Development of the Load Spectrum for Electric Drive System Reliability Test Correlated with Customers' Usage

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***Abstract*—The electric drive system plays a crucial role in electric vehicles, which has been developing towards an Integrated Electric Drive System (IEDS). The highly integrated technology applied in IEDS can effectively improve the power capacity of electric vehicles. However, it also greatly increases the risk of reliability failure. Based on this, this paper proposes a new methodology for determining the loading spectrum correlated with customers' usage, which can be applied to assess the mechanical reliability of the IEDS in a bench test. In this method, the "Torque-Speed" coupling impact of IEDS under different customers' usage scenarios is fully considered. A case study is conducted based on an electric vehicle equipped with an IEDS. Based on the field-tests under sixteen typical customers' usage scenarios, 3,000km of road load data correlated to the IEDS are collected. Then a loading spectrum is developed for the IEDS bench test and is further compared with several standard spectrum in terms of damage character. The result shows that the damage assessment of the IEDS lifespan (10 years & 300,000km) can be achieved by loading a 721h load spectrum in the bench test. The constructed test spectrum can be equated with the damage under customers' usage, which validates the effectiveness of the proposed method. Besides, the comparative analysis results also show that the existing reliability test specifications are hard to reproduce the actual load level of customers, so it is strongly suggested to formulate more rational reliability assessment specifications of the IEDS.**

***Keywords*—electric vehicle, load spectrum, mechanical reliability, integrated electric drive system**

I. Introduction

The Electric Drive System (EDS) plays a key role in electric vehicles. The efficiency, weight, size and reliability of the EDS will show a great impact on the performance of the whole vehicle [1]. Key components of EDS include power electronic control units, power motors, and reducers. Initially, those components were assembled separately in the traditional type of EDS. With the advanced technologies applied in EDS, such as power electronics, large-scale integrated circuits and modern control theory, the Integrated Electric Drive System (IEDS) is developed, which is composed of mechanical and electronic components. And the IEDS has become a hot topic in the research of electric vehicle technologies at present [2]. Compared with internal combustion engine vehicles, the vehicle equipped with the IEDS performs a higher torque and speed capacity, which greatly improves the vehicle power. But the high power from the IEDS will correspondingly increase the risk of system failure due to the "Torque-Speed" coupling impact [3]. Besides, compared with EDS in traditional structures, all sub-modules in the IEDS should be operated as integration and thus require a higher level of reliability. Accordingly, higher demands are placed on the durability of the gears and bearings, the strength of the housing and the sealing of the oil seals in the IEDS. Since the safety of electric vehicles has aroused people's great attention, the service reliability of the IEDS has been taken as a key technology by the electric vehicle industry [4].

The reliability compliance test is an important technology in ensuring the service reliability of the IEDS [5]. And the development of specifications based on the load spectrum are the foundation that determines the accuracy and credibility of the reliability test. At present, standard reliability test specifications are mainly targeting at the conventional vehicles, but less for electric vehicles with the IEDS. Taking the mechanical reliability test as a research case, the existing standards do not meet the reliability evaluation needs of the IEDS [6]. The reasons are analyzed as follows:

1) Most of the existing standard specifications are designed for the life assessment of single components (e.g. motors, gearboxes, IGBTs.) in EDS, including ISO 19453 [7], GB-T 18488 [8], GB-T 29307 [9], etc. Those specifications can be applied to the reliability verification and development of individual components. But there is a lack of reliability standards for an all-in-one integrated IEDS.
2) The existing reliability test specifications are usually based on acceleration test cycles under maximum speed and torque level. Those acceleration test cycles make it hard to effectively reproduce the actual load level under different customers' usage scenarios.

In order to improve the rationality of reliability test specifications, it is particularly important to construct a reliability test load spectrum that can accurately reproduce the user's actual road load levels [10]. Ample research has been carried out on the development of the reliability test load spectrum [11–15]. Existing studies on load spectrum construction techniques basically consist of the following key steps: user research, load data collection, and road condition analysis.

To meet the reliability evaluation needs of electric vehicle IEDS, a new methodology is proposed for the development of loading spectrum for reliability tests correlated with customers' usage. Key steps of the proposed method include road load acquisition, load spectra data analysis targeted at the design lifespan, and loading spectrum development for the IEDS bench test. Then a case study is carried out based on the electric vehicle equipped with the IEDS.

