Fault Diagnosis of Power Components in Electric Vehicles

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Abstract

Battery, power electronics and electric motor are the main components of electric vehicles (EVs). Their failure in EVs may result in severe system breakdown, or even life threat. This paper gives a brief review of fault diagnoses with respect to battery, power electronics and electric motor in EVs. Current and voltage are the most commonly used detection parameters for EVs. Apart from these, temperature, vibration, power, noises, and torque are also utilized on the basis of different detecting techniques. It shows that the battery has already had a relatively well-developed diagnostic system in EVs, namely battery management system. Although many literatures have illustrated various fault diagnostic systems for electric motor and power electronics individually, a few studies have been done specifically for EVs.

Keywords

electric vehicles, fault diagnosis, battery fault diagnosis, electric motor fault diagnosis, power electronics fault diagnosis

1. INTRODUCTION

With the advent of first electric motor in 1834, electric vehicles (EVs) captured overwhelming support from vehicular market worldwide [Chan and Chau, 1997; Chau and Li, 2014]. But the age of the electricity powered vehicle faded out due to the improved gasoline engine till 1933 [Chau et al., 1998]. By 1985, the oil crisis re-aroused world's attention on the development of EVs [Chau and Chan, 1998]. Compared with conventional gasoline engine vehicles that are developing in an accelerated speed, EVs confront more obstacles and grow up in a more fluctuated situation.

In comparison, EVs have simpler structures, lower noises, higher stabilities, and most importantly, environmental protection [Chang, 1993; Chau et al., 2012]. But EVs are still under relatively weak circumstance. A single failure of EVs' core components may result in very costly breakdown, or even life safety threat. In the early stage of fault diagnosis, the study relies on simple protection such as overcurrent, overvoltage, overheating, etc. [Offer et al., 2012]. With the improved technology, the approaches of fault diagnosis in EVs becomes diverse, it varies from the conventional ones to more specific ones such as chemical analysis, torque measurement, frequency analysis, electromagnetic field monitoring, noise and vibration monitoring, etc. [Nandi et al., 2005; Araujo Ribeiro et al., 2003; Offer et al., 2012; Akin et al., 2011]. On the whole, fault diagnosis of EVs has been studied in decades concerning on the core components of EVs, namely batteries, electric motors, and power electronics.

Firstly, battery is introduced for fault diagnosis as it is essential for propulsion of EVs. The damage on the battery influences its operating efficiency, or even life safety threats. It has been stated by the U.S. code of Federal Regulations that each HEV must be equipped with a maintenance indicator by the manufacturer for each battery component [Akin et al., 2012]. At present, battery management system (BMS) is the most commonly developed technique in EVs for better battery performance. The major faults of electric battery are summarized as the following [Gadsden and Habibi, 2011]:

- Over-charge or over-discharge;
- Overheating or undercooling;
- Short circuit or open circuit of inter-cell;
- Inaccurate estimation.

The second essential component is electric motors which are the main motive power source of EVs. A variety of fault diagnostic techniques are proposed for motors, such as motor current signature analysis, mechanical vibration analysis, temperature measurement, gas analysis, and oil analysis [Akin et al., 2009; Akin et al., 2012; Liu et al., 2011; Yu et al., 2008; Chau et al., 2008]. The major faults of electric motor are classified as the following [Benbouzid, 1998; Nandi et al., 2005]:

- Abnormal connecting of stator windings;
- Open circuit or short circuit of stator windings;
- Bearing failure;
- Broken rotor bar;
- Eccentricity-related faults;
- Short circuit of rotor windings.

Thirdly, power electronics are studied for fault diagnosis. It plays an indispensable role in the power exchange of EVs and HEVs [Chau and Chan, 2007]. Currently, the research mainly emphasizes on the study of controllable solid-state switches which are commonly found in the inverters and converters [Vezzini and Reichert, 1996; Masrur et al., 2010]. The major faults of power electronics are shown as follows [Masrur et al., 2010; Chau, 1996]:

- Open switch fault;
- Short switch fault;
- Intermittent gate-misfiring fault.

In this paper, a review of the fault diagnosis in the core components of EVs is presented. In Section 2 to Section 4, the fault diagnoses of battery, electric motor, and power electronics will be discussed respectively. Conclusion will be drawn in Section 5.

