REVIEW

Review and prospect of maintenance technology for traction system of high-speed train

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Abstract

In the past few decades, high-speed trains have witnessed tremendous and vigorous development with the appearance of the oil crisis and industrialization, which became a significant trend in the transportation industry the world over. With the increase of high-speed railway mileage, the amount of high-speed train has grown sharply, the service life of the trains has increased gradually and the components of the vehicle traction system have become worn and aged as a result. Therefore, advanced maintenance technology and its application are key factors to reduce maintenance cost, human resource input and ensure safe, stable and reliable operation of trains. This paper summarizes and discusses the development, application mode, maintenance management and maintenance technology of high-speed railways of the major countries in the world, especially discusses the condition-based maintenance and the key technology of the traction electrical system, and offers the prospect of research direction and the development of traction maintenance technology.

Keywords: high-speed railway; traction system; maintenance technology; condition assessment; life prediction; condition-based maintenance; Prognostic and health management (PHM)

1. Introduction

Since Stephenson invented the first train in the world in 1814, the world’s rail transit has experienced the course of development, climax, slump and comprehensive rejuvenation with the Industrial Revolution. After the advent of Shinkansen High-speed Railway in Tokaido, Japan on October 1964 [1], the high-speed railway—which has
great advantages in transportation volume, environmental protection, comfort and space utilization over other modes of transportation, as well as the advantages of fast speed, low price, punctuality, low pollution, low energy consumption and small occupation of land—has become an indispensable part of urban transportation in the world. The official completion and opening of the Shinkansen High-speed Railway in Tokaido has made great contributions to Japan’s economic take-off. The highest operating speed has risen from 210 km/h as it just opened to 320 km/h up to now [2–6]. Europe’s high-speed rail boom began with France’s operation of the TGV South-East line in 1981 [6]. Germany, Spain, Italy and Britain are experiencing a high-speed railway construction boom, which accelerated the process of European integration, and the pan-European high-speed railway network has gradually formed [7–14]. In 2004, the State Council of China put forward a framework of high-speed railway construction with an emphasis on ‘four verticalness and four horizontalness’. Thus, China began to enter the era of rapid high-speed railway development. At present, China owns the most technologically complete, the largest scale, the longest operating mileage and the largest number of high-speed trains in the world and has set up the most developed high-speed railway network in the world.

By the end of 2020, China’s high-speed railway has increased to 37 900 km of operating mileage, the number of high-speed trains is over 3 300, which covers electric multiple units (EMUs), with different speed grades, different classes and different use environments. By 2025, the national railway operating mileage will reach about 170 000 km, among which high-speed railway (including intercity railway) is about 50 000 km. The railway covers almost all cities with a population of more than 200 000 in urban areas, and high-speed railway covers 98% of cities with a population larger than 500 000 in urban areas. With the opening of new lines and the narrowing of departure intervals in the existing lines, the amount of high-speed trains will continue to grow. As an important part of rail transit, as time goes on, wear, deformation and damage will occur in components of the trains. In order to make the high-speed train run safely, reliably and stably in good condition, it is necessary to carry out planned inspection and maintenance. With the increase of train service time, train maintenance faces enormous challenges including the demands of higher maintenance cost, higher operation cost and efficiency. And the problems of human cost, maintenance cost, condition-based maintenance, health condition and service life are becoming more and more prominent, which have become common and urgent practical problems in the field of rail transit traction system.

Focusing on the maintenance of the high-speed train traction system, this paper introduces the maintenance rules and techniques of high-speed trains, analyses and compares various maintenance techniques, and summarizes their advantages and disadvantages. The paper also expounds the state assessment technology of the traction electrical system, and points out the development direction of maintenance technology of traction electrical system.

2. High-speed train traction system

As shown in Fig. 1, the traction system of the high-speed train is a very complicated system and mainly includes pantograph, traction transformer, traction converter, traction motor and other key components. The pantograph transmits single-phase AC 25kV from the catenary to the traction transformer. Then the traction transformer outputs three-phase AC with controllable voltage, current and frequency to traction motors, and the torque and speed output by the shaft end of the traction motors are transmitted to the wheel sets through the gearbox, which are converted into wheel traction to drive the train at high speed.

Pantograph: the pantograph is installed on the top of the train and leads the power from the catenary to the vehicle. The power reception of a high-speed train is achieved through the close contact between the pantograph and the catenary. Whether the pantograph is normal or not depends on the technical state of the catenary pantograph system. The reliability of the pantograph is the key condition to ensure stable operation of a high-speed train.

Traction transformer: the traction transformer transfers the 25 kV high voltage obtained from the catenary to low voltage used by the low-voltage electrical equipment. The traction transformer generates the required voltage through the electromagnetic induction of the iron core and coil to provide traction power for the traction converters and other equipment. The traction transformer consists of iron core, coil, cooling
device, temperature sensor, temperature relay, pressure relief valve and other components that provide support for reliable operation of the traction transformer.

Traction converter: the traction converter rectifies and inverts the single-phase AC output to three-phase AC with variable frequency. It is the control core of the traction system, and needs to realize high-speed operation, adhesion control, anti-idling, energy feedback, acceleration, deceleration and braking of the train, so as to ensure the safety and reliable operation of high-speed trains.

Traction motor: the traction motor is to convert electrical energy to mechanical energy, drive the gearbox and power bogie shaft to make the train run at high speed. The motor is equipped with speed sensors and temperature sensors to provide feedback signals for train speed control, communication and other functions.

