-cooling or water-cooling techniques, enabling the motors to maintain good performance even under high-load operation. Electronic control units have also started to adopt liquid-cooling technology. At the same time, to improve thermal management efficiency, the thermal management systems of motors, electronic control units, and batteries have been integrated to a certain extent. By reasonably designing the circulation path and heat exchange mode of the coolant, heat sharing and coordinated control among different components can be achieved, reducing the overall energy consumption of the thermal management system.

### **3.2.3. Optimization of Cockpit Thermal Management**

Heat pump technology has started to be applied to the thermal management of electric vehicle cockpits. A heat pump can transfer heat from a low-temperature environment to a high-temperature environment through the reverse Carnot cycle. In heating mode, the heat pump uses the heat in the external environment to heat the cockpit. Compared with traditional PTC heaters, the heat pump can significantly reduce energy consumption and improve the driving range of electric vehicles in cold weather. In cooling mode, the heat pump can also be part of the air-conditioning system to achieve efficient cooling functions. To further improve the efficiency of the thermal management system, the cockpit thermal management has been coordinated and optimized with the thermal management of components such as batteries and motors. For example, in winter, the waste heat generated by motors and batteries can be used to heat the cockpit, reducing the energy consumption of heat pumps or other heating equipment. Meanwhile, in summer, the heat discharged by the cockpit air-conditioning system can be used for heat dissipation of batteries or motors through reasonable heat exchange design, improving the energy utilization efficiency of the entire thermal management system.

## **4. Integrated Solutions**

### **4.1. Integration of Multi-Channel Valves**

Multi-channel valves can connect multiple thermal management loops. By changing the connection state of the internal channels of the valve, the switching of

coolant or refrigerant between different loops can be achieved. For example, in winter, the heat generated by the motor can be guided to the battery loop through the multi-channel valve to heat the battery, or the waste heat of the battery can be introduced into the cockpit heating loop to achieve rational heat distribution. In an integrated thermal management system, the multi-channel valve, as a key control element, can centralize the control logic of a complex multi-loop thermal management system. By combining with the vehicle's control system, the multi-channel valve can achieve automated thermal management control based on preset algorithms and sensor feedback information, reducing the complexity of overall system control. There are mainly three control strategies for the integration of multi-channel valves. The following is a comparison table of the battery temperature control effects of multi-channel valves under different control strategies.

**Table 3.** The control effect of the multi-channel valve on battery temperature under different control strategies.

| Control Strategy               | Battery Temperature Fluctuation Range (°C) | Temperature Control Precision (°C) | Overheating Frequency (times/1000km) |
|--------------------------------|--|------------------------------------|--------------------------------------|
| Rule-Based                     | ±5   | ±2.5                               | 3                                    |
| Model Predictive Control (MPC) | ±3   | ±1.5                               | 1                                    |
| Machine Learning-Based         | ±2   | ±1                                 | 0.5                                  |

## 4.2. Coolant Integration Module

Based on multi-channel integration, multiple coolant loop components such as electronic water pumps, reservoirs, and temperature sensors are integrated together. Special coolant distribution plates are designed to connect the inlets and outlets of water valves, water pumps, and reservoirs, and also play a role in support and installation. The integration of components in an individual coolant integration module is less difficult, and it is suitable for integrated arrangement within a limited space.

## 4.3. Refrigerant Integration Module

Related components in the refrigeration circuit also have the potential for integration. For example, there is a plan to integrate components such as air-conditioning compressors, condensers, evaporators, expansion valves, and drying bottles into one module. The refrigerant integration module is suitable for high-pressure or flammable refrigerants such as R744 or R290. It plays a role in isolation and protection of vehicle interior safety through heat exchange in a secondary loop.

## 4.4. Integration Module of Coolant and Refrigerant

On the basis of the coolant integration module, components related to coolant heat exchange are further integrated onto the module, such as water-cooled