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II. ROAD LOAD DATA COLLECTION

Road load data collection is important in the construction of the load spectrum. The sample data should cover the user's actual road load characteristics. A large number of scholars and research institutes adopt the typical road load spectrum acquisition method based on the designed test route [16]. Due to the complex and alternating dynamic characteristics of the load during vehicle driving, various factors should be considered in road load data collection tests such as road type, traffic flow, driver, load, etc. Based on this, the test routes and test cycles are designed first, and then road load data related to the IEDS are collected.

A. Test Equipment and Collected Signals

The failure of the EDS depends on the torque, rotational speed, current, voltage, and accompanying thermal loads during its operation. Given the strong correlation between torque and current and voltage, torque and rotational speed are considered the dominant failure loads of the mechanical components of the EDS [17]. Based on this, information of the experimental equipment and collected signals are shown in Table 1.

Table 1. Test equipment and collected signals

Test Equipment	Signals	Symbol	Units
TRION™ VGPS	Longitude	–	degree
	Latitude	–	degree
TRION-CAN	Vehicle speed	V	Km/h
	mileage	L	m
	Motor torque	T_m	Nm
	Motor speed	N_m	rpm
Non-contact torque and speed telemeter	Torque at the left shafts	T_L	Nm
	Torque at the right shafts	T_R	Nm
	Rotation speed at the left shafts	n_L	rpm
	Rotation speed at the right shafts	n_R	rpm

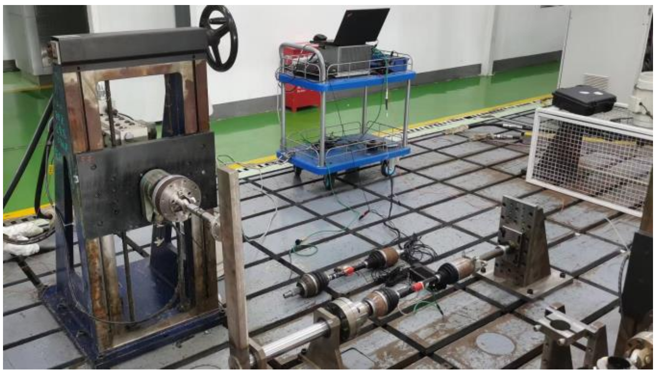

Fig. 1. Torque sensors calibration on bench tests.

Sensor of non-contact torque and speed telemeter was installed on the left and right shafts. Before the test, it is necessary to calibrate the good linear relationship between the strain/voltage and the torque. The torque calibration bench test is shown in Fig. 1. The formula for calculating the torque at the half shaft is shown in Eq. (1). Then the torque and rotation speed load of the IEDS can be calculated in Eq. (2).

$$T_s = \frac{E \cdot \pi \cdot D^3}{64 \cdot (1+\mu)} \cdot \varepsilon \tag{1}$$

where, E is the elastic modulus of the measured material; D is the diameter of the measured shaft; μ is the Poisson's ratio of the measured shaft material; ε is the strain value of the measured shaft.

$$\begin{cases} T = T_L + T_R \\ n = (n_L + n_R)/2 \end{cases} \tag{2}$$

where, T is the torque at the output terminal of the IEDS; n is the torque at the output terminal of the IEDS.

B. Test Routes and Test Cycles

In this paper, Xi'an is selected as the field test area in China. Four test routes are designed including four types of roads: urban roads, expressways, roads across the countryside, and mountain roads. When selecting the test route, the representative road sections that can reflect the characteristics of typical roads are considered first, and the selected roads should be conformed to the requirements of the national standards [18]. Then the fired tests for data collection are carried out under four routes respectively.

Based on the planned test route, factors that have a significant impact on the load data should be fully considered to form a cyclic test event [19]. In this paper, road type, traffic flow, drivers and load factors are considered to form the sixteen combined test cycle events, as shown in Fig. 2. The drivers followed the designed test routes and drove freely according to their personal habits. Eventually, a total of 3,000 km of road load data is collected for the sixteen typical test cycle events. The collected signals of Torque and Rotation speed from the transmission shaft can be illustrated in Fig. 3.