3. High-speed train vehicle maintenance system

As the key part of the high-speed train to ensure safe and reliable operation, the traction electrical system is a multifunctional and highly integrated complex system that integrates mechanical, electrical, communication and other subsystems. In daily operation, the train involves a variety of complex or even extreme conditions, such as high altitude, extreme temperature, acceleration, deceleration, braking, dust and so on. Furthermore, because of different regions and other complex operation environments, the world’s major high-speed railway countries have developed high-speed trains suitable for their own countries. Japan, Europe and China have formed their own independent maintenance system for the train traction electrical system, which provided a solid guarantee for the normal operation of trains and travel services.

3.1 Japan’s Shinkansen high-speed train vehicle maintenance system

Since the privatization of Japan’s national railway in 1987, Japan has formed a top-down railway management composed of national laws, administrative departments and railway operating companies. Thus, rail transit vehicle maintenance and repair are constrained and managed in the form of laws. The state promulgates railway business law and railway operation law; the state administration formulates and stipulates the qualifications of vehicle designers, vehicle maintenance scope, maintenance cycle and test [15–18]; and railway passenger transport companies, in accordance with regulations, formulate driving and maintenance rules. These parties form an organic whole of laws, decrees and ministerial orders, and ensure safe, efficient and reliable operation of the train.

The repair and maintenance of Shinkansen high-speed train vehicles are divided into post-maintenance and preventive maintenance [19]. The former refers to maintenance after failure, and the latter is repair according to the predetermined travel distance or service time. Preventive maintenance includes preventive inspection and postinspection, which includes maintenance that focuses on routine inspection, periodic inspection, bogie inspection, comprehensive inspection and so on, as well as operational inspection and temporary inspection.

The national standard and main contents of maintenance for Japan’s Shinkansen high-speed train are shown in Table 1.
Table 1. Maintenance for Japan’s Shinkansen high-speed train

| Maintenance schedule | Routine maintenance | Alternative maintenance | Bogie maintenance | Full-range inspection |
|----------------------|---------------------|-------------------------|------------------|----------------------|
| Two days             | 30 days or 30 000 km| 1.5 year or 600 000 km  | 3 years or 1.2 million km |

Table 2. Maintenance schedule and contents of TGV high-speed trains

| Schedule              | Items                              | Maintenance cycle | Maintenance contents                                  |
|-----------------------|------------------------------------|-------------------|-----------------------------------------------------|
| First grade           | Routine check                      | 1 500 km–2500 km  | Train operation check and interior and exterior cleaning |
| Maintenance (second grade) | (ECF) check for comfort degree | 9 days            | Main running components check                       |
| Maintenance (second grade) | (VOR) running components check and maintenance | 14 days            | Check and maintenance of gears and other running components |
| Maintenance (second grade) | (VL) Small-scale check           | 3 months         | Inspection of running section, pantograph          |
| Maintenance (second grade) | (VG) General check             | 6 months         | Electrical component test                           |
| Maintenance (second grade) | (GVG) Large-scale check         | 18 months        | Traction system check and maintenance               |
| Parts replacement     | Nonscheduled                      | 8 years          | Replacement of consumable parts, failure recovery   |
| Plant maintenance     |                                    |                  | Comprehensive maintenance of the whole vehicle      |

3.2 European high-speed railway and high-speed train maintenance system

The TGV high-speed trains are mainly power-dispersive. The modular design of the TGV has formed the following four-stage preventive maintenance-based maintenance process.

Stage 1 operational inspection: the inspection of the parts of the running device, the parts under the vehicle body, the pantograph and the on-board device.

Stage 2 periodic inspection: the experiment, testing and inspection of the regulated or replaced wearing parts.

Stage 3 the replacement of components: during the maintenance period, components that meet the potential period of the components or meet the specified period of conditions are replaced during the inspection operation when it is found that their normal functions have reached the limit standard; parts that are damaged by accidents should also be replaced.

Stage 4 the maintenance of the body and structural equipment. The train body is regarded as a special mechanism, which is dealt with every 8 years or so when ‘comfort and beauty’ operation is carried out.

Specific maintenance contents are as shown in Table 2 [20, 21].

3.3 China high-speed train maintenance schedule and system

At present, the number of high-speed trains in China is more than 3 500 groups, covering EMUs of different speed grades, different classes and for different applicable environments. The EMUs cover all provinces, cities and autonomous regions of China. They have operation characteristics of long-distance continuous operation, complex operating environment, complex line conditions and large passenger capacity [24].

At present, based on the technical characteristics and maintenance requirements of EMUs, guided by modern maintenance theory, China Railway Corporation divides high-speed train maintenance into three stages: preventive maintenance, fault repair and active maintenance. According to the preventive maintenance-based
principle, the first to fifth grades of EMUs maintenance is formulated [24–25]. First-grade maintenance is routine inspection; second-grade maintenance is specific repair; the first- and second-grade maintenance belongs to application maintenance, mainly the comprehensive inspection, which includes the brake, the running device and pantograph involving driving safety, and the important component system function test including hollow axle flaw detection, gearbox oil change, bearing lubrication and so on. The purpose is to maintain and enhance the train utilization ratio; the first- and second-grade maintenance can be completed in the train section. Advanced maintenance includes third-grade maintenance of bogie decomposition, fourth-grade maintenance of system decomposition, and fifth-grade maintenance of vehicle comprehensive decomposition, which can be completed at the train station. The advanced maintenance refers to the third to fifth grades of maintenance. The main purpose is to restore basic performance, which can be completed in the train section and the factory. It involves vehicle performance inspection, functional testing, parts repair, parts replacement and recoating. The EMUs maintenance schedule and cycle are shown in Table 3.

