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Reliability Study of the Motor Controller of Pure Electric Vans

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The market of electric vehicles (EVs) is rapidly growing across the world attributed to their unique feature of zero carbon emission. Take the Chinese market as an example, 984,000 pure electric vehicles were sold in China in 2018, which is an increase of 50.8% over the same period of the previous year. This means there will be more and more electric vehicles will run on the road in the future. However, the reliability of these electric vehicles is still an open issue remaining to resolve today. In particular, the reliability of the motor controller in electric vehicles is receiving more concern than ever before. On the one hand, this is because it is well known that power electronic components in the controller are much less reliable than the mechanical components in other EV subassemblies. On the other hand, it is because the failure of motor controller may lead to dangerous accidents on the road. Previously, much effort has been made to try to predict the reliability of motor controller, however detailed investigation of its reliability issues has never been done before. In view of this, a detailed reliability study of the motor controller in pure electric vans will be conducted in this paper, with the consideration of the fact that more than 90% of sold commercial electric vehicles are pure electric vans. In the research, the detailed root causes of the reliability issues in the motor controller will be investigated first and then based on which the failure rates of individual components (e.g. control module, driver module, communication module, and discharging module) in the controller will be estimated with the aid of fault tree analysis and the international standards IEC TR62308-2004, MIL-HDBH-217E and the technical standards for the Chinese electric vehicle industry. Finally, the tendency of the unreliability index of the entire motor controller against the service life of the electric vehicle is estimated based on the fault tree analysis results in order to obtain a more reliable understanding of the reliability performance of the motor controller over time. From such detailed reliability research, it has been found that the reliability performance of the motor controller will degrade gradually over time; and among the four functional modules of the controller the control module is most vulnerable, followed by driver module. This could be due to the application of more electronic components and thinner printed lines on the modules.

Keywords: Reliability, Pure electric van, Motor controller, Fault tree analysis, Motor system.

1. Introduction

The market of electric vehicles is booming across the world today. Take the Chinese market as an example, total 984,000 pure electric vehicles were sold in China in 2018, which is an increase of 50.8% over the same period of the previous year. It is expected that electric vehicles will replace the traditional diesel and petrol vehicles someday in the near future. However, despite the increasing use the electric vehicles are reported still having a number of reliability issues. Particularly, its battery and motor control system are prone to degrade or even develop fault when working in harsh environments and are subjected to time-varying loading conditions. Once a fault occurs in the battery or motor control system, it may lead to dangerous

accidents on the road. Therefore, it is of great significance to investigate the reliability issues in these key components in the electric vehicles, identify the most vulnerable parts in them, and then improve their reliability design based on the research results.

In order to improve the reliability of electric vehicles, much effort has been done before. However, among the existing research achievements in the relevant field, the majority of them are focused on how to improve the control and fault tolerance performance of the vehicles. For example, the fault tolerance performance of multi-phase permanent magnet synchronous motor was investigated by Bolvashenkov et al. (2016) with the aid of a multi-level Markov model; the similar research on motor drives was also conducted by Blanco (2009) by using the Monte Carlo

method in order to get better fault-tolerance mechanisms. The reliability of automated guided vehicles' control system was studied by Yan et al. (2017) using a combined fault tree and Petri net approach; the research was further improved by the authors through introducing genetic algorithm method into the maintenance strategy optimization (Yan et al., 2018), and so on. But few of them was conducted in order to understand the reliability of individual key components in the electric vehicles. In view of this, the reliability of the motor controller in pure electric vehicles is specifically studied in this paper, so that the industry and interested reader can have a deeper understanding of the reliability of electric vehicles.

2. Brief Review of Fault Tree

Fault tree provides a diagrammatic description of the causes of a system failure in terms of the failure of its components. The diagram consists of gates and events. Fault tree analysis is top-down, deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events. More details about fault tree analysis can be found from https://en.wikipedia.org/wiki/Fault_tree_analysis. To date, fault tree has become a popular system quantification technique that can be widely used to evaluate engineering systems during their design and development. The effectiveness of fault tree analysis in system reliability analysis has also been demonstrated by the authors' recent research on the assessment of automated guided vehicle systems (Yan et al., 2017).