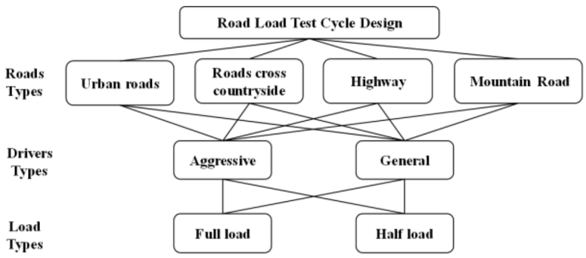

Fig. 2. Road load data collection test cycles design.

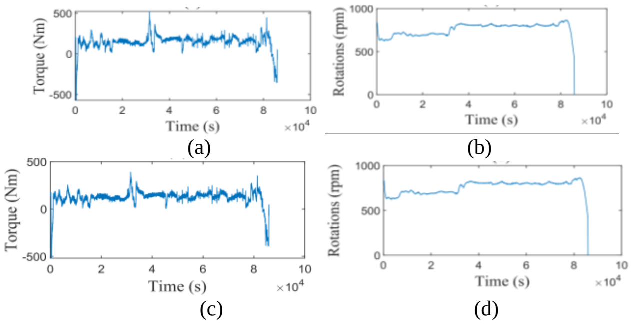

Fig. 3. Collected signals of Torque and Speed from transmission shaft; (a). Torque at the left shaft, (b). Rotation speed at the left shaft, (c). Torque at the right shaft (d). Rotation speed at the right shaft.

III. LOAD SPECTRA DATA ANALYSIS TARGETED AT THE DESIGN LIFESPAN

A. Load Counting Method

Various methods for load counting have been proposed, among which the rainflow counting method is widely used. The rainflow counting method was first proposed by Matsuiski and Endo in 1968, and it has been generally recognized by the engineering community [20]. However, the traditional rainflow counting method is not suitable for rotating parts. The reason is that it can only count the torque load, and the corresponding information of the rotational speed will be lost. It is suitable for torque fluctuations that are regarded as irrelevant to their rotational behavior, while the rotational speed can be ignored. For the high-speed rotating parts (gears, bearings, etc.) of electric vehicles IEDS, its failure-dominant load is mainly the torque and relative motion speed. Therefore, the rotating rainflow counting method is applied in this paper to overcome the disadvantages of the rainflow counting method [21]. The counting rules are illustrated as follows:

Assuming that the speed and torque at moment t are $n(t)$ and $T(t)$, respectively. Gear revolutions r(t) corresponding to t can be calculated in Eq. (3):

$$r(t) = \frac{1}{60} \int_0^t |n(t)|\, dt \tag{3}$$

According to the correspondence between torque and speed, the gear meshing time points are estimated from the speed time domain curve, as well as the value of the torque that the gear is subjected to and transmitted at the moment of meshing at this series of time points, and the triangular waveform of the gear load is predicted, i.e., the gear torque $T_{tooth}(t)$ at time t can be calculated in Eq. (4):

$$T_{tooth}(t) = \varphi(t(t) - floor(r(t))) \cdot T(t) \tag{4}$$

where, $T(t)$ is the shaft torque corresponding to the t moment; $floor(r(t))$ is the largest integer no greater than $r(t)$; $\varphi(x)$ is a relational mapping function, representing that $\varphi(x)$ vary from 0 to 1 and then vary from 1 to 0.

The traditional rainflow counting method is used for the $T(t)$ and $T_{tooth}(t)$ of load curves respectively. Then, the axis matrix A_{shaft} and tooth matrix A_{tooth} are calculated. Finally, based on the rainflow matrix superposition method, we denote A_{total} as Eq. (5):

$$A_{total} = A_{shaft} + A_{tooth} \tag{5}$$

B. Pseudo Damage Calculation

The same stress level produces an equal amount of damage results based on the Palmgren-Mine rule and the linear cumulative damage principle. We denote fatigue damage D as Eq. (6):

$$D = \sum_{i=1}^{M} d_i = \sum_{i=1}^{M} (n_i / N_i) = 1 \tag{6}$$

where, d_i is the rainflow damage under various levels of load; n_i is the number of cycles under the action of T_i; N_i is the number of life cycles (number of failures) under torque and it can be calculated according to the nominal stress method S-N curve; M is the number of load intervals.

The damage calculation model is established to obtain the damage corresponding to the rotating rainflow counting matrix based on the above principle, and the damage situation of the constructed load spectrum is characterized.