Due to the high-density and large-scale operation of Shinkansen high-speed trains in Japan, the electric traction drive system chose the power distribution mode with high redundancy. When the traction system fails, the disconnection of some equipment will not affect the train’s normal operation. The basic principle of each part of the traction system within its service life is ‘preventive maintenance’: set the limit value of preventive maintenance, repair at this stage and repair after special circumstances. In order to reduce operation cost, reduce the train’s failure rate and ensure the train’s normal operation, advanced condition-based maintenance technology has been gradually introduced in recent years, which integrates the condition-based maintenance into ARSI (advanced rolling stock information management system) and realizes the unified management of maintenance data and vehicle data, so as to deepen the maintenance technology and technical system.

In Europe, train operation density and volume are not large. In the early design stage, the traction system of high-speed trains mainly adopts the power centralization mode, which can ensure the normal operation of the electric traction drive system and minimize operation costs. The maintenance of the traction system of European trains has changed from qualitative and traditional experience management to quantitative scientific management; the detection of state and quality has changed from static detection to dynamic detection and comprehensive detection; and the maintenance management system has changed from a separate system to a comprehensive, networked and intelligent system covering the whole train.

Under the guidance of modern maintenance theory, China’s high-speed trains have established a maintenance system of preventive maintenance, fault repair and active maintenance. At present, the system is faced with problems, such as long daily running distance, high maintenance readiness rate, long maintenance stop time and high maintenance cost. It has taken measures, such as extending the first-level maintenance cycle, revising and optimizing maintenance procedures, unifying advanced maintenance mileage, improving maintenance quality and so on. The measures of shortening test run mileage and optimizing maintenance production mode have achieved the effects of significantly shortening maintenance stop time, greatly

| Series                      | First-grade maintenance | Second-grade maintenance | Third-grade maintenance | Fourth-grade maintenance | Fifth-grade maintenance |
|-----------------------------|-------------------------|--------------------------|-------------------------|--------------------------|-------------------------|
| CRH1 series                 | 4 000 km or 48 h in service | 30 000 km/45 days | 1.2 million km or 3 years | 2.4 million km or 6 years | 4.8 million km or 12 years |
| CRH2 and CRH380A series     | 4 000 km or 48 h in service | 30 000 km/45 days | 600 000 km or 1.5 years | 1.2 million km or 3 years | 2.4 million km or 6 years |
| CRH3, CRH380B and CRH380C series | 4 000 km or 48 h in service | 30 000 km/45 days | 1.2 million km or 3 years | 2.4 million km or 6 years | 4.8 million km or 12 years |
| CRH5 series                 | 4 000 km or 48 h in service | 30 000 km/45 days | 2.4 million km or 6 years | 4.8 million km or 12 years |
| CR300AF, CR400AF, CR300BF and CR400BF series | 4 000 km or 48 h in service | 30 000 km/45 days | 1.2 million km or 3 years | 2.4 million km or 6 years | 4.8 million km or 12 years |
Table 4. Relationship between failure consequence and maintenance strategy

| Failure type                        | Maintenance strategy                                      |
|------------------------------------|-----------------------------------------------------------|
| Potential failure                  | Predictive maintenance                                     |
|                                    | Mandatory preventive maintenance                           |
|                                    | Periodic preventive maintenance                            |
| Failure with safety                | Mandatory preventive maintenance                           |
| Economic failure (operation failure)| according to the economy, preventive, predictive or postmaintenance can be selected |
| Economic failure                   | Postmaintenance                                            |

reducing the maintenance rate and gradually reducing maintenance cost. Generally speaking, the current maintenance strategy is based on the principle of preventive maintenance, and the new maintenance technologies have entered the stage of trial and small-batch application.

The future development trends of traction system maintenance technology are to carry out necessary and appropriate maintenance according to the state of the equipment, master the working state of the equipment through monitoring and analyse, then determine whether the equipment is in a normal state according to the state standard, and carry out appropriate and necessary maintenance when the equipment state is close to the failure control line with no fault, so as to achieve a state of being neither out for repair nor remaining repair.

4. Maintenance technology of high-speed train traction system

The high-speed train traction system maintenance technology stems from the beginning of maintenance when the components were broken, develops to preventive maintenance, then to condition-based maintenance and now into the current prognostic and health monitoring (PHM) technology. The application of new materials and new devices promotes the development of detection technology and maintenance technology on electric traction system of High-speed train. Current high-speed trains mainly adopt reliability-centred maintenance technology (RCM), condition-based maintenance (CBM) and fault prediction and PHM.

4.1 Reliability-centred maintenance technology

The RCM originated in the American aviation industry in the 1960s. Boeing 747 aircraft’s maintenance outline was based on RCM. Due to its prominent performance, RCM was widely extended in the United States armed forces in the 1970s. China’s civil aviation introduced RCM in 1979. In the mid 1980s, China’s military scientific research department began to study RCM theory and its application, and then published the first RCM national military standards GJB1378 ‘Requirements and Methods for Formulating the Outline of Equipment Preventive Maintenance’ in 1992. Through nearly four decades of development, it has been gradually applied to power systems, construction machinery and railway systems.