3. The Motor Controller

Motor controller is critical to ensure the safe operation of the motor in an electric vehicle. It can be in various forms to meet the specific needs of different applications (Senty, 2012). In order to ease understanding, a schematic diagram of the motor controller in a pure electric van is shown in Fig. 1.

Fig. 1. Schematic diagram of the motor controller in a pure electric van

From Fig.1, it is seen that the motor controller in the pure electric vehicles is also a very complex system, which consists of multiple components including outer casing, thin-film capacitor, copper row, IGBT, driver module,

control module, active discharging module, communication module, sealing ring, cooling water jacket, and so on. Some of these components are, in fact, also the assemblies of many small parts. For example, the printed circuit board is the assembly of a number of connections, components, and board; the control module is composed of a control chip, resistances, capacitances, connections, and wire board. In the operation, an IGBT gate control signal will be output from the control chip based on the position signal measured by the position sensor. The components in the motor controller are described in Table 1.

Table 1. Motor controller components

No.	Component
1	Phase lines
2	Power line
3	Wiring slot
4	Cooper row
5	Discharging module
6	Housing shell
7	Communication module
8	Master chip
9	Thin-film capacitor
10	Control module
11	Current transducer
12	Driver module
13	Insulated-gate bipolar transistor (IGBT)
14	Seal ring of shell

4. Reliability Study of the Motor Controller

Due to fault tree analysis has been accepted as a mature technology for reliability analysis, it will be employed in this section to perform the reliability analysis of the motor controller in the following. As indicated by Fig.1, the motor controller in a pure electric van basically comprises two groups of parts. The first group of parts are power electronic components, and the second group of parts are for building a housing shell. As the housing shell is usually reliable and is rarely damaged in operation, it has little chance to affect the reliability of the motor controller. Therefore, the reliability of the housing shell will not be considered in this study. The research will be mainly focused on investigating the reliability of the first group of parts. For facilitating the research, these power electronic components are further classified into five classes based on the functions that they are designed to implement, i.e., busbar capacitors, control module, driver module, discharging module, communication module and IGBT. Since a fault occurring in any of these components can lead to the failure of the motor controller, the reliability block diagram of the motor controller can be described by the following diagram.

Fig. 2. Reliability block diagram of the motor controller

Based on Fig.2, the reliability of the motor controller can be predicted by (Elsayed EA, 2012)

$$R_c(S_2) = \prod_{i=1}^5 P(cx_i) \quad (1)$$

where $P(cx_i)$ indicates the reliability probability function of the i -th component in Fig.2.

If the failure of the motor controller is defined as a top event (S2) in the fault tree and the failures of individual components are defined as basic events ec1 to ec14, then the fault tree of the motor controller is built. It is shown in Fig.3.

Fig.3 Fault tree of the motor controller

In Fig.3, gc1 to gc4 are used to represent intermediate events, which are the logical combinations of several basic events that are related to the intermediate events. All these events are explained in Table 2.

Table 2. Failure events of individual components

Intermediate event	Code	Failure rate	Basic event	Code	Failure rate
Failure of control module	gc1	λ_{gc1}	PCB failure of control module	ec1	λ_{c1}
			SMCs failure of control module	ec2	λ_{c2}
			Master chip failure of control module	ec3	λ_{c3}
Failure of driver module	gc2	λ_{gc2}	PCB failure of driver module	ec4	λ_{c4}
			SMCs failure of driver module	ec5	λ_{c5}
			Optocoupler failure	ec6	λ_{c6}
Failure of discharging module	gc3	λ_{gc3}	PCB failure of discharging module	ec7	λ_{c7}
			SMCs failure of discharging module	ec8	λ_{c8}
			MOSFET failure	ec9	λ_{c9}
Failure of communication module	gc4	λ_{gc4}	PCB failure of communication module	ec10	λ_{c10}
			SMC failure of communication module	ec11	λ_{c11}
			Communication chip failure	ec12	λ_{c12}
Failure of other controller components	gc5	λ_{gc5}	Busbar capacitor failure	ec13	λ_{c13}
			IGBT failure	ec14	λ_{c14}

Note: SMC – surface mounted component, PCB – Printed circuit board.