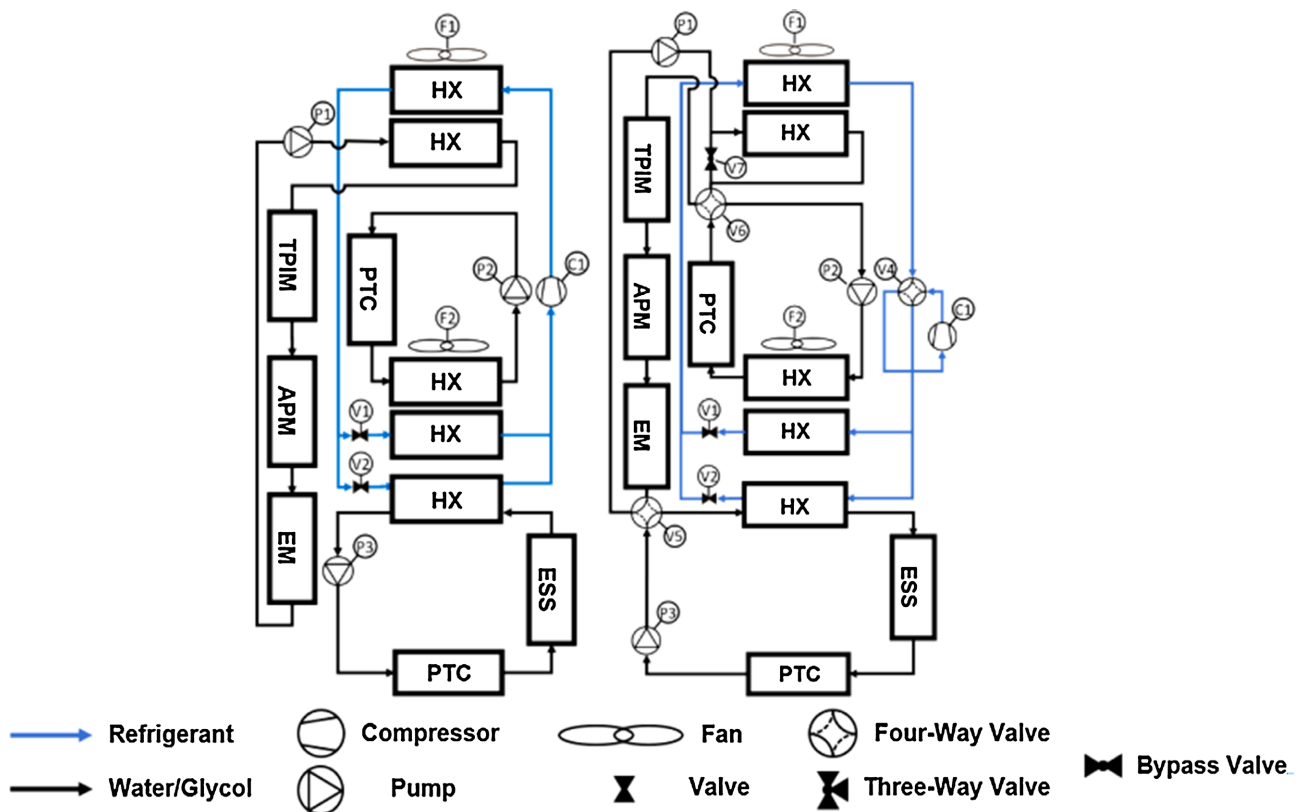
condensers, battery coolers, and their expansion valves. According to system requirements, special refrigerant distribution plates can also be designed to connect the inlets and outlets of the refrigerant ends of condensers, battery coolers, and expansion valves, and also support the installation of refrigerant temperature and pressure sensors, playing a role in support and installation and preventing the challenges brought by the weight of additional components to the coolant distribution plate.

### 4.5. Advantages and Challenges of Integration

Integration brings new opportunities for new vehicle development by vehicle manufacturers, and at the same time poses new challenges to vehicle design.

#### 4.5.1. Modularization of Platform Vehicles

Compared with scattered systems, the thermal management system integration module can significantly reduce the space and weight occupied by the entire thermal management system. The integration module provides a complete solution by first-tier suppliers, which can simplify the process of vehicle manufacturers in managing multiple suppliers. See **Figure 1**, modular design is also beneficial for cross-platform applications, facilitating rapid development and verification on new platforms, and even directly reusing universal solutions.



**Figure 1.** Schematic flow diagrams of all battery electric vehicle (BEV) integrated thermal management system (ITMS) architectures: (a) Baseline (Base); (b) Heat pump, PTC, and waste heat recovery (WHR).

#### **4.5.2. Cost Reduction**

Material costs are continuously reduced with the increase in the degree of integration. Compared with the situation before integration, the integrated multi-channel water valve reduces the number of actuators as well as multiple mechanical materials such as housings, seals, and valve cores compared to multiple water valves. The volutes of water pumps, coolant pipes, and coolant joints are also saved during integration. Besides material costs, the assembly line cost of vehicle manufacturers can also be reduced, mainly because the installation of the thermal management integration module requires only a very few processes, shortening workstation costs and improving assembly efficiency.