The RCM has gone through three stages. The maintenance mode of the first stage is breakdown maintenance, which referred to no repair until the product was broken. The second stage was prevalent in the 1960s to 1980s, which referred to preventive maintenance only based on time consideration, carrying out maintenance no matter whether the part is broken or not, as it was referred to as time-based maintenance (TBM). The third-stage maintenance mode is based on RCM. RCM is a systematic engineering method used to determine the preventive maintenance requirements of the product and optimize the maintenance system. The basic idea of the RCM is to analyse the function and failure of the system. It is based on design characteristics, operation function, a failure model and consequence analysis of the equipment [26]. It defines the consequences of each failure in the system, determines the preventive countermeasures of each failure and on the premise of safety and integrity, applies the available safety and reliability data to estimate the critical state of subsystems and components and decide what needs to be repaired, improved, redesigned and replaced; determines the necessity and feasibility of maintenance; and finally formulates the maintenance content, maintenance type, maintenance time interval and maintenance grade to achieve a system maintenance strategy with minimum maintenance downtime loss. The relationship between failure and maintenance strategy is shown in Table 4.

Based on the RCM theory, Wang [27] established the preliminary RCM method for a high-speed train and expounded the detail of
RCM in high-speed trains, then put forward some suggestions. D’Addio and Savio [28] proposed a random Petri network-based probabilistic method, so as to implement the RCM-centred maintenance plan on railway vehicles more effectively. Sun [29] established the decision model of maintenance mode for important functional components, and also developed the support system for maintenance decision for key parts of high-speed train. Li [30] studied the feasibility of advanced maintenance extension scheme through RCM theory. Based on the RCM theory, Diwei [31] put forward the logical decision diagram of RCM maintenance for diesel locomotives. Li [32] integrated the actual situation of the equipment to the maintenance system. Grubler [33] redefined the maintenance plan of locomotives based on RCM. At present, the maintenance of the electric traction system of high-speed trains in China is also based on the theories of RCM and modern maintenance. It follows the principle of planned preventive maintenance, and formulates the maintenance system of different grades of maintenance.

4.2 Condition-based maintenance technology

Preventive maintenance comes from planned preventive maintenance. With the progress of monitoring methods and the development of computers, a relatively perfect system was formed in the 1980s, named CBM. Based on the analysis of fault mechanisms and the results of a nondisassembly test, the CBM system will make adjustment, repair and replacement of the maintenance object when a ‘potential fault’ occurs, thus avoiding the occurrence of a ‘functional fault’ [34–37].

Traditional preventive maintenance methods commonly lead to unnecessary machine inspection. Through the CBM, the operation of key systems can be monitored in real time. Thus, potential wear or failure of moving parts can be identified during its development. The CBM is not based on time intervals but on the actual condition of the system [38], which is implemented by applying the use, diagnosis and prediction processes of monitoring systems and performed on health condition. Check and maintenance the system and contents of Shinkansen prescribe inspections of the traction system including motor, traction transformer, traction converter and coupling, while vehicle inspection mainly depends on human, the content of condition confirmation is relatively high and more operators are needed [39].

Caviglia and Magro [40] prolonged the service life of components thanks to the ability of CBM practice to detect early degradation of locomotives. In Ref. [41], a stochastic mathematical model was proposed to optimize and predict tamping operations in ballasted tracks based on condition-based preventive maintenance.

In order to fundamentally change the inspection system, flexibly use the data obtained from the equipment of the vehicle and the data of the vehicle conditions monitored by the ground equipment, and promote the research of maintenance [42–45], the Vehicle Data Analysis Centre, set up in July 2015, carried out the preventive preservation of active vehicle data and the inspection of vehicle data for Tokaido Shinkansen vehicles, and expanded its scope of application in turn. Owing to improved performance, lower cost of sensing technology and a shortage of experienced maintenance technicians, Shinkansen’s expectation of condition monitoring and preservation is gradually increasing, and a maintenance system combining the installation of sensors on vehicles to collect condition detection data and the regular inspection of the original data to carry out analysis and predict the aging trend is under development. In order to achieve the effective use of condition benchmark preservation of the vehicle condition data in CBM, in 2016, the Shinkansen CBM technology promotion project was set up. In July 2017, a new vehicle diagnosis centre was set up to construct a system for quantitative diagnosis of the soundness of vehicle machine parts. On the other hand, in order to further promote the flexible use of vehicle and maintenance data, ground equipment is being reformed and upgraded. The tablet terminal for the unified management of the vehicle and maintenance data and maintenance operation was introduced in 2019. Through the introduction of new maintenance methods using the latest technology, re-examination of the inspection system and optimization of the repairmen were implemented. Through re-examination of the maintenance operation and organizational system as defined, an effective operational implementation system was built. According to the on-site experience and technical judgement, a system to support appropriate line maintenance practices and optimize maintenance was built [46–49].

With the accumulated experience of maintenance technology, the improvement of component quality, the development of maintenance technology and the application of new technology, the maintenance standard of Shinkansen high-speed
vehicle has also improved, and the preventive function has developed into a more efficient and effective individual maintenance mode.

The main advantage of the CBM is that equipment problems can be detected and repaired early before failure. The CBM can be a turnkey solution provided by the manufacturer of the high-speed train traction system through the monitoring system, or a strategy implemented by the user focused on active measures.

### 4.3 Prediction and health management technology

Since the 1960s, in response to the increasing complexity of the environment and system in the aerospace field [50], the United States had to solve various problems in product development. With the development of fault detection and maintenance technology, the PHM was proposed, and quickly the United States as the representative of the Western military powers attached great importance to it. Through condition monitoring, fault detection and diagnosis, prediction, operation and maintenance optimization and other technical support, PHM predicts and manages the possible future risks of the system, reduces the cost of maintenance support and improves the operational readiness rate and task success rate, so that the machinery and equipment can run more safely and reliably. With the help of various intelligent algorithms and reasoning models, the running condition monitoring, prediction, discrimination and management of electric traction system components are realized, and fault detection and isolation are realized also. Finally, intelligent task planning and intelligent maintenance based on equipment conditions (past, present and future condition) are realized, replacing current postmaintenance and time-based periodic maintenance. The main functions of PHM technology are shown in Fig. 2 [51]. The PHM technology has become the key technology to ensure the operation of a high-speed train traction system and reduce the cost of the whole life cycle in the future.

