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Standardized Research on High-Voltage Safety of Drive Motor Systems

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Abstract: This paper focuses on the high-voltage safety of drive motor systems in new energy vehicles and conducts standardized research on functional safety design in the concept phase. In view of the lack of high-voltage hazard analysis for drive motor systems in existing standards, based on theories such as GB/T 34590 and ISO 26262, the safety levels are deeply analyzed. The HAZOP method is innovatively used, and 16 types of guidewords are combined to comprehensively analyze the system functions, identifying vehicle hazards such as high-voltage electric shock caused by functional abnormalities, including high-voltage interlock function failure and abnormal active discharge. Subsequently, safety goals such as preventing high-voltage electric shock are set, functional safety requirements such as accurately obtaining collision signals and timely discharging high-voltage electricity are formulated, and requirements for external signal sources and other technologies are clearly defined, constructing a complete high-voltage safety protection system. The research results provide important technical support and standardized references for the high-voltage safety functional design of drive motor systems in new energy vehicles, and are of great significance for improving the high-voltage safety level of the new energy vehicle industry, expecting to play a key role in subsequent product development and standard improvement.

Keywords: Drive motor system; High-voltage safety; Functional safety design; HAZOP method

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1. Introduction

The drive motor system, as the power source of new energy vehicles, can not only provide power for new energy vehicles but also offer auxiliary braking force during vehicle braking. Different from the energy source of traditional fuel vehicles, the drive motor system in new energy vehicles uses high-voltage electricity instead of fuel. Although the use of high-voltage power brings rapid power response, it also poses potential hazards to people due to high voltage, as well as potential thermal hazards caused by the high heat generated by high-voltage and high-energy.

GB/T 34590 Road Vehicles—Functional Safety and ISO 26262 Road Vehicle—Functional Safety provide theoretical methodologies, study the functional abnormal behaviors of different systems, and analyze the corresponding potential hazards and safety levels [1]. GB/T 43254-2023 Functional Safety Requirements and Testing Methods for Drive Motor System of Electric Vehicles studies the torque-related hazards, safety acceptance criteria (such as controllability, confidence level, and other quantitative indicators), and evaluation methods of drive motor systems in new energy vehicles under different working conditions under the theoretical guidance of GB/T 34590 and ISO 26262 [2,3]. However, this standard does not include relevant analyses of high-voltage hazards and thermal hazards. This paper will analyze the corresponding safety levels and functional safety development cases of high-voltage hazards and thermal hazards of drive motor systems in new energy vehicles.

2. Research background

There are no specific regulations regarding high-voltage hazards and thermal hazards of motor drive systems in international regulations.

The Society of Automotive Engineers (SAE) issued SAE J2980 Considerations for ISO 26262 ASIL Hazard Classification in 2015 and its second edition in 2018 [4]. Based on the methodology of ISO 26262, this standard provides development guidelines for hazard analysis and risk assessment (HARA), definition of S/E/C key parameters, and ASIL levels for vehicle motion control-related electronic control systems such as steering, driving, suspension, and braking. ISO 26262 "Road Vehicle—Functional Safety" provides a theoretical methodology for road vehicle functional safety.

Domestically, referring to SAE J2980 and combining with China's actual situation, GB/Z 42285-2022 Road vehicles—ASlL determination guidelines for electrical and electronic system was developed and issued. It provides methods and examples for determining the Automotive Safety Integrity Level (ASIL) of automotive electrical and electronic systems, guiding the identification and classification of hazard events, and has important reference significance for enterprises to deepen their understanding of the GB/T 34590 series of standards and practice vehicle electronic control system functional safety technologies.

3. Definition of drive motor system-related items

The drive motor system defines functional concepts, operational and environmental constraints, similar functions, behaviors implemented by related items or elements, assumptions outside related items, failure modes and hazards, and potential consequences. The definition of the drive motor system-related items also specifies the boundaries, internal and external interfaces, and initial architecture of the drive motor system.

The boundaries, elements, interfaces, and interactions of the drive motor system-related items are shown in **Figure 1** below.