#### **4.5.3. Challenges of Front-End Compartment Arrangement**

The thermal management system integration module is less flexible in installation than scattered components and requires a specific area to be demarcated in the front compartment of the vehicle. In the current trend of electric vehicles giving more space to the passenger compartment, the available space in the front compartment has become particularly compact. Therefore, a reasonable installation space is a major prerequisite for designing the thermal management integration module. Besides space, the integration module concentrates the weight of the thermal management system at several nearby installation points, which also poses difficulties for the design of the front-compartment load-bearing capacity. Finally, there are problems of noise and vibration. The vibration and noise generated by the simultaneous operation of multiple actuators such as water pumps, water valves, and expansion valves are physically close to each other, and the periodic flow of coolant and refrigerant in the internal pipelines of the integration module also generates continuous vibration and impact.

#### **4.5.4. After-Sales Maintenance**

When one component in the integration module fails, the entire module needs to be removed from the vehicle for maintenance or replacement. On the one hand, this increases after-sales maintenance costs, and on the other hand, it also raises the technical threshold for product maintenance.

### **5. Towards Higher Integration**

#### **5.1. Electronic and Electrical Integration**

Currently, the current thermal management integration solution is still under exploration. Considering the mass-production time requirements of vehicle manufacturers and the capability level of suppliers, currently, mechanical integration of the thermal management system still dominates. The next-generation thermal management integration will have the opportunity to integrate the actuator and sensor electronic and electrical components in the thermal management integration module, using an integrated drive and control board to achieve drive control of the execution of water pumps, water valves, and expansion valves, as well as the collection and measurement of coolant temperature sensors and refrigerant

temperature and pressure sensors. The integrated thermal management drive control board only requires a microcontroller and a bus communication module to access the vehicle network, and can also be embedded in the functional domain controller or regional controller according to the platform planning of the vehicle's electronic and electrical architecture by the vehicle manufacturer, achieving a higher level of integration.

## 5.2. Software Function Integration

On the basis of electronic and electrical hardware integration, corresponding software functions can also achieve a high degree of integration. For example, integration of communication software and protocols, integration of protection and diagnostic functions, integration of online upgrade functions, etc. With the development of the trend of software-defined vehicles, in the future, the intelligence, economy, and safety of the thermal management system can be improved through software remote upgrade on the same set of hardware.

In the process of running the vehicle thermal management system, firstly receive the battery thermal management request sent by the BMS, the passenger compartment demand sent by the AC, and the thermal management request sent by the electric drive system, and then determine the current thermal management function mode state by judging the auxiliary signals such as the vehicle charging state, vehicle speed information, and ambient temperature, and send the control signal to each controlled component of the thermal management system.