The research is carried out on fault prediction and health management techniques in aviation equipment, rail transit and other fields at home and abroad [52–54]. Zhang et al. [55] proposed a wireless sensor network system to provide a test bench in order to advance PHM progress. Galar et al. [56] established a method based on data and a model to accurately identify any fault of the train equipment and the system health condition, so as to reduce the train life cycle cost (LCC). Ardakani et al. [57] set up the railway switch point transponder PHM strategy and technical framework, carrying out data analysis and assessing machine health condition by collecting current and voltage signals. Ref. [38], based on the application of PHM technology, proposed the maintenance framework for high-speed train traction power supply system (TPSS). The case studies illustrated how the implementation of the PHM system narrowed the gap between theoretical modelling and practical application of TPSS in fault detection, health diagnosis and maintenance decision. Ref. [58] applies PHM technology to the electric door system of a subway passenger car. Through big data statistics and analysis, fault mode and hazard analysis, scientific and reasonable organization and arrangement of vehicle maintenance procedures, early warning of failure, accurate fault maintenance and low operating cost are realized.

Nowadays, only the US maturely applies the PHM in aerospace and other fields. In other countries, the accuracy of practical models for the PHM engineering needs to be further improved, and successful application cases are few. The PHM needs the guarantee of physical basic conditions, massive data collection, big data analysis [53] and also intensive industry knowledge, experience, model and engineering implementation capability.

### 4.4 Summary

High-speed train operating conditions are complex, failures are various, the safety of train operation is of great responsibility, high-speed railway traction system maintenance stages and

![Fig. 2. Prognostic and health monitoring (PHM) technology and application scope.](https://academic.oup.com/tse/article/3/3/tdab017/6368635)
Table 5. Comparison of advantages and disadvantages of various maintenance technologies

| Maintenance technology | Advantage | Disadvantage |
|------------------------|-----------|--------------|
| RCM                    | The system is simple, and the maintenance content, maintenance type, maintenance interval and maintenance level are determined. | Overrepair and underrepair exist. |
| CBM                    | On the basis of equipment condition monitoring, the maintenance time and mode are arranged according to the results of monitoring, analysis and diagnosis. | Lack of health status and remaining life analysis. |
| PHM                    | It can realize fault prediction, health management and residual life assessment. | High technical requirements for components and systems, and the system needs to be improved. |

system face the issues of low efficiency and heavy load, among others; costs are high in repairing maintenance, there is a lot of waste in preventive maintenance as equipment is replaced when it operates fine; therefore, CBM is relatively better targeted and more accurate, but still has some limitations. The rapid development of high-speed railway puts forward higher requirements for the management of the traction power supply system for high-speed train vehicles. Ensuring the safety and reliability of traction power supply system and realizing health diagnosis, early fault warning and condition maintenance are the prerequisites for improving train maintenance efficiency, reducing labour intensity and ensuring the normal operation of high-speed trains. At present, the maintenance schedule of high-speed trains is mainly based on the RCM system and partly based on CBM [46, 59–60, 88]. With the development of sensor technology, big data, cloud computing, intelligent models and algorithm technology, high-speed trains are gradually developing towards state perception, state management, fault prediction, health monitoring and remaining life prediction, so as to achieve ‘accurate’ maintenance. This can effectively shorten the unscheduled stopping time of a train, reduce the maintenance cost, extend the service life of the traction system, and improve the availability and safety of equipment. The advantages and disadvantages of the above traction system maintenance technology are shown in Table 5.

5. Key maintenance technology of traction electrical system of high-speed train

At present, some key components (motor bearings, gearbox bearings) can be predicted by temperature changes in the electric traction system of the high-speed train. Maintenance of the electric traction system is mainly preventive, supplemented by a fault maintenance system, which can easily cause excessive and insufficient maintenance. This leads to an increase of maintenance cost and reduction of the utilization rate of high-speed trains because of the failure during two maintenance periods [61]. Based on the failure mechanism of critical components, this paper collects and analyses a large number of fault samples and field service data, carries out large sample fault reduction and accelerated life tests, and grasps the degradation law of component performance parameters, establishing the condition assessment and life prediction model, and finally realizing the CBM and health management of key components of traction electrical system.

5.1 Condition assessment technology for high-voltage components of traction electrical systems

Sensys and Lloyds Register have developed a line-side Automatic Pantograph Monitoring System (APMS), which does not require a physical attachment to the catenary; instead, it uses radar and laser sensors to assess the speed and location of a pantograph as it passes along the contact wire. High-definition cameras record images to allow a detailed examination on the condition of the carbon strip [62]. Two Alstom Pendolino trainsets of Virgin Trains on the UK’s West Coast Main Line have been fitted with monitoring equipment, and can identify faults in the overhead electrification while running in regular service. Accelerometers on the pantograph frame detect unusual impacts from defects, such as kinks, loose equipment or steps at contact wire joins. If any events are greater than the threshold values, the details are sent by Bluetooth to a receiver interfaced to the Train Management System, and this feeds an alarm to the Alstom Traintracer monitoring system [63].

In order to reduce the wear of pantograph and catenary, prolonging working time of the friction
pair and ensuring the quality of current collection, a new type of pantograph active control strategy is designed. The strategy is based on the theory of friction and wears with electric current, control theory and micro-control technology, and is characterized by the dynamic wear test of catenary and the contact force control [64].