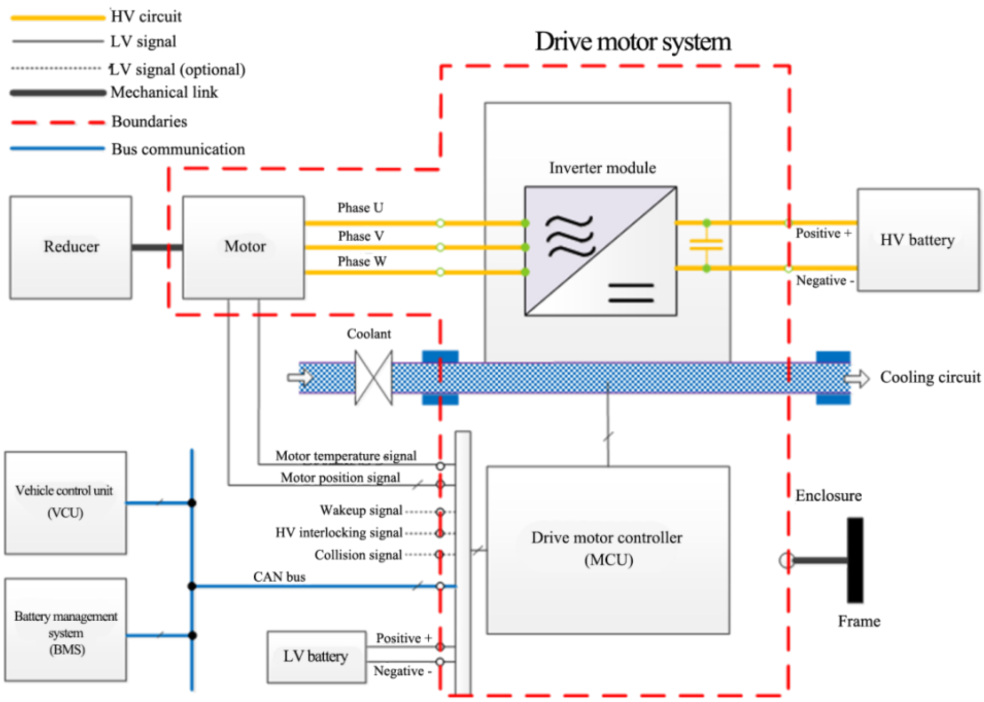

Figure 1. Example of boundaries, elements, interfaces, and interactions of drive motor system-related items

The purpose of the functional safety design of drive motor system is to prevent personal injury caused by functional abnormality when working in any scenario. For drive motor system, different regulations should be referred to for different product markets. The following table gives examples of reference regulations for different markets (**Table 1**). Regulatory requirements can provide input for subsequent hazard analysis and risk assessment, functional safety concept, and technical safety concept. **Table 2** gives the terms and abbreviations involved in the drive motor system.

Table 1. Examples of regulatory references for different markets

Product market	Examples of regulatory references
China and countries or regions that recognize Chinese automotive regulations	GB 7258 - 2017 Technical Conditions for the Safety of Motor Vehicle Operation GB/T 18488 - 2024 Drive Motor Systems for Electric Vehicles, GB 18384 - 2020 Safety Requirements for Electric Vehicles GB/T 43254 - 2023 Functional Safety Requirements and Testing Methods for Drive Motor Systems of Electric Vehicles GB 34660 - 34660 Road Vehicles - Electromagnetic Compatibility Requirements and Test Methods GB/T 34590 - 2022 Road Vehicles - Functional Safety ISO 26262 - 2018 Road vehicles - Functional safety GB/T 28382 Technical Conditions for Pure Electric Passenger Vehicles
The European Union and countries or regions that recognize EU automotive regulations	ECE R79 Uniform provisions concerning the approval of vehicles with regard to steering equipment ECE R10 Uniform provisions concerning the approval of vehicles with regard to electromagnetic compatibility ECE R155 Uniform provisions concerning the approval of vehicles with regard to cybersecurity and cybersecurity management systems

Note: The recommended regulatory references for China and countries or regions that recognize Chinese automotive regulations in the table are non-exhaustive. Regulatory requirements can be added according to specific circumstances.

Table 2. Terms and abbreviations

Term	Explanation	Term	Explanation
ABS	Antilock Brake System	FSR	Functional Safety Requirement
ADAS	Advanced Driving Assistance System	HARA	Hazard Analysis and Risk Assessment
ASIL	Automotive Safety Integrity Level	HV	High Voltage
CANFD	Controller Area Network with Flexible Data Rate	MCU	Motor Control Unit
EAS	Electronic Active Suspension	PMSM	Permanent-Magnet Synchronous Motor
EDU	Electric Drive Unit	SG	Safety Goal
EMC	Electromagnetic Compatibility	SS	Safe State
FSC	Functional Safety Concept	TCS	Traction Control System

This section should list the functions of the drive motor system and define and explain the purpose, functional logic, and functional operation mode of each function. **Table 3** shows an example of drive motor system function definitions.