2. BATTERY FAULT DIAGNOSIS

2.1 Battery fault characteristics

Battery system fault can be classified into four groups, namely battery voltage fault, battery current fault, battery temperature fault, and battery state of charge (SOC) fault, which are listed in Table 1 in detail [Jung et al., 2002; Alaoui, 2013].

It is found that battery faults mainly relate to the variations of battery voltage, current, temperature, and charging problems.

Table 1 Classification of battery system faults

Battery Voltage Fault	Low voltage fault
	Over voltage fault
	High-voltage insulation fault
	High-voltage loop fault
Battery Current Fault	Short circuit fault
Battery Temperature Fault	Low temperature fault
	Over temperature fault
Battery SOC Fault	Pre-charge fault
	Over charge fault
	Over discharge fault

2.2 Approach for battery diagnostic

BMS is widely used in battery to monitor the battery system core parameters, such as SOC, state-of-health (SOH), battery temperature, battery current and battery voltage [Rahimi-Eichi et al., 2013; Offer et al., 2012]. It aims to provide a safe, reliable and cost-efficient solution to the battery [Chatzakis et al., 2003].

The basic schematic presentation of the BMS structure is shown in Figure 1 [Chatzakis et al., 2003]. The battery voltage, current and temperature are measured and converted to the subsystems of BMS for thermal management, SOC estimation, and SOH estimation. It effectively contributes to the enhancement of battery performance and battery lifespan. However, it is limited to the accuracy of parameter estimation and functionalities [Jung et al., 2002; Ibrahim et al., 2011]. Except for BMS, battery faults can be tested by an individual diagnostic system that is shown in Figure 2 [Jung et al., 2002]. It consists of hardware and software parts. Hardware part is used for battery signal measurements and modulations. Software part is responsible for battery status testing and fault diagnoses. The fault signatures are obtained by using time domain waveform analysis and current pulse method

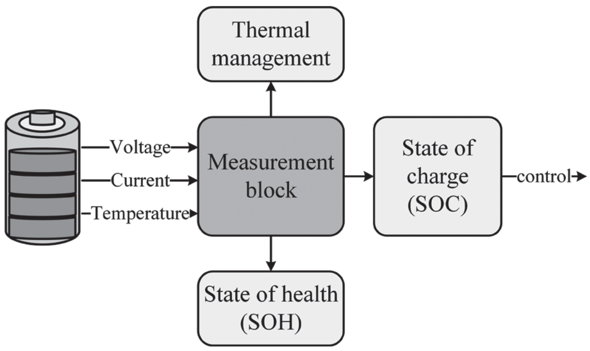

Fig. 1 Schematic presentation of BMS

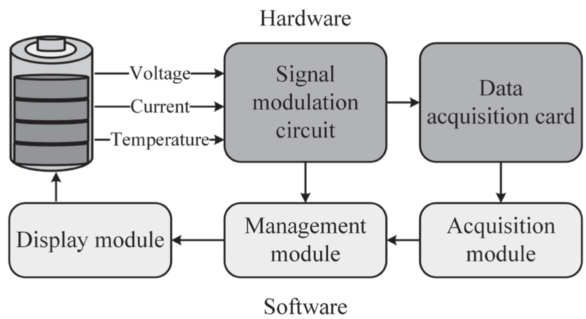

Fig. 2 Schematic presentation of battery diagnostic system

[Offer et al., 2012; Affanni et al., 2005]. It can be observed by comparing signals before and after short circuit pulse is inserted.

In summary, BMS emphasizes on the battery system monitoring. It shows significant improvement on battery system performance. However, it is limited to the estimation accuracy, which indicates more accurate algorithms are in demand. For specific battery faults, battery diagnostic system is required in addition to BMS. In comparison, it is more flexible but extra manufacture is needed.

3. ELECTRIC MOTOR FAULT DIAGNOSIS

3.1 Electric motor fault characteristics

According to the root cause of faults, electric motor faults can be generally categorized into two groups: electrical faults and mechanical faults [Benbouzid, 1998; Li et al., 2012]. Those faults can also be summarized by the locations of fault occurrence in the electric motor, which are listed in Table 2 [Benbouzid, 1998; Toliyat et al., 2012; Nandi et al., 2005]. Figure 3 shows an exploded diagram of induction motor and a pie chart describing fault occurrence percentage. The pie chart indicates bearing faults and stator-related faults are the most common faults in electric motors [Nandi et al., 2005].

