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Reliability Study of BEV Powertrain System and Its Components—A Case Study

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Abstract: The powertrain system is critical to the reliability of a battery electric vehicle (BEV). However, the BEV powertrain is a complex system; it includes the motor, motor controller, power distribution unit, battery system, etc. The failure of any of these components may result in the failure of the entire powertrain system and eventually cause serious traffic accidents on the road. However, how much does each component affect the reliability of the entire system, and which components are the most vulnerable in the entire system? These questions are still unanswered today. To develop a reliability design for a BEV powertrain system, it is essential to conduct detailed research by investigating the most vulnerable component parts of the entire powertrain. In the present study, a fault-tree model of the entire powertrain and its subsystems was developed. Based on this model, the failure rates of all components were calculated first. Then, trends in the reliability indices for the entire powertrain and its components were estimated against BEV service life. From the estimation results, we learned that with increased service time, the reliability of the entire powertrain system is indeed much lower than that of its individual subsystems. Moreover, through comparative research, we found that the battery module is the most unreliable component not only of the battery system, but the entire powertrain system. Additionally, it was interesting to find that the reliability of the motor components was higher than that of other subsystem components, but that the reliability indices for the entire motor were not the highest among all the powertrain subsystems studied in this paper. We believe the findings of the present study will be of great significance to an improved understanding of the reliability design and maintenance of BEVs.

Keywords: reliability; electric vehicle; powertrain system; fault-tree analysis; battery electric vehicles (BEVs)

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1. Introduction

As a means of reducing environmental emissions from the automotive industry, electric vehicles (EVs) have attracted increasing interest in recent years. Taking China as an example, about 5000 electric vehicles (EVs) were sold in 2011, but by the end of 2018, the total had reached 984,000, which was an increase of 50.8% over the previous year [1,2]. In addition, EVs are also very popular in other countries and regions around the world. According to a global electric vehicle outlook 2020 report released by the International Energy Agency (IEA), so far, 17 countries have announced a "100% zero emissions goal by 2050" to phase out internal combustion engine vehicles [3]. This means that there will be more and more BEVs running on the road [4,5]. However, despite the increasing interest in BEVs in recent years, their reliability, and particularly the reliability of their powertrains, are still a matter of concern today.

In order to improve the reliability of BEV powertrain systems, many related efforts have been made. For example, a reliability study of the battery system has been conducted [6] and a reliability-based design concept for Li-ion battery packs proposed [7], providing a way to improve the reliability of battery packs by optimizing the configuration of redundant cells. The reliability of different battery packs with different configurations and different numbers of battery cells was compared [8], and it was found that due to thermal disequilibrium effects, battery pack reliability does not increase monotonically as the number of redundant battery cells grows. In other studies [9,10], a multi-fault diagnostic method was proposed to improve the reliability of battery system operation; this method was further improved by adding a function to estimate the charging state of the battery pack [11]. In order to accurately assess the reliability of lithium-ion batteries, a reliability model considering the dependency among cells for the overall degradation of lithium-ion battery packs was built in [12]. Apart from these, the reliability of the stator and rotor components in permanent magnet synchronous motors for BEVs has been studied using a combined fault tree and Petri net approach [13,14]. The fault logic of failures caused by key components of the drive motor (i.e., stator and rotor windings and bearings) has also been investigated [15–17] using the approach of fault tree analysis (FTA); the results showed that different components have different effects on the reliability of the entire drive motor and also suggested that reliability issues in the drive motor and motor controller should be investigated together when assessing the reliability of the motor system; otherwise, an unreliable reliability prediction may be obtained. Given that electronic device lifetime determines the reliability of a BEV inverter to a large extent, the reliability of the insulated gate bipolar translator (IGBT) module has been predicted using the methods of the coffin-manson model and survey statistics [18–20]. The reliability of fuel cell electric vehicle (FCEV) power conditioners and their sub-systems has been investigated with the aid of FTA [21]. An investigation into the reliability of a single-motor drive system in a belt conveyor also has been investigated, providing a useful way to optimize drive system reliability, etc. [22].

There is no doubt that these research efforts will benefit reliability studies of powertrain systems. It should be noted that these reliability studies were mainly focused on powertrain components or subsystems and did not discuss issues from the perspective of an entire powertrain system. However, the powertrain systems in BEVs are very complex, consisting of multiple subsystems, such as the battery system, power distribution unit, motor controller, drive motor, etc. All these subsystems are required to work synchronously as a whole, and the failure of any one of them can cause the breakdown of the entire powertrain system. In addition, the structure, type, and characteristics of components or parts may also affect the reliability of the entire system to varying degrees. However, this issue has not been considered before. Hence, the purpose of this research was to fill these gaps in knowledge by looking into the reliability issues associated with BEV powertrain subassemblies, components, and subsystems. It is our hope that this study will provide useful reference experience and theoretical guidance to future efforts in the reliability design and aftersales maintenance of BEVs.

2. The Powertrain System in BEVs

As the core system in a BEV, the powertrain system is similar to the engine and transmission system in a traditional diesel or petrol-fueled vehicle. However, in terms of energy conversion and power transmission, BEVs are different from traditional diesel or petrol vehicles. To facilitate an easier understanding, a schematic diagram of the energy and power transmission process in a BEV is shown in Figure 1. From the figure, we can see clearly that the powertrain system of a BEV mainly consists of a battery system, a power distribution unit (PDU), a motor controller, and a drive motor. When BEVs work normally, the electric energy stored in the battery system is first input into the PDU, then to the motor controller through the PDU. Finally, the electric energy is transformed to mechanical energy to operate the BEV by driving the motor system. Conversely, when BEVs brake or experience wheel slip, the feedback energy will be stored in the battery system through the powertrain system. In order to better understand the relationship between the BEV powertrain system structure and the logical connections with its subsystems, a structural diagram of a BEV powertrain system is shown in Figure 2. Briefly, the functions of the subsystems and components of the powertrain are described below.