Table 3. Function definitions of drive motor system

Number	Function name	Function description and purpose	Operation mode
1	Output drive torque	This function aims to enable the drive motor controller to control the drive motor to output the given drive torque based on the drive torque command from the vehicle control unit, combined with the current speed and load status of the drive motor.	Drive mode
2	Output brake torque	This function aims to enable the drive motor controller to control the drive motor to output the given brake torque based on the brake torque command from the vehicle control unit, combined with the current speed and load status of the drive motor.	Brake mode
3	Active discharge	This function aims to enable the drive motor controller to actively activate the discharge circuit (such as resistors/windings) based on the active discharge command from the vehicle control unit or the collision signal* (from CAN/hard-wire signal), combined with the current state of the drive motor, and control the rapid discharge of the support capacitor.	Shutdown mode
4	High-voltage interlock function**	This function aims to enable the drive motor controller to continuously monitor the integrity of the interlock circuit at its high-voltage bus connection port. When the interlock circuit is detected to be disconnected and the disconnection persists for 1 s, the high-voltage interlock status flag is set to "Unlock," the high-voltage shutdown is performed within the safe time, a node-level 1 fault is reported, and the DTC is stored.	Normal operation
5	Boost charging function	This function aims to enable the drive motor controller to control the opening/closing of the upper and lower bridge arms based on the boost command from the vehicle control unit, so that the charging circuit can boost the charging voltage lower than the target voltage to the target voltage through the motor windings acting as inductors.	Charging mode
6	Drive motor controller cooling	This function aims to enable the drive motor controller to dissipate the heat generated by the drive motor controller to the external environment based on the current temperature and other states of the drive motor controller, and reduce the temperature of the drive motor controller.	Normal operation
7	Drive motor cooling	This function aims to enable the drive motor controller to dissipate the heat generated by the drive motor to the external environment based on the current temperature and other states of the drive motor, and reduce the temperature of the drive motor.	Normal operation

Note: Collision signal*: Applicable to products of the drive motor system that receive this signal. High-voltage interlock function**: Applicable to products of the drive motor system with this function.

The initial architecture of the drive motor system is shown in **Figure 2**.

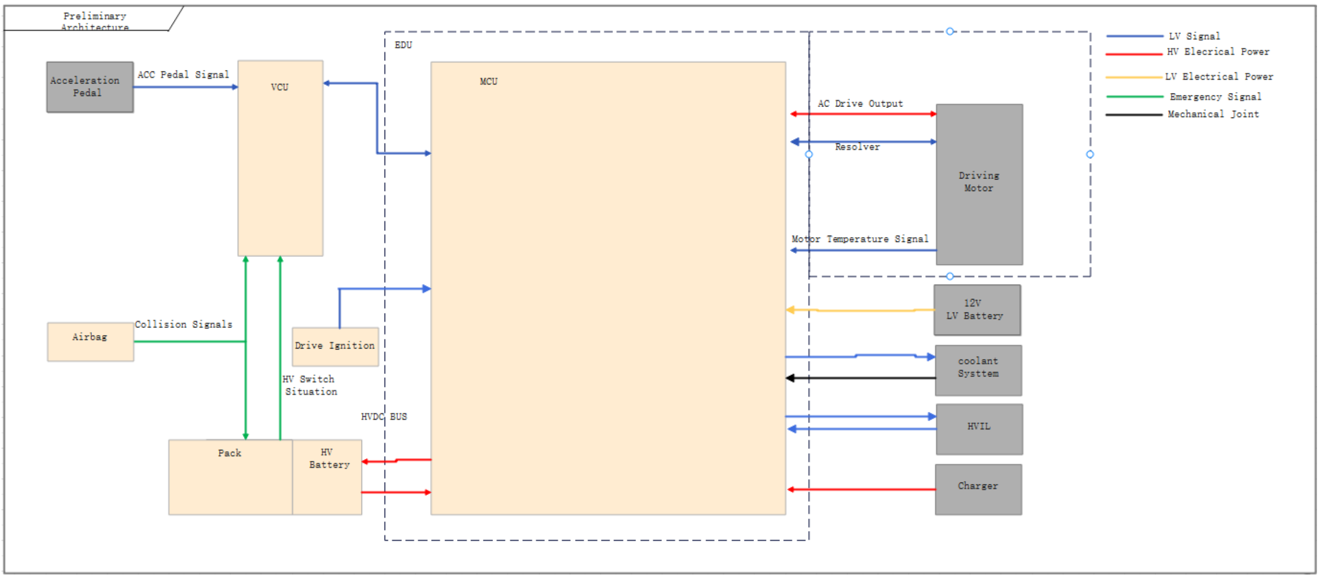

Figure 2. Initial architecture of the motor system

The description of the drive motor-related system is shown in **Table 4** below.