In Table 2, the capacitor is used to balance the power during the change of power frequency and the power output

from the rectifier. In the meantime, it is also used to absorb the energy produced by the drive motor when the power switching devices are switched off in the scenario of an urgent stop. It can also provide instantaneous peak power as required so that the inverter can be well protected in the presence of a sudden change of the power. As the capacitors used in the motor controllers of pure electric vans are usually film capacitors, its failure rate can be evaluated by using the following equation

$$\lambda_{c13} = \left(\frac{\sum_{i=1}^j (\pi_{t_{c13}})_i t_i}{\tau_{on} + \tau_{off}} + 1.4 \times 10^{-3} \left[\sum_{i=1}^j (\pi_n)_i (\Delta T_i)^{0.68} \right] \right) \times 10^{-10} \quad (2)$$

where $(\pi_t)_i$ is the temperature factor related to the i -th junction temperature of the capacitor mission profile;

$(\pi_{t_{c13}}) = e^{2900 \left(\frac{1}{303} - \frac{1}{273 + t_{A_{c13}}} \right)}$ is a factor reflecting the influence of ambient temperature $t_{A_{c13}}$; τ_{on} is the total working time ratio of the capacitor; τ_{off} is time ration for the capacitor being in storage (or dormant) mode; $(\pi_n)_i$ is the i -th influence factor related to the annual cycles number of thermal variation with the amplitude ΔT_i ; ΔT_i refers to the i -th thermal amplitude variation of the mission profile.

The control module in Table 2 is composed of a master chip, a printed circuit board (PCB), and some surface-mounted components (SMCs). The SMCs include inductors, resistors, capacitors, transformers, integrated chips, diodes, etc. So, the reliability of control module relies on the reliability of the master chip, PCB and SMCs. The failure rate of these components can be evaluated by

$$\begin{cases} \lambda_{c1} = 0.005 \pi_{t_{c1}} \pi_c \left[N_t \sqrt{\frac{S+N_t}{S}} + \frac{(1+0.1\sqrt{S})N_p \pi_L}{3} \right] \\ \quad \times (1 + 0.003 \times [\sum_{i=1}^j (\pi_n)_i (\Delta T_i)^{0.68}]) \times 10^{-9} \\ \lambda_{c2} = \sum \lambda_s \times 10^{-9} + \\ \quad (\sum \lambda_f + 1.003 [\sum_{i=1}^j (\pi_n)_i (\Delta T_i)^{0.68}]) \\ \quad \times 10^{-9} \times \sum \lambda_d \\ \lambda_{ci} = (C_{i1} \pi_{it} + C_{i2} \pi_{iE}) \pi_{iQ} \\ \lambda_{cc} = \lambda_{cb} \pi_{cE} \pi_{cQ} \pi_{cT} \pi_{cS} \pi_{cch} \\ \lambda_{cg} = \lambda_{gb} \pi_{gE} \pi_{gQ} \pi_{gT} \\ \lambda_{cr} = \lambda_{rb} \pi_{rE} \pi_{rQ} \pi_{rR} \\ \lambda_{cm} = \lambda_{mb} \pi_{mE} \pi_{mQ} \pi_{mr} \pi_{mA} \pi_{mC} \pi_{mK} \end{cases} \quad (3)$$

where $\pi_{t_{c1}} = e^{1740 \left(\frac{1}{303} - \frac{1}{273 + t_{A_{c1}}} \right)}$ is a factor that is used to indicate the influence of ambient temperature $t_{A_{c1}}$; π_c indicates the influence of the number of layers; N_t is the total number of holes; S is the surface area of board; N_p is the number of tracks. Its default value is $N_p = \frac{\sum N_s + \sum N_f}{2}$, in which N_s is the number of lines that connect to every component, N_f is the number of components that connect to every hole; π_L is the coefficient of line track width, ΔT_i is the variation of temperature; λ_d is the interconnection failure rate. Other parameters in (3) are further explained in