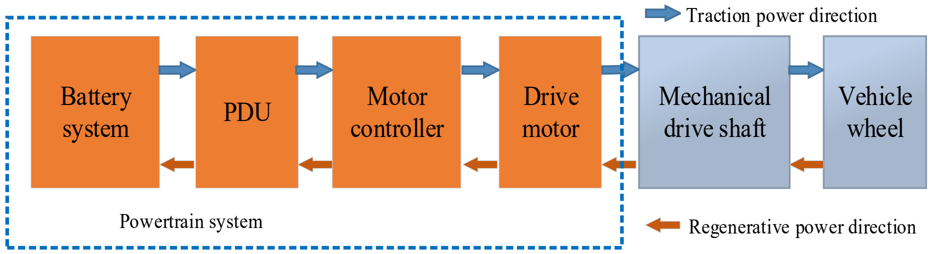


Figure 1. Schematic diagram of energy and power transmission process of BEVs.

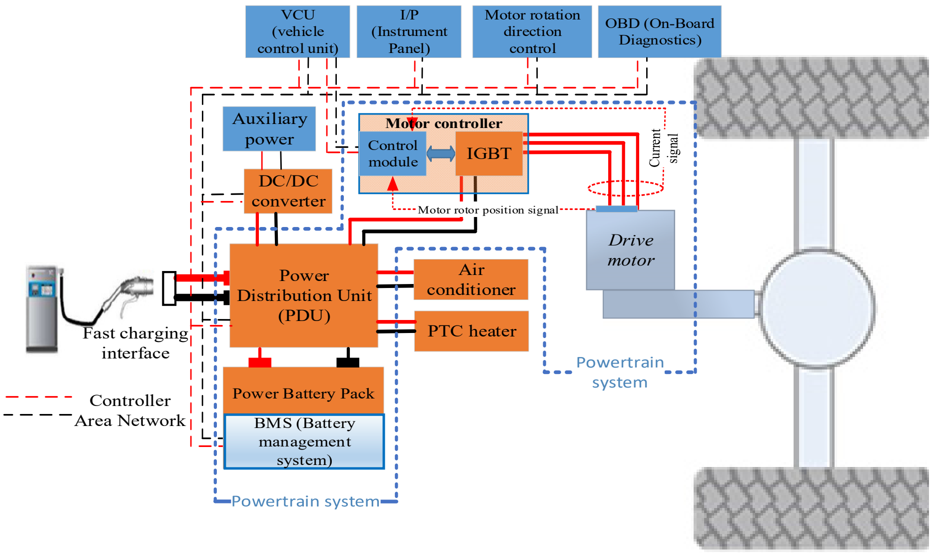


Figure 2. Structural diagram of powertrain system in a BEV.

The battery system is mainly used to store electrical energy and is composed of multiple battery cells connected in series and in parallel. Besides the battery cells, the battery system also includes a battery management system (BMS) controller, power electronic components, etc. The BMS controller is responsible for monitoring and managing the battery modules. It can measure the voltage, current, and temperature of individual battery cells. Based on these measured data, an appropriate control strategy is implemented to prevent abnormal conditions of the battery pack, such as over-discharging, overcharging, and overheating. The power electronic components handle the functions of protecting the battery cells from being damaged by excessive current, controlling the power-on and power-off operation of the electric system, and cutting off the power supply to the BEV powertrain in case of an emergency.

The PDU handles the functions of redistributing the power output from the battery system and providing interfaces for other systems or BEV components.

The motor controller is mainly used to control the drive motor, ensuring that it runs reliably and steadily, and transmit current working-status information on the drive system (i.e., motor and motor controller) to the vehicle controller in real time.

The drive motor is an energy conversion device [23]. It has two main functions: converting electrical energy into mechanical energy when the vehicle is driving, and then converting mechanical energy into electrical energy under braking or wheel-slipping conditions.

From the above description, we can understand that the powertrain system of a BEV is a complex system that consists of many components, the failure of any one of which may result in the failure of the entire powertrain system [24,25]. However, to what extent does each subsystem and its components affect the reliability of the entire system, and which components are the most vulnerable in the entire powertrain system? These questions are still unresolved today. To answer them, we conducted a detailed reliability study of the BEV powertrain.

3. Reliability Study of Powertrain System

As described above, the powertrain system in a BEV is composed of a battery system, PDU, motor controller, and drive motor, so, the following research on the reliability of the powertrain system was carried out in terms of these four aspects. It is worth noting that due to their housing shell, the components in a BEV powertrain are usually reliable and rarely damaged in operation and pose little risk of affecting the reliability of the entire system [26]. Therefore, the reliability of the housing shell was not considered in this study.

The schematic diagram of the battery system and PDU are shown in Figure 3. From the figure, we can see that the battery system is composed of a battery module and its related components, such as the BMS controller, fuse, relay, and signal detection devices, etc. The BMS controller consists of two parts (i.e., BMS master controller and BMS slave controller) [6]. Both the master controller and the slave controller are integrated circuit boards composed of printed circuit boards (PCBs) and surface mounted components (SMCs). The PDU is used to redistribute the power output from the battery system and provide interfaces for other systems or components in a BEV; it is mainly composed of relays, fuses, and connectors.

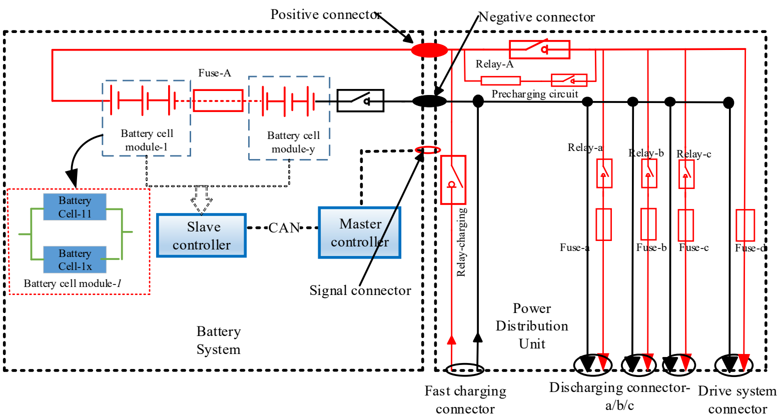


Figure 3. Schematic diagram of the battery system and PDU.