Table 4. Functional descriptions of related systems

Related system serial number	Related system name	Related system functional description
System_1	VCU	Function_1: Driving torque control Function_2: Active discharge control Function_3: Brake energy recovery control Function_4: Vehicle energy management Function_5: CAN network maintenance and management Function_6: Vehicle status control and monitoring Function_7: Boost charging request and control
System_2	MCU	Function_1: MCU receives key signals and safety-related signals from VCU through CAN. Function_2: MCU sends key signals and safety-related signals to VCU through CAN. Function_3: MCU converts DC input into AC output and outputs the required torque. Function_4: MCU realizes active discharge. Function_5: MCU monitors the temperatures of the motor, IGBT, and PCB, and derates the operation when the temperature is too high. Function_6: MCU realizes the boost charging function. Function_7: MCU has the high-voltage interlock function.
System_3	Ignition Signal	Function_1: The device receives the key-press signal and converts it into an ignition signal to wake up the MCU.
System_4	High-Voltage Battery	Function_1: The high-voltage battery provides energy for the MCU.
System_5	12V Battery	Function_1: The 12V battery supplies power to the MCU control board.
System_6	Drive Motor	Function_1: The motor converts electrical energy into mechanical energy to drive the vehicle. Function_2: The motor receives the exciter of the resolver and feeds back the resolver signal. Function_3: The motor feeds back the motor temperature signal.
System_7	Coolant System	Function_1: The coolant system cools the MCU and the drive motor.
System_8	High-Voltage Interlock Circuit	Function_1: The high-voltage interlock circuit detects the abnormal opening of high-voltage equipment.
System_9	DC Charger	Function_1: The DC fast-charge is boosted by the MCU and then charges the high-voltage battery

4. Drive motor system hazard analysis and risk assessment

The purpose of HARA analysis is to analyze the risk of personal injury accidents caused by vehicle hazards, due to electronic and electrical system failures, quantitatively evaluate the risk level from the three dimensions of severity, controllability, and exposure, and define safety goals from the perspective of functional safety design and testing. HARA analysis provides sufficient support for the implementation of functional safety requirements activities in the later stage.

Hazard analysis and risk assessment are carried out based on the definition of related items. In this process, related items that do not contain internal safety mechanisms should be evaluated, that is, safety mechanisms that will be implemented or have been implemented in previous related items are not considered. When using the HAZOP method, it is necessary to use guidewords combined with functions for analysis. There are 16 categories of guidewords in total. The specific connotations and explanations of HAZOP guide words are shown in **Table 5**.

Table 5. Specific connotations of HAZOP guidewords

Serial number	Guideword	Meaning
1	No	Sudden loss of function
2	Less	Function output below expectations
3	More	Function output above expectations
4	Part of	Only partial function execution (e.g., A instead of A+B)
5	As Well As	Unintended additional function execution
6	Reverse	Opposite functional logic
7	Unintended	Unplanned function output
8	Early	Premature function output
9	Later	Delayed function output
10	Before	Early output in sequence
11	After	Late output in sequence
12	Periodic	Periodic abnormal output
13	Other than	Completely different function manifestation
14	Stuck	Function stuck at a fixed state
15	Misuse	Unintentional function misoperation
16	From Experience	Failures outside the above categories

The HAZOP analysis guidewords for this related item function refer to SAE J2980:2018 Considerations for ISO 26262 ASIL Hazard Classification. The vehicle mode definition and state transition refer to the related item definition. The HAZOP analysis matrix is shown in **Table 6** below.

Table 6. HAZOP analysis matrix

Function	Function loss	Incorrect function (excessive)	Incorrect function (insufficient)	Incorrect function (reverse)	Unintended function	Stuck output
Cooling function	Inability to cool	Excessive cooling	-	-	Unplanned cooling	Stuck at excessive/ insufficient cooling
Active discharge	Failure to discharge	-	-	-	Unplanned discharge	Discharge stuck
High-voltage interlock	Failure to lock	-	-	-	Incorrect locking	-

According to the requirements of Chapter 6 of GB/T 34590.3-2022, based on the abnormal performance of the drive motor system, the possible vehicle-level hazards (the most serious case) are analyzed as shown in **Table 7**.