For M load cycles contained in a load spectrum, the total damage can be calculated as:

$$D = \sum_{i=1}^{M} (\frac{n_i}{N_k})(\frac{T_i}{T_k})^m \tag{7}$$

where, N_k is the number of cycles corresponding to the fatigue strength limit T_k in the S-N curve; m is determined by the corresponding material properties.

C. Load Spectrum Extrapolation

The measured road speed torque load count matrix is synthesized according to the proportional coefficient of road working conditions. The non-parametric density estimation extrapolation method is used to construct the life cycle load spectrum with the vehicle design life mileage as the goal.

Assuming that the random variable x obey an unknown probability density function $f(x)$, from which the sample $\{x_1, ..., x_n\}$ performs a kernel density estimation of the function $f(x)$. The kernel density estimation at any point x can be defined Eq. (8):

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} w_i = \frac{1}{nh} \sum_{i=1}^{n} K(\frac{x - x_i}{h}) \tag{8}$$

where, $K(\cdot)$ is the kernel function, such as the Gaussian kernel, Parzen window, Epanechikov, etc.; h is a bandwidth or smooth parameter.

Taking $f(x)$ as a probability density function, it must be guaranteed that it is not negative and that the sum of integrals is 1. The above condition can be guaranteed by requiring the kernel function to be the distribution density, then the constraint of $K(\cdot)$ is:

$$K(x) > 0, \int K(x)dx = 1 \tag{9}$$

The $f(x)$ of probability density function is calculated based on the nonparametric kernel density estimation. The extrapolated load distribution $S=K \cdot f(x)$. Here, K is the extrapolation factor, which is the ratio of the target lifetime mileage to the measured load mileage.

Based on those steps of the load spectrum extrapolation method, the result of load spectra data analysis targeted at the design lifespan is shown in Fig. 4. The Torque load distribution contains 128 intervals. The torque limit value and the number of cycles has increased after the extrapolation, where the upper limit of torque value is 3957.34 Nm and the lower limit of torque value is −3895.98 Nm.

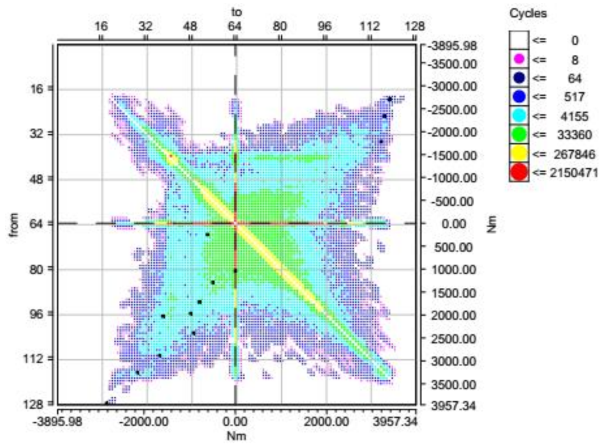

Fig. 4. Rainflow Matrix of load spectrum targeted at the design lifespan.

IV. Loading Spectrum for the IEDS Bench Test

Load spectrum block is the most typical forms used in fatigue bench test [22]. Traditional types of load spectrum block usually designed based on 8 extreme loads definition. Based on this method, to improve the correlation between the test spectrum and the users' actual spectrum, this paper takes the influence of positive and negative torque and loading speed into account. 8 degrees of loading are designed according to the load distribution under user operating conditions. Then, the user life-cycle load spectrum is transformed into the reliability test spectrum based on the damage equivalence principle. The load spectrum for the IEDS bench test is developed in following steps:

The joint torque-speed distribution counting method is used to count the load distribution under user operating conditions. Assuming a discontinuous time interval Δt_j (j=1,⋯,m_i) in the rotational speed time history $n(t)$, the number of revolutions N_i under a given torque interval of T_i is calculated in Eq. (10).

$$N_i = \sum_{j=1}^{m_i} \int_{\Delta_j} n(t)\mathrm{d}t \tag{10}$$

where m_i is the number of time intervals under the T_i interval.

Based on this, a three-dimensional distribution matrix of torque, speed and frequency is obtained, as shown in Figure 6. Then the loading torque level is determined by the median of the segmental torques for each interval (T_1, T_2, ..., T_n), and the loading speed is determined by the weighted average of the speed to frequency.