Similarly, a schematic diagram of the motor system is shown in Figure 4. In that figure, we can see that the motor controller is mainly composed of DC-link capacitors, copper busbars, the IGBT, and function modules (i.e., drive module, control module, communication module, and discharging module). In contrast, the drive motor is mainly composed of bearings, rotor, stator, sensors, and other associated components.

The modules of the motor controller are integrated circuit boards, which are mainly composed of PCBs and SMCs such as inductors, resistors, capacitors, transformers, integrated chips, diodes, etc. According to IEC TR62308-2004 [27], when evaluating the reliability of these components, they can be divided into two parts (i.e., PCB and SMCs), as show in Figure 5.

Based on the above detailed description of the powertrain system, a fault- tree model of the entire powertrain system is shown in Figure 6.

In this figure, "powertrain system failure" is defined as the top event. Failures of the battery system, PDU, motor controller, and drive motor are intermediate events (or logic gate events) of the entire model. $gb1$ to $gb5$, $gc1$ to $gc5$, and $gm1$ to $gm4$ are intermediate events of the powertrain subsystems, which are the logical combination of relevant basic events. All these events are explained in Table 1.

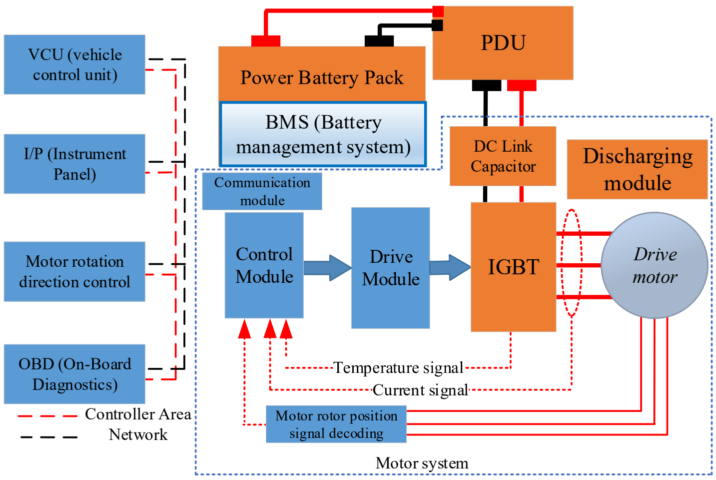


Figure 4. Schematic diagram of the motor system.

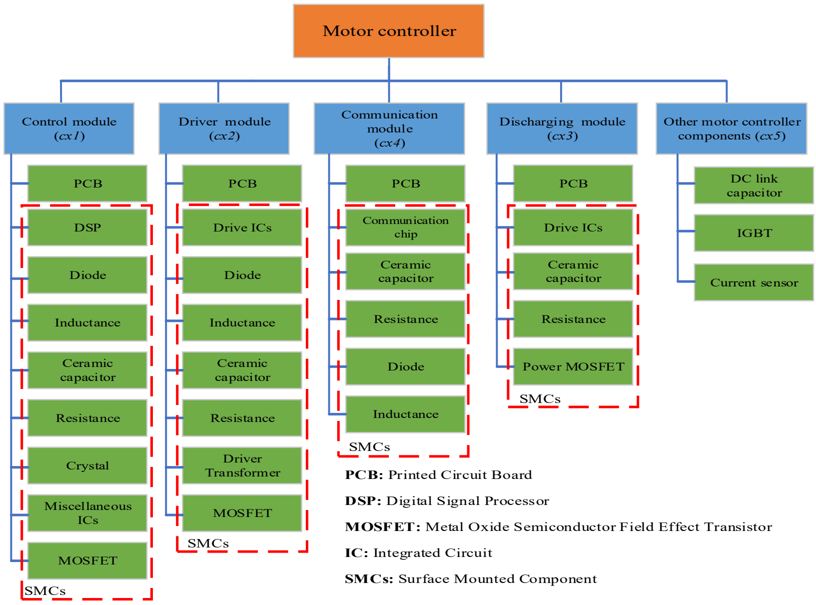


Figure 5. Modules and components of the motor controller.

From Figure 6, we can see that the reliability of the powertrain system depends on the reliability of its subsystems (i.e., battery system, power distribution unit, motor controller, and drive motor), whereas the reliability of individual subsystems depends on the reliability of their respective components. Therefore, the failure rate of a powertrain system and its subsystems can be estimated by

$$\begin{cases} \lambda_s = \lambda_{s1} + \lambda_{s2} + \lambda_{s3} + \lambda_{s4} \\ \lambda_{s1} = \lambda_{gb1} + \lambda_{gb2} + \lambda_{gb3} + \lambda_{gb4} + \lambda_{gb5} \\ \lambda_{s2} = \lambda_{ep1} + \lambda_{ep2} + \lambda_{ep3} \\ \lambda_{s3} = \lambda_{gc1} + \lambda_{gc2} + \lambda_{gc3} + \lambda_{gc4} + \lambda_{gc5} \\ \lambda_{s4} = \lambda_{gm1} + \lambda_{gm2} + \lambda_{gm3} + \lambda_{gm4} \end{cases} \quad (1)$$

where λ_s is the failure rate of the BEV powertrain system; λ_{s1} to λ_{s3} are the failure rates of the battery system, PDU, motor controller, and drive motor, respectively; λ_{gb1} to λ_{gb5} are the failure rates of battery system intermediate events; λ_{ep1} to λ_{ep3} are the failure rates of PDU components (or basic events); λ_{gc1} to λ_{gc5} are the failure rates of motor controller intermediate events; and λ_{gm1} to λ_{gm4} are the failure rates of motor controller intermediate events. Detailed explanations are listed in Table 1.

Table 1. Failure events of powertrain system.