3.2 Approach for electric motor diagnostic

Several studies have been done to investigate the fault signatures of electric motor in the past decades. As summarized in Table 2, most of electric motor failures show explicit stator current harmonic components. Motor current signature analysis (MCSA) is the most commonly used tool for fault diagnosis in electric motor. And digital signal processor (DSP) based techniques are used for the current signature analysis [Akin et al., 2012; Fan et al., 2008].

Rotor-related fault diagnostic approaches can be broadly listed in the following [Nandi et al., 2005; Akin et al., 2011; Liu et al., 2008; Zhao et al., 2012]:

- Fast Fourier Transformer (FFT) spectrum analyzer;
- Reference frame theory analysis (RFTA);
- Time and frequency domain analysis;
- Pattern recognition;
- Time-stepping coupled finite element state space method;

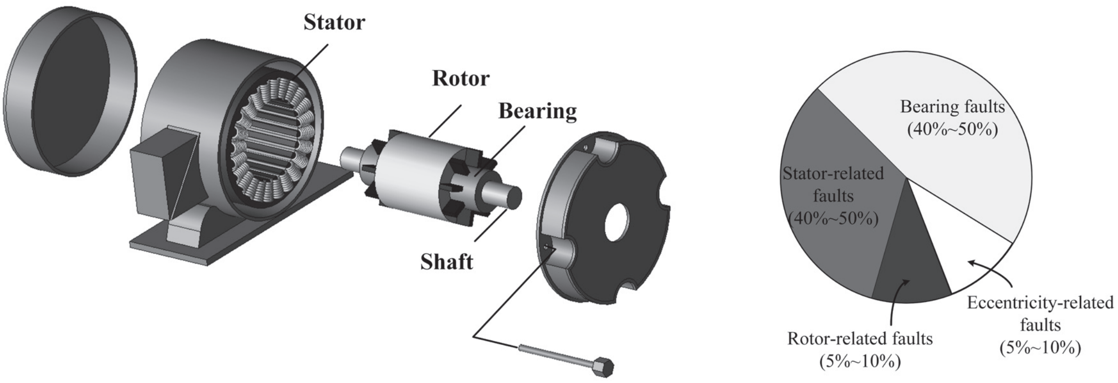

Fig. 3 Electric motor fault locations and the corresponding fault occurrence rates

Table 2 Classification of electric motor faults and the corresponding stator current spectrum

Electrical faults		Mechanical faults	
Rotor-related faults	Stator-related faults	Bearing faults	Eccentricity-related faults
Broken rotor bar	Abnormal connection of stator windings	Outer bearing race defect	Bend shaft
Cracked rotor end rings		Inner bearing race defect	Static air-gap irregularities
Shorted rotor field windings	Open or short circuit of stator windings	Ball defect	Dynamic air-gap irregularities
		Train defect	
$f_s = (\frac{\eta}{p}(1-s) \pm s)f$ When η/p = 1,2,3….	$f_s = (\frac{n(1-s)}{p} \pm k)f$ When n = 1,2,.; k = 1,3,5..	$f_{bea} = \lvert f \pm nf_v \rvert$ Where n = 1,2,..., f_v = vibration frequency	$f_{ecc} = \left[(N_r + n_d)(\frac{1-s}{p}) \pm k\right]f$ n_d = No. of rotor bars; k = 1,3,5…

- State and parameter estimation techniques

Figure 4 is the frequency spectrum comparison result of motor line current with RFTA and FFT when broken rotor bar faults occur [Akin et al., 2011]. It is observed that both RFTA and FFT illustrate explicit harmonic component in stator current. And the magnitudes tested by RFTA are nearly the same as the FFT spectrum analyzer outputs. But RFTA is able to clearly indicate the current magnitude at a certain frequency.
Stator-related fault diagnostic approaches can be broadly listed in the following [Nandi et al., 2005; Liu et al., 2009; Ondel et al., 2012]:

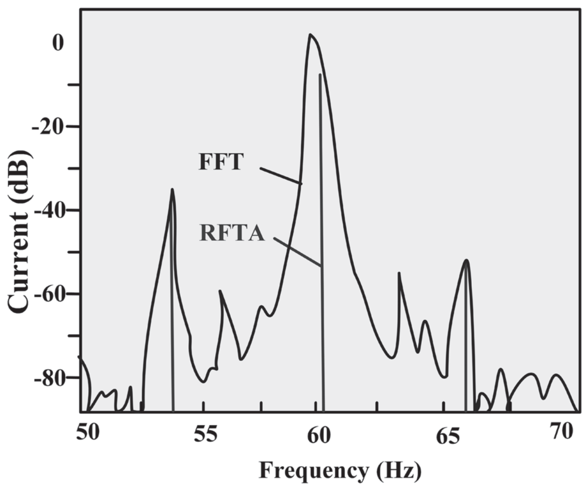

Fig. 4 Broken bar fault signatures detected by RFTA and FFT

- Flux-based detection;
- Power decomposition technique;
- Statistical process control;
- Concordia pattern recognition.