Then the frequency and duration of loading at each level of loading torque and speed will be determined based on the damage equivalence principle, as shown in Eq. (11):

$$N_{eq} = \sum_{i=1}^{k} N_i \left(\frac{T_i}{T_{eq}}\right)^m \tag{11}$$

where T_{eq} and N_{eq} are the equivalent load torque and frequency, respectively; T_i and N_i are the original torque and frequency, respectively; m is the power exponent of the S-N curve. For automotive components, m=5.The value of m can be determined according to the study objectives and materials.

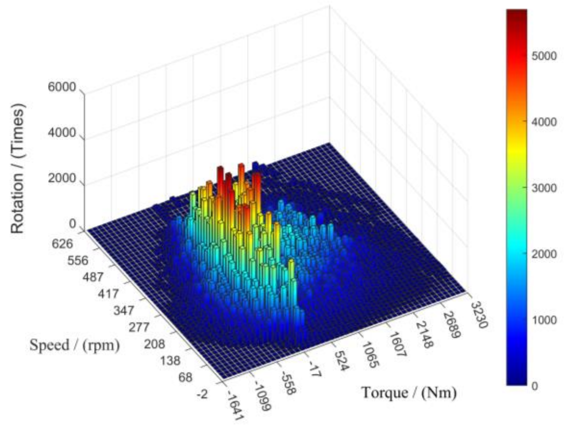

Fig. 5. Three-dimensional distribution matrix under user operating conditions.

V. Results and Discussion

In the case study mentioned above, the constructed IEDS reliability test spectrum in the bench test is shown in Table 2. The result shows that the damage assessment of lifespan (10 years & 300,000km) can be achieved by loading 721 hours load spectrum in a bench test. The constructed test spectrum can be equated with the damage under customers' usage. At the same time, test costs can be effectively reduced and test cycles shortened. The method proposed in this paper provides an effective solution for improving the relevance of the test loading spectrum to the user's operating conditions. In particular, an acceleration test spectrum can be further designed for further study.

Table 2. Reliability test spectrum in the bench test

Loading Mode	Torque (Nm)	Cycles (times)	Speed (rpm)	Time (h)
Torque in Positive	2,926	936,165	630	25
	1,708	2,045,627	320	107
	1,099	2,258,800	260	145
	490	1,013,954	100	169
Torque in nagetive	–304	454,000	100	7
	–727	2,054,143	260	61
	–1,336	1,177,711	320	132
	–2,823	272,918	630	7

Table 3. Comparison between the IEDS spectrum and the standards spectrum in damage characters

Spectrum	IEDS	GB-T 29307-2012	QC-T 1022-2015
Pseudo damage	5.22	2.54	7.58

The load spectrum developed for the IEDS bench test is compared with two standard spectrums in terms of damage character, including the Chinese national standard GB-T 29307-2012, and Chinese industry standard QC-T 1022-2015. The comparative results are shown in Table 3. From the result, it can be seen that QC-T 1022-2015 can lead to an over-assessment in damage when used for the reliability assessment of IEDS. And QC-T 1022-2015 shows an inadequate assessment of the IEDS. The existing reliability test specifications are hard to effectively reproduce the actual load level of customers.

VI. Conclusion

Taking the electric vehicle equipped with the IEDS as the research target, a new methodology is proposed for the determination of the loading spectrum correlated with customers' usage. The main conclusions are as follows:

1) Based on the proposed method in this paper, 3,000km road load data correlated to the IEDS are collected, and the IEDS reliability test spectrum in bench test is developed. The result shows that the damage assessment of lifespan (10 years & 300,000km) can be achieved by loading a 721h load spectrum in a bench test. It provides an effective solution for improving the relevance of the test loading spectrum to the user's operating conditions.
2) The load spectrum that is developed for the IEDS bench test is compared with three typical standard spectrums in terms of damage character. The result shows that the existing reliability test specifications are hard to effectively reproduce the actual load level of customers, so it is strongly suggested to formulate more rational reliability assessment specifications of the IEDS.

The reliability of the IEDS involves the performance of mechanical and electronic components. This paper mainly focuses on the mechanical reliability of the IEDS. In future studies, the reliability of the IEDS including EMC immunity, differential endurance, high-speed endurance, and environmental endurance will be further studied in the future.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Yuzhou Yang: Investigation, Data curation, Formal analysis, Writing - original draft; Xuan Zhao: Supervision, Conceptualization; Qiang Yu: Investigation, Validation; Shu Wang: Visualization, Software; Man Yu: Reviewing and Editing; all authors had approved the final version.

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