Table 3. Then, the failure rate of the control module in the motor controller can be evaluated by

$$\lambda_{gc1} = \lambda_{c1} + \lambda_{c2} + \lambda_{c3} \quad (4)$$

Table 3. Other parameters in (3)

Sym	Meaning	Sym	Meaning	Sym	Meaning
λ_s	SMCs failure rate	π_{cQ}	Capacitance quality factor	π_{rE}	Resistance environment factor
λ_f	Failure rate of THCs	π_{cT}	Capacitance temperature factor	π_{rQ}	Resistance quality factor
λ_{ci}	Integrated chip failure rate	π_{cs}	Capacitance electric stress coefficient	π_{rR}	Resistance value coefficient
C_{i1}	Integrated chip complexity failure rate	π_{cch}	Capacitance surface mount factor	λ_{cm}	MOSFET failure rate
π_{iT}	Integrated chip temperature stress coefficient	λ_{cg}	Inductance failure rate	λ_{mb}	Basic failure rate of MOSFET
π_{iE}	Integrated chip environment factor	λ_{gb}	Base failure rate of inductance	π_{mE}	MOSFET environment factor
C_{i2}	Encapsulation complexity failure rate	π_{gE}	Inductance environment factor	π_{mQ}	MOSFET quality factor
π_{iQ}	Integrated chip quality factor	π_{gQ}	Inductance quality factor	π_{mA}	MOSFET application factor
λ_{cc}	Ceramic capacitance failure rate	π_{gT}	Inductance temperature factor	π_{mC}	MOSFET construction coefficient
λ_{cb}	Basic failure rate of capacitance	λ_{cr}	Resistance failure rate	π_{mr}	MOSFET rated power factor
π_{cE}	Capacitance environment factor	λ_{rb}	Base failure rate of resistance	π_{mK}	MOSFET species coefficient

Note: THCs – Through hole components.

As the hardware components of the driver module, discharging module, and communication module of the motor controller are similar to the control module, their failure rates can be estimated in the same way, i.e.

$$\begin{cases} \lambda_{gc2} = \lambda_{c4} + \lambda_{c5} + \lambda_{c6} \\ \lambda_{gc3} = \lambda_{c7} + \lambda_{c8} + \lambda_{c9} \\ \lambda_{gc4} = \lambda_{c10} + \lambda_{c11} + \lambda_{c12} \\ \lambda_{gc5} = \lambda_{c13} + \lambda_{c14} \end{cases} \quad (5)$$

where $\lambda_{gc2} - \lambda_{gc5}$ refer to the failure rates of the driver module, discharging module, communication module and the other components in the motor controller, respectively.

5. Failure Rate Calculation

According to the design documents and Bill of Material (BOM) provided by the motor systems manufacturer, it is known that the model of busbar capacitor is C362H557K19802 and the model of IGBT is FS400R07A3E3. As there are many SMCs on the PCB and

they have a variety of specifications, it is not realistic to evaluate the failure rate of every component. To deal with this issue, the SMCs in BOM list are classified first according to their types, such as resistance, inductance, capacitance, etc. Then, the failure rate of the same type of SMCs is calculated by using the following counting method.

$$\begin{cases} \lambda_{tci} = n_i \lambda_{ci} \\ \lambda_{tcc} = n_c \lambda_{cc} \\ \lambda_{tcg} = n_g \lambda_{cg} \\ \lambda_{tcr} = n_r \lambda_{cr} \\ \lambda_{tcm} = n_m \lambda_{cm} \end{cases} \quad (6)$$

All variables in the above equations are explained in Table 4.

Table 4. Variables in (6)

Symbol	Meaning	Symbol	Meaning
λ_{tci}	Total failure rate of resistance	n_i	Number of resistances
λ_{tcc}	Total failure rate of capacitance	n_c	Number of capacitances
λ_{tcg}	Total failure rate of inductance	n_g	Number of inductances
λ_{tcm}	Total failure rate of MOSFET	n_m	Number of MOSFET
λ_{ci}	Failure rate of a single resistance	λ_{cc}	Failure rate of a single capacitance
λ_{cg}	Failure rate of a single inductance	λ_{cm}	Failure rate of a single MOSFET

According to the international standard IEC TR62308-2004, MIL-HDBH-217E and the technical standards for the Chinese electric vehicle industry, the failure rates of all SMCs are calculated. The parameters used for calculating the failure rate are listed in Table 5, and failure rate calculation results are listed in Table 6.