Open or short circuit in motor windings is related to winding insulation failures [Toliyat et al., 2012]. In accordance with this fault impact on the operational temperature, thermal analysis is consequently widely applied for the detection of short turn faults by using pattern recognition algorithm [Ondel et al., 2012]. Temperature is used as the fault indicator. In [Ondel et al., 2012], a simplified thermal model of induction motor is implemented by comparing the heating results between the normal motor and the motor of short-circuit fault. It shows that short-circuit fault could result in additional losses that behave in thermal signatures.
Bearing fault diagnostic approaches can be broadly listed in the following [Nandi et al., 2005; Devaney et al., 2004; Schoen et al., 1995]:

- Envelop detection technique;
- Artificial neural networks (ANNs);
- Vibration spectrum analysis.

There are four types of bearing faults which are the main sources of motor vibration, namely outer race defect, inner race defect, ball defect, and train defect [Devaney et al., 2004; Yu and Chau, 2011]. Each defect type has its unique vibration frequency component which is given by [Devaney et al., 2004]:
For the outer bearing race defect:

$$f_v\,[Hz] = (N/2)\,f_r\,[1 - b_d \cos(\beta)/d_p]$$

For the inner bearing race defect:

$$f_v\,[Hz] = (N/2)\,f_r\,[1 + b_d \cos(\beta)/d_p]$$

For ball defect:

$$f_v\,[Hz] = d_p f_r\ /2b_d\ \{1 - [b_d \cos(\beta)/d_p]^2\}$$

For train defect:

$$f_v\,[Hz] = (f_r\ /2)\ [1 - [b_d \cos(\beta)]$$

where f_r, b_d, d_p, and N are the rotational frequency, ball diameter, ball pitch diameter, and number of balls respectively.
The basic idea of bearing fault diagnosis relies on the vibration spectrum analysis [Duque et al., 2005; Li et al., 2011]. Both vibration analysis and motor current signature analysis are proposed as effective methods detecting bearing faults [Chow et al., 1991; Duque et al., 2005; Akin et al., 2012]. The traditional vibration spectrum analysis has the shortcoming of low accuracy in detecting defect frequency components. Envelop detection technique is improved in efficiency and accuracy by using band pass filter and Hilbert transform [Hochmann et al., 2005]. It detects power spectrum instead of traditional current spectrum.
In summary, thermal analysis, vibration analysis and motor current analysis are widely used for motor fault diagnoses. Motor current analysis has the advantage of cost-effective compared with other techniques.

4. POWER ELECTRONICS FAULT DIAGNOSIS

4.1 Power electronics fault characteristics

As shown in Figure 5, power electronics in EVs are initially constituted by power switches and power elements [Vezzini, 1996; Zhu et al., 2008]. Open switch fault and short switch fault are the most common faults in power switches [Chau and Wang, 2005].
As shown in Table 3, the advent of open switch faults