Table 7. Vehicle-level hazards caused by functional abnormalities

Impact of functional abnormality	Most severe vehicle-level hazard
Inability to cool the motor	Vehicle fire (QM(C))
Inability to cool the motor controller	Vehicle fire (ASIL-A)
Internal MCU failure	Vehicle fire (ASIL-A)
Unintended boost charging/over-boosting	Vehicle fire (ASIL-A)
Inability to perform active discharge	High-voltage electric shock (ASIL-A)
High-voltage interlock failure	High-voltage electric shock (ASIL-A)

Developing functional safety concepts mainly includes the following activities: First, define the functions or degraded functional behaviors of related items according to the safety goals analyzed in the HARA phase; define the constraints on appropriate and timely detection and control of related faults according to their safety goals (**Table 8**); define countermeasures or measures at the level of related items to obtain the required fault tolerance or sufficient mitigation of the impact of related faults caused by the related items themselves, drivers or external measures; allocate functional safety requirements to system architecture design or external measures.

Table 8. Examples of safety goals

No.	Safety goal ID	Description	ASIL	FTTI (ms)	Safe state
1	EDU_SG2	Prevent high-voltage electric shock	A	3000	Derating alarm

The initial architecture for high-voltage safety is shown in **Figure 3**.

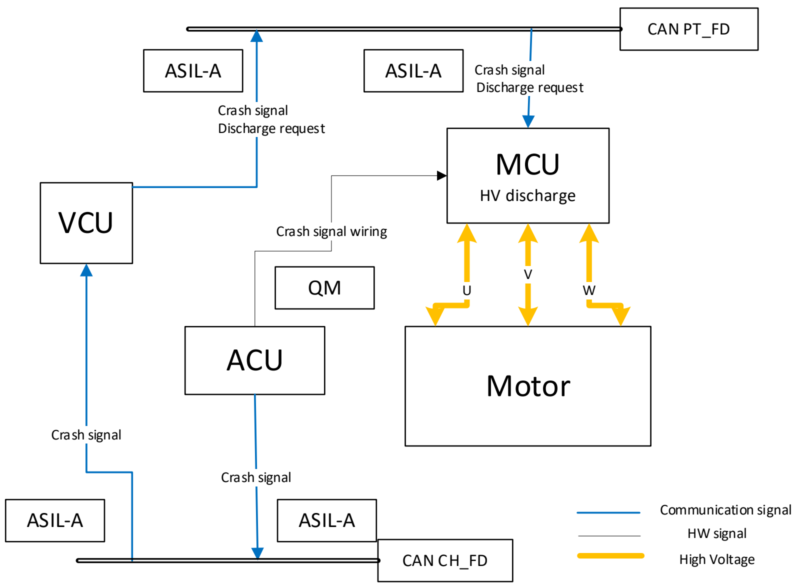

Figure 3. Initial architecture for high-voltage safety

The derived functional safety requirements are shown in **Table 9**.

Table 9. High-voltage safety functional requirements

SG2	Prevent high-voltage electric shock	ASIL	FTTI (ms)	Safety state
FSR_HV_1	Correctly acquire collision signals	A	50	Warning
FSR_HV_2	Accurately acquire discharge requests	A	50	Warning
FSR_HV_3	Accurately measure bus voltage	A	50	Warning
FSR_HV_4	Discharge high voltage to < 60V upon discharge request/collision signal	A	2800	Warning
FSR_HV_5	Report an error if voltage does not drop to < 60V within the specified time	A	-	Warning
FSR_HV_6	Prohibit fault clearance during the current driving cycle	A	-	-

Requirements for external measures and requirements for other technologies:

(1) The source of the discharge request signal of the drive motor system guarantees ASIL A level;

(2) The source of the collision signal received by the drive motor system guarantees ASIL A level;

(3) The source of the signal of the high-voltage interlock function received by the drive motor system guarantees ASIL A level;

(4) A conspicuous high-voltage warning should be posted on the drive motor system;

(5) The drive motor system should be isolated from high and low voltage;

(6) For the drive motor system without a high-voltage interlock function, personnel cannot touch the high-voltage part of the drive motor system without special tools.

5. Conclusion

This study focuses on the high-voltage safety of drive motor systems in new energy vehicles and conducts standardized functional safety design research in the concept phase. Aiming at the lack of high-voltage hazard analysis in existing standards, it deeply analyzes safety levels based on GB/T 34590 and ISO 26262.

By applying the HAZOP method with 16 guidewords, it comprehensively identifies vehicle hazards such as high-voltage electric shock caused by functional abnormalities like interlock failure and abnormal discharge. Safety goals (e.g., preventing electric shock) and functional safety requirements (e.g., accurate signal acquisition, timely discharge) are defined, along with external and technical requirements, forming a complete high-voltage safety protection system. The research results provide critical technical support and standardized references for high-voltage safety design, significantly improving the safety level of new energy vehicle drive motor systems and expecting to play a key role in future product development and standard refinement.

Disclosure statement

The authors declare no conflict of interest.

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