Intermediate Event	Code	Failure Rate	Basic Event	Code	Failure Rate
Battery system failure (S1)					
Failure of battery module	*gb*1	λ_{gb1}	Failure of signal connector for battery system	*eb*1	λ_{eb1}
			Failure of battery cells	*eb*2	λ_{eb2}
			Failure of signal connectors for battery cells module	*eb*3	λ_{eb3}
Failure of master controller of BMS	*gb*2	λ_{gb2}	Failure of PCB for master controller	*eb*4	λ_{eb4}
			Failure of SMCs for master controller	*eb*5	λ_{eb5}
Failure of slave controller of BMS	*gb*3	λ_{gb3}	Failure of PCB for slave controller	*eb*6	λ_{eb6}
			Failure of SMCs for slave controller	*eb*7	λ_{eb7}
Failure of power electronic device	*gb*4	λ_{gb4}	Failure of fuse for main circuit	*eb*8	λ_{eb8}
			Failure of relay for main circuit	*eb*9	λ_{eb9}
Failure of sensors	*gb*5	λ_{gb5}	Failure of current sensor	*eb*10	λ_{eb10}
			Failure of voltage sensor	*eb*11	λ_{eb11}
			Failure of temperature sensor	*eb*12	λ_{eb12}
Power distribution unit failure (S2)					
Power distribution unit failure (S2)			Failure of relay	*ep*1	λ_{ep1}
			Failure of fuse	*ep*2	λ_{ep2}
			Failure of connector	*ep*3	λ_{ep3}
Motor controller failure (S3)					
Failure of control module	*gc*1	λ_{gc1}	PCB failure of control module	*ec*1	λ_{ec1}
			SMCs failure of control module	*ec*2	λ_{ec2}
Failure of driver module	*gc*2	λ_{gc2}	Failure of driver module PCB	*ec*3	λ_{ec3}
			Failure of driver module SMCs	*ec*4	λ_{ec4}
Failure of discharging module	*gc*3	λ_{gc3}	Failure of discharging module PCB	*ec*5	λ_{ec5}
			Failure of discharging module SMCs	*ec*6	λ_{ec6}
Failure of communication module	*gc*4	λ_{gc4}	Failure of communication module PCB	*ec*7	λ_{ec7}
			Failure of communication module SMC	*ec*8	λ_{ec8}
Failure of other controller components	*gc*5	λ_{gc5}	DC link capacitor failure	*ec*9	λ_{ec9}
			IGBT failure	*ec*10	λ_{ec10}

Table 1. *Cont.*

Failure of drive motor (S4)					
Rotor failure	$gm1$	λ_{gm1}	Failure of rotor armature winding	$em1$	λ_{em1}
			Failure of rotor shaft	$em2$	λ_{em2}
Stator failure	$gm2$	λ_{gm2}	Failure of stator winding	$em3$	λ_{em3}
			Failure of stator core	$em4$	λ_{em4}
Transducer failure	$gm3$	λ_{gm3}	Failure of temperature sensor	$em5$	λ_{em5}
			Failure of position sensor	$em6$	λ_{em6}
Failure of other motor components	$gm4$	λ_{gm4}	Failure of spline	$em7$	λ_{em7}
			Failure of bearing oil seal	$em8$	λ_{em8}
			Failure of bearing	$em9$	λ_{em9}

Likewise, the intermediate event failure rates of the battery system, motor controller, and drive motor can be expressed as

$$\begin{cases} \lambda_{gb1} = \lambda_{eb1} + \lambda_{eb2} + \lambda_{eb3} \\ \lambda_{gb2} = \lambda_{eb4} + \lambda_{eb5} \\ \lambda_{gb3} = \lambda_{eb6} + \lambda_{eb7} \\ \lambda_{gb4} = \lambda_{eb8} + \lambda_{eb9} \\ \lambda_{gb5} = \lambda_{eb10} + \lambda_{eb11} + \lambda_{eb12} \\ \lambda_{gc1} = \lambda_{ec1} + \lambda_{ec2} \\ \lambda_{gc2} = \lambda_{ec3} + \lambda_{ec4} \\ \lambda_{gc3} = \lambda_{ec5} + \lambda_{ec6} \\ \lambda_{gc4} = \lambda_{ec7} + \lambda_{ec8} \\ \lambda_{gc5} = \lambda_{ec9} + \lambda_{ec10} \\ \lambda_{gm1} = \lambda_{em1} + \lambda_{em2} \\ \lambda_{gm2} = \lambda_{em3} + \lambda_{em4} \\ \lambda_{gm3} = \lambda_{em5} + \lambda_{em6} \\ \lambda_{gm4} = \lambda_{em7} + \lambda_{em8} + \lambda_{em9} \end{cases} \quad (2)$$

where λ_{eb1} to λ_{eb12} are the failure rates of battery system components (or battery system basic events); λ_{ec1} to λ_{ec10} are the failure rates of motor controller components (or motor controller basic events); and λ_{em1} to λ_{em9} are the failure rates of motor components (or motor basic events). Detailed explanations of all parameters and symbols in Formula (2) are listed in Table 1.