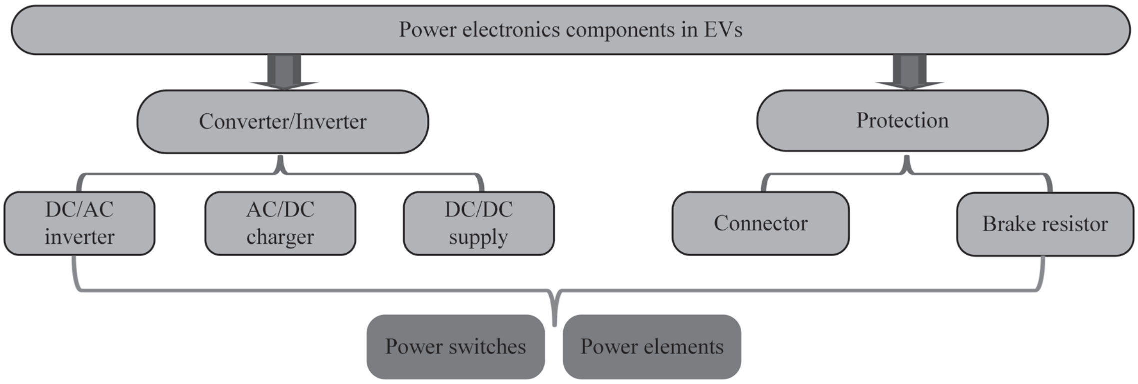

Fig. 5 Main components of power electronics in EVs

Table 3 Classification of power electronics

	Symptoms	Fault indicator	Approach	Comments
Open switch fault	DC current offset	Current vector trajectory	Park's method	Load dependent
			Normalized DC current method	Complicated
			Modified normalized DC current method	High efficient
		3-phase current mean value	Wavelet-neural network method	High cost, intelligent
			Current deviation method	High implementation effort
		Voltage	Voltage comparison in time domain	Extra sensor needed
			Voltage sensing by lower switch	Quick detection
Short switch fault	Non-zero DC current component	Phase current	Average current Park's vector approach	No protection
		Device current	Current mirror method	High cost
		Gate voltage	Protection by gate voltage limiting	Inaccurate detection
			Gate voltage sensing method	Complicated
			Two-step gate pulse	Reliable, low di/dt
			Voltage and time criterion	Fast reaction, fault tolerant

results in explicit DC current offset [Lu and Sharma, 2008]. The 3-phase current is the most commonly used fault indicator in the open switch fault diagnosis. Current vector trajectory and 3-phase voltage can also be utilized as effective detection parameters. Similar to open switch faults, short switch faults use current and voltage for the fault diagnosis since it will produce non-zero DC current component [Lu and Sharma, 2008. Unlike open switch fault, short switch faults could cause failure in a very short period. So it requires highly efficient diagnostic system.

4.2 Approach for power electronics diagnostic

Techniques of open switch faults diagnoses can be generally divided into two categories, voltage measurement-based techniques and current measurement-based techniques [Karimi et al., 2009; Rodriguez et al., 2007]. Modified normalized DC current method is developed on the basis of normalized DC current method and Park's method. It uses the current vector trajectory to determine the faulty signals [Liu et al., 2011; Kim et al., 2008]. Wavelet-neural network method is applied by using wavelet transform and neural network to observe the 3-phase current [Mamat et al., 2006]. The 3-phase voltage can also be detected in open switch faults by comparing the measured voltage with their reference voltage as a residual. It is called voltage comparison in time domain [Araujo Ribeiro et al., 2003]. Besides, the inverter pole voltage measurement, machine phase voltage measurement, system line voltage measurement, and machine neutral voltage measurement are identified as efficient methods [Lu and Sharma, 2008].

The simplest idea for the short switch fault detection is to install a fast-acting fuse to isolate the faulted switch [Song et al., 2013]. This idea mainly focuses on the short switch isolation. It requires extra expenses for fuse installation. Another approach is a field programmable gate array based experiment which manages to detect the short switch faults within less than 10 μs [Karimi et al., 2009]. This technique efficiently conquers the shortcoming of short switch faults that require rapid reaction. Voltage and time criterion uses two comparators to detect DC-link voltage and time that during which fault occurs [Mendes et al., 1999; Zhao et al., 2013]. In addition, other approaches such as de-saturation method, current mirror method and gate voltage sensing method play good role in short switch fault diagnoses [Lu and Sharma, 2008; Rodriguez et al., 2007; Huang and Flett, 2007; Liu et al., 2013].

As summarized in Table 3 and Figure 5, power switch is the determinant component in power electronics of EVs. So the power electronics fault diagnostic system mainly consists of open switch and short switch fault detection. Compared with open switch fault, short switch fault has a higher demand in the operation speed of diagnostic system.

5. CONCLUSION

In this paper, a review of fault diagnosis in the aspects of battery, electric motor and power electronics for EVs is presented. In summary,

- BMS is commonly applied in battery for a safe and reliable battery performance. Addition diagnostic system may be required for specific faults.
- MCSA gains significant popularity in electric motor fault diagnosis compared with other techniques. But more attention should be drawn to the diagnostic efficiency and accuracy.
- Fault diagnosis of power electronics in EVs emphasizes on the studies of power switches. A few literatures concern the fault on power elements.

It has been found that many literatures have investigated the fault signatures of these components individually, but inadequate research has been done particularly for EVs. So the corresponding technologies are not mature enough and further research is essential to implement a better vehicular diagnosis system.

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