Ning Zhou et al. [65] investigated some characteristics of different failure behaviours of the pantograph and catenary, and the influence of structural defects on the dynamical performance of the pantograph-catenary system. A pantograph-catenary monitoring system that includes sensor and data collection modules, positioning modules, data analysis and diagnosis modules, and display and data storage modules was established. Two specified faults were introduced to describe how to develop such a monitoring scheme based on pantograph condition-based recognition.

The reliability of a power transformer is strongly dependent on the condition of its oil and paper insulation. Recently, a considerable amount of work has been published on the dynamics of aging of oil-impregnated paper insulation in transformers. In order to test the insulation state of traction transformer, Zhou et al. [66] used a frequency-domain dielectric spectrum test to reflect the change of insulation state. By using a differential evolution algorithm and the quadratic interpolation method (CS-DQ algorithm), a diagnosis method of traction transformer insulation paper is proposed, which can effectively distinguish the insulation state. Ashkezari and Ma [67] developed an intelligent algorithm for automatically processing the data collected from oil tests and determining a health index for the transformer insulation system. Okabe [68] identified the degree of degradation of transformers, through managing the volume resistivity and dielectric loss tangent trends in electric terms, the interfacial tension trend in physical terms and the total acid value trend in chemical terms. He also proposed other effective methods of evaluating aging degradation by analysing the insulating oil components. Saha [69] applied pattern recognition techniques to determine a health index for the oil and paper insulation of a transformer, although it faced considerable challenges before becoming practical. Pradhan and Ramu [70] detailed the diagnostic testing and condition monitoring program to find and determine the most sensitive parameters that can serve as indices of aging, and hence as a reasonably accurate indicator of possible imminent failure of apparatus insulation in service. At present, the degradation degree of the traction transformer is still determined by the detection of transformer oil and insulating paper. In train operation, the normal operation of the traction transformer is mainly monitored by a winding short circuit, main circuit grounding and other faults. Transformer degradation diagnosis based on state and health management still needs to apply the theoretical research to the actual application process of existing vehicles.

5.2 Condition assessment technology for traction converter power module

The traction converter is composed of many electrical components, the most important of which is the power module, but the core of the power module is mainly the power semiconductor device Insulated Gate Bipolar Transistor (IGBT). For a high-speed train traction system, IGBT devices work long hours under nonstationary conditions, such as high temperature, high voltage and high current; therefore, the power fluctuates in real time with different operating conditions, such as train start-up, acceleration, high-speed operation and braking, and the fluctuation is often unpredictable, so IGBT is also the most easily failed electrical component. The IGBT fault accounts for more than 70% of the power module fault [71].

IGBT failures are mainly divided into defect failure (self-defect failure), random failure (open circuit, short circuit) and fatigue failure (performance deterioration) [72]. In addition to the inherent characteristics of the structure and material of the device, the failure is mainly due to the interaction of various factors, such as the accumulation of internal fatigue damage and the external operating environment. The failure modes are mainly thermomechanical stress failure and electrical stress failure. The thermal stress failure is mainly reflected in the welding layer crack, the welding layer cavity and the falling off and breaking of the bonding wire. The electrical stress failure is mainly overvoltage, overcurrent and overheat caused by voltage or current exceeding the allowable range.

At present, the fault diagnosis method for converter power module in China is mainly based on device parameter condition detection technology, system output waveform detection technology and residual life prediction technology based on condition detection.
Device parameter condition detection is widely used in IGBT power device modules and other fault detection, which has been widely studied and extensively applied. Failure of IGBT devices may be due to changes in saturation voltage drop, steady-state thermal resistance, gate signal or threshold voltage affecting the device parameters [73–78]. IGBT device parameters can shift when leaving the factory, or the error may increase with the use of time. Faulty devices can be eliminated by screening in the early stage, and the IGBT process quality assessment system can be established through the change of parameters. When combined with professional analysis tools and methods, the process quality assessment of the device and the device fault traceability analysis are realized [79, 80]. For practical application, the saturation voltage drop measurement of the device is simple and accurate, but it can be easily affected by the junction temperature and the current of the IGBT device. The steady-state thermal resistance can directly reflect the aging situation, but the junction temperature is not easy to measure. Gate signal measurement is not affected by the device operating state, but with high requirements for real-time measurement, and stray parameters affect the measurement accuracy.

System output waveform detection is mainly based on the subtle changes of the traction system output waveform to monitor the IGBT condition [81–83]. Ref. [81] monitored device operation status by reducing IGBT internal bonding wires to simulate bond wire shedding, and increasing thermal conductivity to simulate thermal resistance to increase monitoring output waveform. Ref. [82] used the corresponding fault waveform of fault simulation as the monitoring input, and fault as the output using the quantum neural network to identify the fault of IGBT modules autonomously.

Sobanski and Orlowska-Kowalska [84] addressed a IGBT single-switch open-circuit fault diagnosis of a two-level voltage source inverter in an induction motor drive system with the direct torque control strategy; the proposed fault diagnostic method has been proved by experimental tests [84].

Residual life prediction technology is based on condition detection. The life prediction models of power devices mainly include analytical and physical models [85]. The analytical model is based on coffin-mansion, Norris-Landzberg, Bayerer models or accelerated life test. The IGBT analytical model and model parameters are obtained by data statistics to calculate the lifetime of the device [85–87]. The physical model is based on the failure and deformation mechanisms of stress-strain damage and the fracture principle. The analytical life does not involve the failure mechanism of the device or the material and technology of the device, and the model parameters need to be modified and optimized through a large number of experiments. The analytical model can only predict new devices that have not yet been used. The physical model analyses and studies the failure mechanism of the device from different materials. It is necessary to understand the physical characteristics of the material and the design process of the device to predict its lifetime accurately.