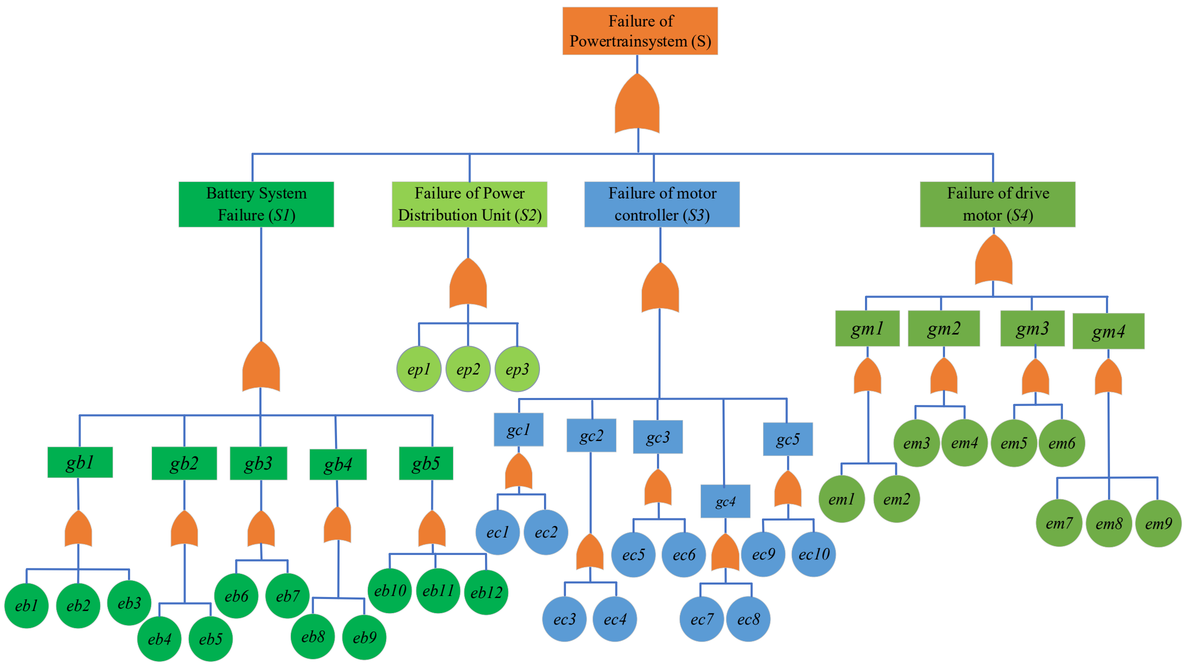


Figure 6. Fault tree model of BEV powertrain system.

4. Case Study

Based on the aforementioned failure rate estimation methods, a case study was performed in this section in order to quantitatively assess the reliability of a powertrain and its components. The BEV of interest is shown in Figure 7, and the performance parameters of its powertrain are listed in Table 2.

(**a**). Manufacture of electric vehicle

(**b**). Production of BEVs

(**c**). Battery system

(**d**). Drive system

Figure 7. BEV powertrain system and its subsystem

Table 2. Performance parameters of BEV powertrain system.

Items	Parameters	Items	Parameters
Motor type	Asynchronous induction	Controller capacity	70 KVA
Maximum output power	35 kW	Maximum working voltage	DC450 V
Maximum speed	9000 rpm	Frequency range	0~600 Hz
Peak torque	150 Nm	Peak point current	250 A
Nominal voltage	AC227 V	Controller nominal voltage	DC320 V
Nominal voltage of cell (V)	3.68	The number of total battery cells connected in parallel in battery system	5
Operating voltage range of cell (V)	2.9–4.0	Nominal voltage of battery system	312.8 V
The number of total battery cells connected in series in battery system	85	Total energy of battery pack	25.9 kwh
Continuous charging current	1.5 C	Continuous discharge current	1 C
Protection level	IP67	Auxiliary voltage	9–36 V

4.1. Failure Rates of Powertrain Components

As mentioned earlier, the BEV powertrain system is composed of multiple subsystems (i.e., battery system, PDU, motor controller, and drive motor). The structures and parts of these subsystems are shown in Appendix A Figure A1. With help from manufacturer engineers, the model, specifications, and number of parts or components in the powertrain subsystem of this BEV have been listed in Appendix A Table A1. The types, specifications, and number of surface mounted components (SMCs) on the PCBs are listed in Appendix A Table A2. The PCB parameters of the motor controller and the BMS controller are listed in Appendix A Table A3. Hence, according to international standards IEC TR62308-2004 [27], FIDES guide-2009 [28], MIL-HDBK-217F [29], and NSWC-09 [30], the failure rates of all the components of the powertrain could be estimated with Formulas (1) and (2). The calculation results are listed in Table 3.

Table 3. Failure rates of subsystem components in powertrain.

Components	Code	Failure Rate λ/FPMH	Sub-Components or Parts	Code	Failure Rate λ/FPMH
Battery system					
Battery module	*gb*1	3.453	Signal connector for battery system	*eb*1	0.1757
			Battery cells module	*eb*2	3.2000
			Signal connectors for battery cells module	*eb*3	0.0768
Master controller of BMS	*gb*2	1.7010	PCB of master controller for BMS	*eb*4	0.3567
			SMCs of master controller for BMS	*eb*5	1.3443
Slave controller of BMS	*gb*3	1.6324	PCB of slave controller for BMS	*eb*6	0.3356
			SMCs of slave controller for BMS	*eb*7	1.2968
Power electronic device	*gb*4	0.9213	Fuse of main circuit (i.e., Fuse A)	*eb*8	0.7600
			Relay of main circuit (i.e., Relay B)	*eb*9	0.1613
Sensors	*gb*5	1.544	Current sensor	*eb*10	0.6450
			Voltage sensor	*eb*11	0.6350
			Temperature sensor	*eb*12	0.2640
Power Distribution Unit					
			Relay	*ep*1	0.1870
			Fuse	*ep*2	0.7500
			Connector	*ep*3	0.0172
Motor controller					
Control module	*gc*1	1.888	PCB of control module	*ec*1	0.2357
			SMCs of control module	*ec*2	1.6527
Driver module	*gc*2	1.495	PCB of driver module	*ec*3	0.1041
			SMCs of driver module	*ec*4	1.3907
Discharging module	*gc*3	0.282	PCB of discharging module	*ec*5	0.0053
			SMCs of discharging module	*ec*6	0.2762
Communication module	*gc*4	0.341	PCB of communication module	*ec*7	0.0086
			SMCs of communication module	*ec*8	0.3319
Other controller components	*gc*5	0.516	DC link capacitor	*ec*9	0.0510
			IGBT*3	*ec*10	0.4650
Drive motor					
Rotor	*gm*1	0.300	Rotor armature winding	*em*1	0.2772
			Rotor shaft	*em*2	0.0226
Stator	*gm*2	0.252	Stator winding	*em*3	0.2520
			Stator core	*em*4	0.0003
Transducer	*gm*3	0.258	Temperature sensor	*em*5	0.2195
			Position sensor	*em*6	0.0375
Other motor components	*gm*4	0.568	Spline	*em*7	0.0385
			Bearing oil seal	*em*8	0.4465
			Bearing	*em*9	0.0830