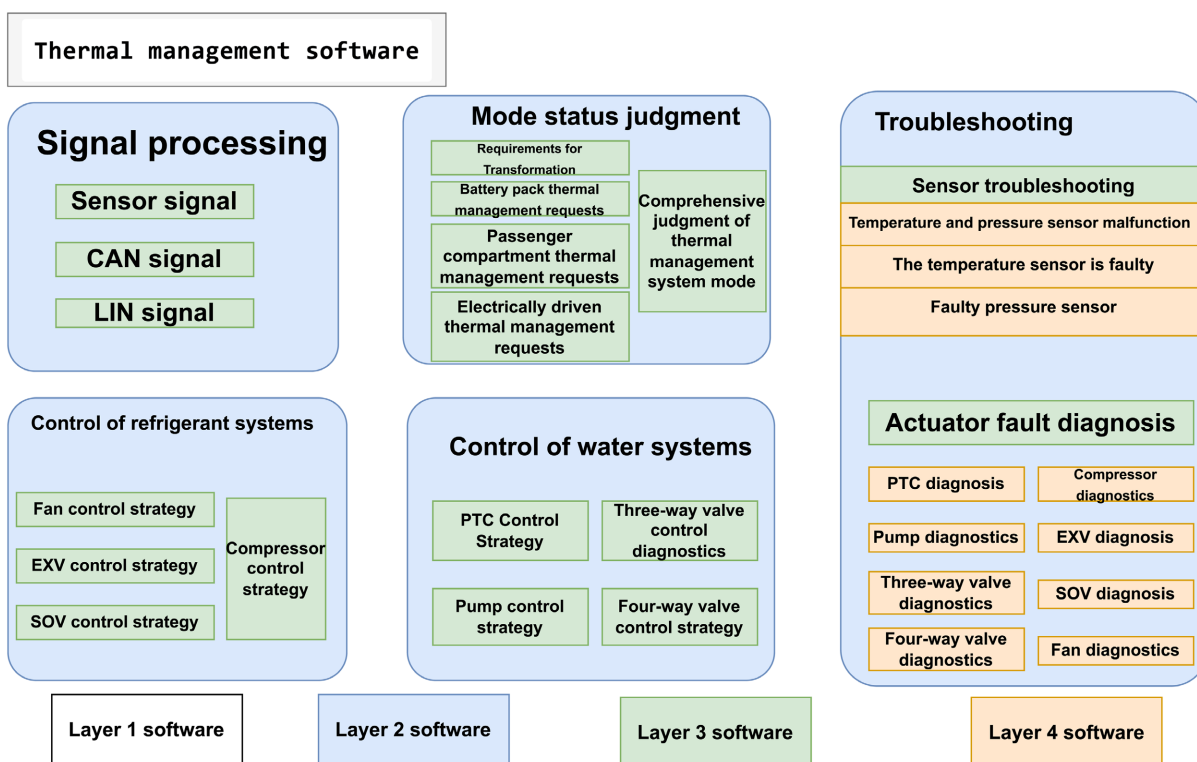


Figure 2. The internal part of the thermal management system software for the whole vehicle.

The thermal management function mode control software is divided into 4 layers, the first by judging the auxiliary signals such as the vehicle charging state, vehicle speed information, and ambient temperature. The second layer is the main body of the thermal management software, the second layer is divided into the software module of signal processing, mode state control, control and diagnosis of two subsystems (water system and refrigerant system). The third layer is the detailed strategy of the second layer, and the fourth layer is the diagnostic program of each actuator component under the sensor and actuator diagnosis software module.

### **5.3. System Integration Architecture Optimization**

The integrated thermal management system of electric vehicle realizes the optimization of the architecture by integrating multiple thermal management subsystems, thus reducing the cost and improving the efficiency. In traditional thermal management of electric vehicles, independent cooling or heating circuits are often built for batteries, motors and electronic equipment, which not only leads to numerous components and complicated pipelines, but also makes the space utilization rate low and the cost high.

Under the integrated architecture, it is one of the key strategies to adopt a shared heat exchanger and a unified coolant circuit. An integrated heat exchanger is designed, which can handle the heat dissipation demand of the battery pack and the heat generated by the electric control system of the motor simultaneously. Through reasonable flow channel design, the coolant can flow in order between different subsystems to ensure the effective transfer and dissipation of heat. This sharing mechanism reduces the number of heat exchangers and reduces the material cost and manufacturing cost. At the same time, the simplified pipeline layout reduces the filling amount and circulating resistance of coolant, improves the working efficiency of the pump, and then reduces energy consumption.

In addition, the compact integrated design helps to improve the space utilization. Integrating multiple thermal management components, such as heaters, coolers and valves, into one module reduces the space occupied by the system and is beneficial to the overall layout optimization of electric vehicles. For example, some new electric vehicles integrate the thermal management module into the limited space in the front cabin of the vehicle, which not only frees up more space for other components, but also shortens the heat transfer path, reduces the heat loss and improves the thermal management efficiency.

### **5.4. Intelligent Thermal Management Control Strategy**

Intelligent control strategy is another core element of integrated thermal management system for electric vehicles to improve efficiency and reduce costs. Through advanced sensor network and complex control algorithm, the precise regulation of thermal management system is realized.

First of all, dynamic control based on real-time monitoring data is the foundation.

High-precision temperature sensors, flow sensors, etc. are arranged in key parts such as battery pack and motor to obtain the thermal state information of the system in real time. Based on these data, the control unit dynamically adjusts the rotating speed of the cooling water pump, the air volume of the fan and the opening of the valve. For example, when the battery generates a lot of heat when discharging under high load, the control unit quickly increases the speed of the cooling water pump and turns on the corresponding cooling fan to ensure that the battery temperature is maintained in the optimal working range. This dynamic control avoids excessive cooling or heating under the traditional fixed control mode, improves energy utilization efficiency and reduces energy consumption cost.

Furthermore, the predictive control strategy further improves the system performance. Using the running data of vehicles, such as driving speed, road conditions, driving mode and environmental temperature, combined with machine learning algorithm, the future heat load changes are predicted. For example, before the vehicle climbs a hill or runs at a high speed, the power output of the cooling system should be increased in advance to prevent the key components from overheating. This predictive control not only protects the components, prolongs the service life and reduces the maintenance cost, but also reduces the operating power of the low-heat management system under low load conditions, thus saving energy and reducing consumption.

## 6. Conclusion

The functional requirements of the thermal management system are constantly increasing, and the system complexity, types, and quantity of components are growing rapidly. Integration has become a solution to simplify the system and reduce costs. The first step is the physical and functional integration of multiple coolant valves, realizing the switching of the thermal management loop on one valve. Then, through mechanical integration with other actuators, sensors, and heat exchangers in the coolant loop and refrigeration loop, the space utilization rate of the thermal management system is improved, providing convenience for the modular design of vehicle models by vehicle manufacturers. In the future, it will also complement the integration of the electronic and electrical architecture to achieve a higher degree of drive, control, and software integration.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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