In Ref. [88], based on the research of model analysis and a physical model, combined with a large number of field application data and accelerated life test data, the model was modified, the service degradation law of IGBT was mastered, and the IGBT lifetime prediction system was constructed. Through the research on the service performance degradation law of IGBT, the full life-cycle state assessment technology capability basing on IGBT port health factor was constructed. The early access of the health status assessment support product zero failure application.

Device junction temperature control and external thermal management based on condition monitoring is an important way to improve the reliability of power modules and power devices. At present, there are internal junction temperature control and external thermal management through switching frequency, modulation mode, drive waveform modulation, load current regulation, etc. The advantages and disadvantages of each state control technology are shown in Table 6 [89].

The power module is the core of the traction converter, which is also related to the operation reliability of traction system. Reliability evaluation and state evaluation of the power module of power devices have been carried out worldwide. Due to a comprehensive understanding of semiconductor chip design, manufacturing, packaging, power module and train system application in Western developed countries, the research on converter reliability is relatively mature. From failure mechanism to condition monitoring, from reliability evaluation to lifetime prediction, there are more sufficient studies. Domestic research on
Table 6. Comparison of power module state control technology

| Method                              | Advantage                                      | Disadvantage                                      |
|-------------------------------------|------------------------------------------------|--------------------------------------------------|
| Simple and fast dynamic response    | Limited adjustment range                       | Changeable output power                           |
| Method                              | Simple, obvious effect and fast dynamic         |                                                  |
| response                            | Limited adjustment range                       | Changeable output power                           |
| Fast dynamic response and little influence from load | Limited adjustment range complex control circuit |                                                  |
| Easy to realize, obvious effect     | Poor real-time and complex control             |                                                  |
| Obvious junction temperature fluctuation restraining | Slow dynamic response, increasing average junction temperature | |

power module fault diagnosis and packaging reliability has made some progress, but due to the late start, the research on lifetime prediction and condition monitoring needs to be further deepened and improved in China.

5.3 Condition assessment techniques for traction motors

5.3.1 Traction motor bearings. Bearing fault is the most important fault form of motor mechanical fault, which is often caused by the wear of components, installation error, load impact, electrical corrosion and so on, during the operation of the motor. It usually shows the damage to the bearing inner ring, outer ring, rolling body and cage. The current bearing fault diagnosis methods are mainly based on vibration signal, acoustic emission signal, acoustic signal, temperature signal, electrical signal [90–93] and so on, which use the time domain analysis method, frequency domain analysis method and time-frequency analysis method [94–96]. In this exploration process, resonance demodulation, empirical mode decomposition, wavelet transform, deep learning and other methods have been developed [97–100], which can effectively extract fault features and identify fault modes.

The shaft temperature detection method is widely used in the fault monitoring of motor bearings of EMUs. CRRC Zhuzhou Institute Co. and Waycom Technology Co. have already developed and applied the shaft temperature detection system in large quantities on high-speed trains. According to the fault mechanism of the bearing, the bearing failure will result in an abnormal temperature rise. The temperature monitoring system applies this principle and gives fault feedback by detecting whether the bearing temperature exceeds the safety threshold; when the anomaly bearing temperature is detected, the fault will be reported in time and the speed reduction protection will be implemented [101], so that appropriate measures can be taken by the crew. This method is suitable for fault detection with severe faults. It is insensitive to early faults and is a kind of 'post' fault detection method, which cannot effectively detect early faults. The failure rate of the temperature sensor itself is very high and it often gives false alarms, seriously affecting the normal traffic order.

A locomotive running part monitoring system, advanced truck defect diagnosis and record system (ATDR), is widely equipped in AC electric locomotives [102, 103] for condition monitoring of running parts (including motor bearing). TangZhi Science & Technology’s ATDR uses generalized resonance demodulation technology [104–108], which can be used for early fault diagnosis of motor bearings. The implementation process is shown in Fig. 3. The technology extracts the impact signal using a resonance demodulation method, carries the resonance demodulation transformation and separates the high-frequency fault information to carry on the diagnosis, then identifies the bearing fault, realizing the on-line monitoring and the early fault warning. This method needs to install a temperature vibration composite sensor and a speed sensor; it also needs to carry on additional equipment transformation of the locomotive, the installation and maintenance of the sensor is difficult and the sensor itself is easily affected by a harsh working environment, which will affect the diagnosis effect. A vibration method can be easily affected by the working environment, such as complex vibration spectrum, causing a false alarm.

Trackside acoustic detection system (TADS) (a vehicle rolling bearing fault track edge acoustic diagnosis system) is a widely used bearings detection technology on railway freight vehicle [109], the daily monitoring of vehicles can reach about 125 000. This method uses acoustic diagnosis technology and computer network technology to collect and analyse the noise signals of
locomotive bearings in operation through the sound acquisition array, to evaluate the working condition of bearings and to carry out early fault warning. The device is usually arranged on the locomotive running line, and the locomotive bearing parts are monitored in real time through the acoustic acquisition device on the rail edge. At present, the TADS system is seriously affected by noise, which leads to frequent false alarms and increases the workload of personnel doing the checks. Because the TADS system is statically installed next to the track, it is impossible to carry out on-line tracking and monitoring.