From Table 3, some interesting conclusions were obtained, as follows:

(1) In the battery system, the failure rate of the battery module is the highest and can be as high as 3.453, followed by the BMS master controller and the BMS slave controller with failure rates of 1.70010 and 1.6324, respectively. Power electronic devices are relatively reliable in battery systems and have the lowest failure rate (of 0.9213).
(2) The faults of the PDU are mainly caused by relays, fuses, and connectors. The failure rate of the fuse in this study is the highest, up to 0.75, followed by the relay with a failure rate of 0.187. By contrast, the connectors are free of faults and have the lowest failure rate in the PDU.
(3) Among all the modules of the motor controller, the control module has the highest failure rate, as high as 1.884; conversely, the failure rate of the discharging module is the lowest, as low as 0.2815. The driver module, communication module, and other components also tend to develop faults in operation, but their failure rates vary in the range of 1.4948–0.282.
(4) Drive motor failures are primarily caused by bearings, stators, rotor windings, etc. From the research results, it was found that the oil seal of the bearing is the most vulnerable part in the drive motor (failure rate of 0.4465), followed by the position sensor and rotor/stator windings; their failure rates change in the range of 0.0252–0.0375. The temperature sensor is also prone to fail in operation. By contrast, the spline and shaft are relatively more reliable.
(5) From the perspective of the entire powertrain system, the battery module is the most vulnerable part (its failure rate is as high as 3.2), followed by the control module SMCs and drive module SMCs of the motor controller, which have failure rates of 1.6257 and 1.3907, respectively.

4.2. Reliability Assessment of Powertrain System

In order to gain a more comprehensive understanding of the reliability of the BEV powertrain, the reliability indices of the entire system and its components were evaluated in this section with the aid of the following formula [31]:

$$R(t) = e^{-\lambda t} \tag{3}$$

According to the calculation results in Table 3, we were able to derive the failure rate used to calculate the reliability of the BEV powertrain with the help of Formulas (1) and (2). The calculation results are listed in Table 4.

Substituting the parameters in Table 4 into Formula (3), reliability parameters were obtained for a power system operating over 12,000 h and 25,000 h, respectively (shown in Figure 8).

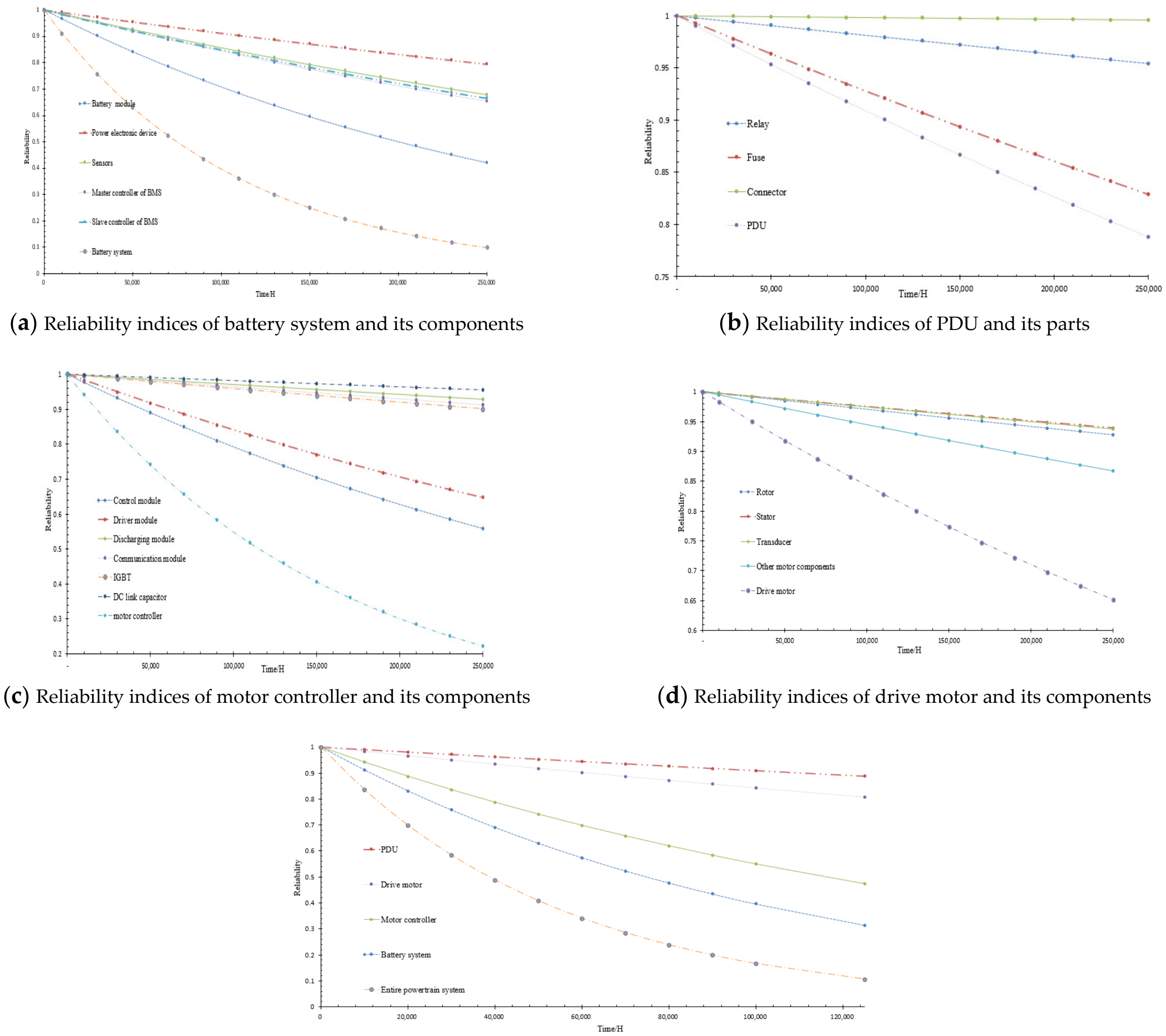
From Figure 8, we can see the following:

(1) All the components and subsystems in the powertrain system will become more and more unreliable with increases in their service time, i.e., the longer their service time, the lower their reliability indices tend to be. This agrees very well with the research conclusions obtained from the failure rate calculation results in Tables 3 and 4.
(2) From the perspective of the entire powertrain system, the battery system is much less reliable than the other subsystems, followed by the motor controller and drive motor; by contrast, the PDU is relatively more reliable. For example, after the powertrain system has run continuously for 10,000 h, the reliability index of the battery system, PDU, motor controller, and drive motor are 0.396, 0.887, 0.549, and 0.824, respectively (shown in Figure 8e). The most important point is that regardless of service time, the calculation results for the reliability index of the entire powertrain system are much lower than the corresponding values for the reliability indices of other, single components. For example, after the powertrain system has run continuously for 125,000 h, its reliability is about one-third that of the battery system, and less than one-eighth that of the PDU. This further indicates that we should take into account

all the components when evaluating the reliability of the powertrain system, because the failure of any single component in the powertrain can, to varying degrees, affect the reliability of the entire system.

(3) Among the components of all subsystems of the BEV powertrain system, the battery module is the most unreliable component in the battery system, fuses are the most unreliable parts in the PDU, and the control module is the most unreliable component in the motor controller; their reliability indices are 0.396, 0.887, 0.549, and 0.824, respectively, after the powertrain system has run continuously for 250,000 h (shown in Figure 8a–d).

(4) The battery module is the most unreliable component in not only the battery system, but the entire powertrain system; conversely, the connector is the most reliable component in the entire system.



(**a**) Reliability indices of battery system and its components

(**b**) Reliability indices of PDU and its parts

(**c**) Reliability indices of motor controller and its components

(**d**) Reliability indices of drive motor and its components

(**e**) Reliability indices of the entire powertrain system and its subsystems

Figure 8. Reliability indices of powertrain system.

Table 4. Failure rates of powertrain system and its sub-systems.

Subsystem of Powertrain	Code	Failure Rate λ/FPMH	Subsystem of Powertrain	Code	Failure Rate λ/FPMH
Battery system	$S1$	9.251	Drive motor	$S3$	5.990
PDU	$S2$	0.954	Motor controller	$S4$	1.715
Powertrain system	S	17.910			

5. Conclusions

In order to provide a more reliable and comprehensive understanding of the reliability of the entire powertrain system in BEVs, a detailed study of the reliability issues in all components of the powertrain system was described in this paper. According to the investigation reported above, the following conclusions can be drawn.

- The reliability of the powertrain system and its subsystems will decrease gradually as their time in service increases. However, the reliability of the powertrain system decreases faster than any of the subsystems. For example, after the powertrain system has run continuously for 125,000 h, its reliability is about one-third that of the battery system and less than one-eighth that of the PDU.
- From the view of the entire BEV powertrain system, the battery module is the most vulnerable part in not only the battery system, but the entire powertrain system (failure rate of 3.076), followed by the control module and drive module of the motor controller (failure rates of 2.234 and 1.741, respectively), the BMS master controller (failure rate of 1.701), and BMS slave controller (failure rate of 1.632). Among the subsystems in a BEV powertrain, the battery module is the most vulnerable part in the battery system; the fuse is the most vulnerable part in the PDU; the control module is the most vulnerable part in the motor controller; and the oil seal of the bearing is the most vulnerable part in the drive motor.
- The research results in this paper also suggest that, due to the finding that the battery system and motor controller were much more unreliable than other system components, more care should be paid in the future reliability design of BEV powertrain systems to foster improvements in the overall reliability of electric vehicles.

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Appendix A

Table A1. Components or parts of subsystems in powertrain system.