Table 5. Parameters for failure rate calculations

Name	codes	Value/FPMH
PCB layer coefficient of control module (4 layers)	π_{cc1}	1.4
PCB layer coefficient of driver module (4 layers)	π_{cc2}	1.4
PCB layer coefficient of discharging module (2 layers)	π_{cc3}	1
PCB layer coefficient of communication module (2 layers)	π_{cc4}	1
Track width factor of PCB in control module (0.23mm)	π_{Lc1}	3
Track width factor of PCB in driver module (0.6mm)	π_{Lc2}	1
Track width factor of PCB in discharging module (0.6mm)	π_{Lc3}	1
Track width factor of PCB in communication module (0.35mm)	π_{Lc4}	2
Tracks number of PCB in control module	N_{pc1}	720
Tracks number of PCB in driver module	N_{pc2}	510
Tracks number of discharging module	N_{pc3}	20
Tracks number of communication module	N_{pc4}	38
Number of SMCs on control module	N_{sc1}	609

Number of SMCs on driver module	Nsc2	463
Number of SMCs on discharging module	Nsc3	14
Number of SMCs on communication module	Nsc4	32
Number of THCs of control module	Nfc1	0
Number of THCs of driver module	Nfc2	0
Number of THCs of discharging module	Nfc3	2
Number of THCs on communication module	Nfc4	0
Surface area of control module	Sc1	144
Surface area of driver module	Sc2	144
Surface area of discharging module	Sc2	24
Surface area of communication module	Sc3	28

From Table 6, it is found that the PCB of control module is the most vulnerable part in the motor controller (i.e., its failure rate is as high as 3.058), followed by the PCB of the drive board module (i.e., its failure rate is 1.116). The master chip and communication chip, as well as optocoupler, are also prone to develop fault in operation. But they are relatively more reliable than the PCB of the control and driver module. Their failure rate varies in the range of 0.2-0.35. In comparison, the IGBT and SMCs, as well as the PCB of the communication module and discharging module, have little chance to develop fault in operation as their failure rate is below 0.1.

Table 6. Failure rates of motor controller parts

Code	Failure rate /FPMH	Code	Failure rate /FPMH
λ_{gc1}	3.44	λ_{c6}	0.243
λ_{gc2}	1.402	λ_{c7}	0.005
λ_{gc3}	0.027	λ_{c8}	0.018
λ_{gc4}	0.283	λ_{c9}	0.004
λ_{gc5}	0.136	λ_{c10}	0.012
λ_{c1}	3.058	λ_{c11}	0.019
λ_{c2}	0.072	λ_{c12}	0.252
λ_{c3}	0.310	λ_{c13}	0.051
λ_{c4}	1.116	λ_{c14}	0.085
λ_{c5}	0.043		

6. Unreliability Index

Furthermore, the unreliability index F_c of the motor controller is estimated by using the following equation

$$F_c(t) = 1 - R_c(S_2) \quad (7)$$

When the service life of the motor system is respectively 10,000, 30,000, 50,000 and 70,000 hours, the corresponding values of the unreliability index are calculated and the results are shown in Fig.4.

Fig.4 Unreliability index of the motor controller

From Fig.4, it is clearly seen that the unreliability index of the motor controller increases gradually with the increase of the service life of the motor controller. That indicates the degradation of the reliability of the motor controller over time.

7. Conclusion

In order to understand the reliability of the motor controller in pure electric vehicles, a detailed reliability study is conducted in this paper with the aid of fault tree analysis. Through conducting this research, it is found that due to aging issue, the reliability of the motor controller will decrease gradually with the increase of the service time of the electric vehicle. Among the components of the motor controller, the PCB of control module is most vulnerable, followed by the PCB of the drive board module. Obviously, more care should be paid in the future reliability design of the PCBs so that the overall reliability of the electric vehicles can be promoted.

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