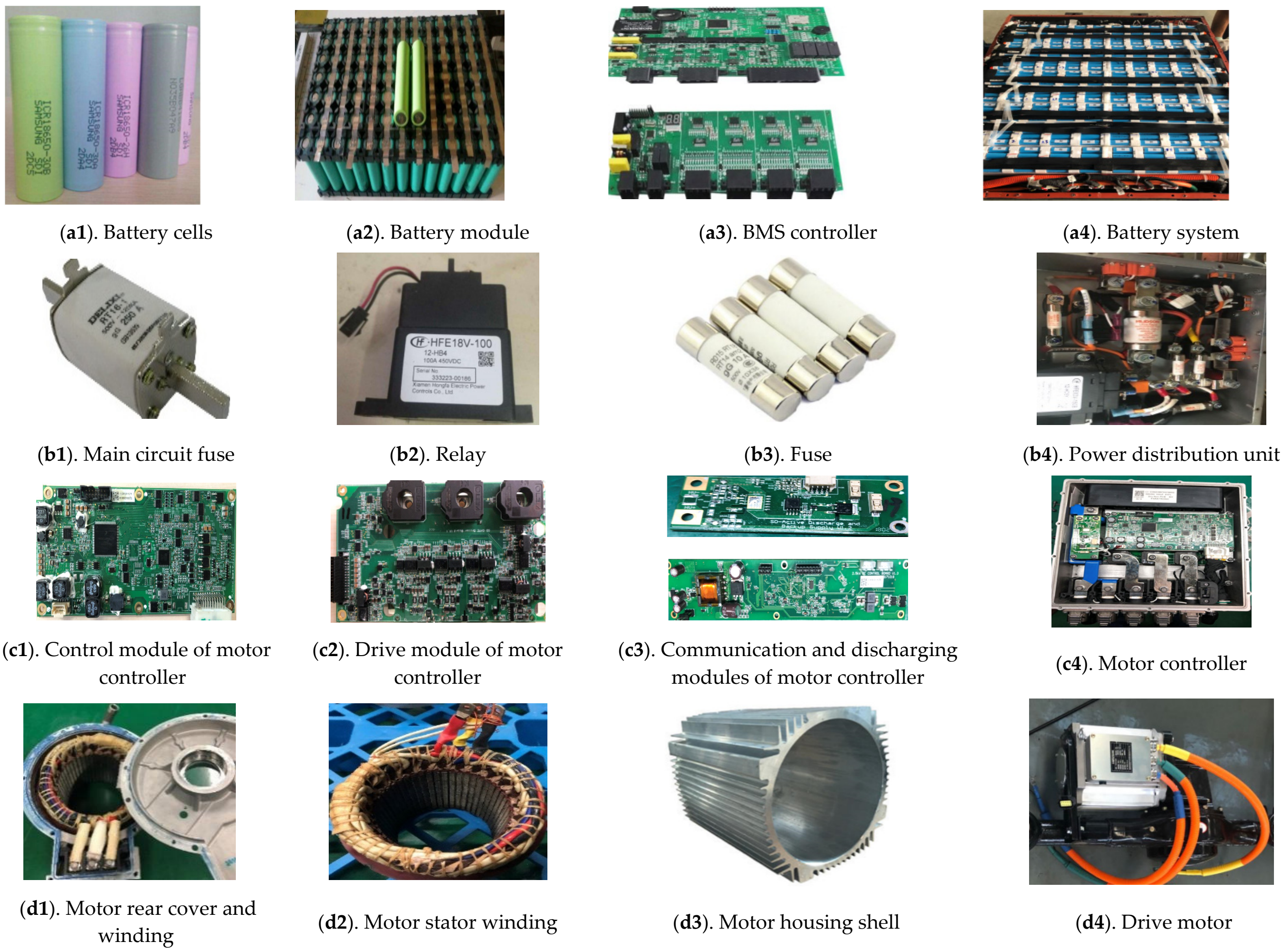
Component or Part	Model/Specification	Number	Part	Model/Specification	Number
Component or part of battery system					
Positive connector for main circuit	EVH1-F1ZK-M8A	1	Negative relay for main circuit	EV200	1
Negative connector for main circuit	EVH1-F1ZK-M8B	1	Positive relay for main circuit	HFZ16V-50-900	1
Signal connector for battery system	Amphenol12492	1	Fuse for main circuit	MSD	1
Current sensor	PL-2/75 Mv 400 A	1	Signal connectors for battery cells	Amphenol-TP1	96
Temperature sensor	NTC10K	10	Master controller of BMS	BCU0V3	1
Voltage sensor	R34-7	1	Slave controller of BMS	BMU1V1	1
Fastening screw for battery module	M6	97	Battery Cell	18650	85S5P
Component or part of PDU					
Main circuit fuse	URSU5-250		Positive relay for main circuit	HFE82	1
Positive connector for main circuit output	EVH1-F1ZK-M8A	2	Negative connector for main circuit	EVH1-F1ZK-M8B	2
Component or part of motor controller					
Control module	NA	1	Drive module	NA	1
Communication module	NA	1	Discharging module	NA	1
IGBT	FS400R07A3E3	1	DC Link capacitor	C362H557K19802	1
Current failure sensor	PL-2/75 mV 200 A	2			
Component or part of drive motor					
Hexagonal socket head cap screw	M6 × 20-12.9-NiZn/M6 × 12-NiZn	28	O-rings	104 × 2.65GB/T 3452.1	2
Oil seal	TC 40 × 52 × 8 Fluorine rubber	2	Position sensor	TS2225N1994E102	1
Elastic ring for shaft	GB/T 894.1 40	2	Winding	Wire diameter-7 mm	1
Deep-groove ball bearing	6206-2Z/C3, WT	2	Temperature sensor	PT1000	2

Table A2. Parameters for PCB failure rate calculations.

Name	Controller Module	Driver Module	Communication Module	Discharging Module	BMS Master Controller	BMS Slave Controller
PCB layer coefficient	1.4	1.4	1	1	1.4	1.4
PCB layers	4	4	1	1	4	4
Track width of PCB	0.23	0.6	0.35	0.6	0.35	0.35
Track width factor of PCB	3	1	2	1	2	2
Number of SMCs	553	368	38	24	386	463
Number of THCs	0	0	0	4	4	4
Surface area of PCB	104	104	25	23	154	160

Table A3. Type, failure rates, and number of SMCs on PCB.

Components	Type of Package	Single Device Failure Rate/FPMH	Number of SMCs on Controller Module	Number of SMCs on Driver Module	Number of SMCs on Communication Module	Number of SMCs on Discharging Module	BMS Master Controller	BMS Slave Controller
Capacitor	0603-C/RB.3.6	0.00306/0.065	235	136	9	4	146	87
Diode	SOD/SOT	0.00554	49	64	5	3	19	21
Op-amp chip	TSSOP	0.01263	14	4	0	0	2	4
Inductance	MSS	0.06762	20	21	8	2	3	3
MOSFET	SOT/DPAK	0.059700	11	11	2	0	8	5
Resistance	0603-R	0.00018	223	123	13	10	156	98
Master chip	LQFP144	0.30950	1	0	0	0	1	1
Optocoupler	SO8	0.08100	0	3	0	0	4	8
Transformer	CEER117	0.013100	0	6	0	1	0	0
Power MOSFET	D-PAK	0.07500	0	0	0	4	0	0
Communication chip	TSSOP	0.12600	0	0	1	0	2	4



(**a1**). Battery cells (**a2**). Battery module (**a3**). BMS controller (**a4**). Battery system

(**b1**). Main circuit fuse (**b2**). Relay (**b3**). Fuse (**b4**). Power distribution unit

(**c1**). Control module of motor controller (**c2**). Drive module of motor controller (**c3**). Communication and discharging modules of motor controller (**c4**). Motor controller

(**d1**). Motor rear cover and winding (**d2**). Motor stator winding (**d3**). Motor housing shell (**d4**). Drive motor

Figure A1. Components of subsystems in powertrain system.

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