In order to solve the problems existing in the motor bearing diagnosis at this stage, a series of bearing fault simulation tests with different deterioration degrees under different fault modes were carried out. The industry pioneered a noninvasive traction motor bearing fault condition assessment technology based on the existing control signals of the converter. The accurate identification of a bearing fault and evaluation of its deterioration state are realized, and the blind test verification and on-site loading verification of a certain EMUs are carried out, as shown in Figs. 4 and 5. At present, this method has been applied to locomotives, EMUs and urban rail transit, and has played a positive role. For example, in May 2019, the early warning of bearing failure at the nondrive end of a traction motor of an EMU was successfully given, and timely warning was given, as shown in Fig. 6.

5.3.2 Traction motor insulation. The insulation fault of a traction motor is the phenomenon where the insulation structure is aging and the insulation performance decreases gradually during the long-term operation of the motor, which is subjected to the comprehensive action of electrical, magnetic, thermal and mechanical shocks. Stator insulation fault is the most common electrical fault, which usually manifests as the insulation fault between strands, turns and layers of stator windings. In view of stator insulation failure, academic circles have carried out extensive and in-depth research, and the detection methods are mainly divided into two categories: on-line and off-line [110–112]. On-line detection methods mainly include stator insulation fault detection based on electrical, magnetic and temperature signals, among which the detection method based on electrical signal is the main research direction. The off-line detection evaluates the motor
stator insulation condition through periodic preventive off-line tests, including insulation resistance, winding DC resistance, ground insulation withstand voltage, interturn withstand voltage, polarization index and absorption ratio. Detailed typical methods and characteristics of motor stator insulation fault detection are shown in Table 7 [113–120].

Germany’s ICE high-speed train initially adopted the power concentration type, and the ICE3 in operation in 2,000 were power-dispersive type, the traction equipments were distributed along the train and installed under the bottom plate of the vehicle body. ICE high-speed train vehicle maintenance system implements regular inspection, maintenance and condition. The early ICE1 and ICE2 high-speed trains used a five-stage maintenance system including L, N, F1, F2 and overhaul maintenance [21–23]. With the research and optimization of maintenance technology, ICE3 adopted the maintenance approach by combining parts exchange maintenance and main parts centralized maintenance, which is divided into three categories, A–C. Category A is mainly responsible for daily operation inspection and error inspection of main components, category B is responsible for low or small maintenance of EMUs and temporary repair; category C is responsible for advanced or extensive maintenance of EMUs. The specific maintenance schedule is shown in Table 8.

In the application of rail transit engineering, the stator insulation fault detection is mainly...
Table 7. Typical methods and characteristics of motor stator insulation fault detection

| Mode of detection | Monitoring signal | Method | Characteristic |
|-------------------|-------------------|--------|---------------|
| On-line | Electrical signal | Symmetry component analysis of Park transformation, Fast Fourier transform | Simple and easy to handle, but vulnerable to inherent asymmetric interference |
|        |        | Wavelet transform | Analysis of signal frequency components and affected by changes in speed load |
|        |        | Neural network/supporting vector machine | It is suitable for variable speed load and needs to select suitable wavelet basis function |
|        | Magnetic signal | External magnetic flux leakage field, Internal air gap magnetic field | Noninvasive, weak signal, easily disturbed |
|        | Temperature signal | Threshold method | Invasive, need to change motor structure |
| Off-line | — | Insulation resistance, DC resistance of winding, withstand voltage to ground insulation, interturn withstand voltage, polarization index, absorption ratio | Ex-post detection, depending on the location of the temperature measuring point |

Table 8. The maintenance schedule of Germany's ICE EMUs

| Type | Item | Mileage/km | Maintenance content |
|------|------|------------|---------------------|
| A    | L grade inspection | 2 700 | Inspection and diagnosis of wheel-pair and running device, vehicle cleaning |
| A    | N grade inspection | 20 000 | Maintenance of brake system, communication system, anti-skid |
| B    | ISS10 grade inspection | 60 000 | Maintenance of brake system, air conditioning, kitchen, seat, battery, etc |
| B    | ISS20 grade inspection | 120 000 | Maintenance of traction motor, wheel-pair bearing, axle box bearing, etc |
| B    | ISS30 grade inspection | 240 000 | Maintenance of air compressor, traction transformer cooling system |
| B    | ISS40 grade inspection | 480 000 | Maintenance of vehicles |
| C    | Rev grade extensive maintenance | 1 200 000 | Vehicle body inspection and maintenance (factory maintenance) |

Carried out by on-line temperature monitoring, grounding detection and off-line insulation detection. For on-line temperature monitoring, the abnormal change of coil temperature during insulation failure of motor stator is used as an assessment index [121], but the temperature measuring points arranged in practical application are limited, so it is difficult for this monitoring method to play an effective role. Grounding detection uses the difference between the intermediate voltage and the half voltage of the traction system to detect the grounding fault. When the difference is greater than the preset threshold, it is considered that the traction system has a grounding fault, which triggers grounding protection. This method is widely used in the field of rail transit grounding fault on-line detection: many institutes or companies, such as the China Academy of Railway Sciences, CRRC Zhuzhou Institute Co. and Yongji Motor and Electric Equipment Company Co. and other units adopt this method. However, this method can only play a protective role when the motor insulation fault develops to grounding, and cannot realize the early warning of the motor stator insulation fault.

Stator insulation off-line detection is a common maintenance method in the rail transit field. Generally, during the maintenance of the traction motor, preventive off-line testing is carried out to evaluate the insulation condition of the motor stator [122]. The main contents include: partial discharge test of motor stator winding; insulation resistance test of motor stator winding to ground; polarization index test of motor stator winding; interturn insulation test of motor stator winding [123–125]. The off-line detection method of motor stator insulation fault is relatively perfect. At present, it is widely used in the daily maintenance operation of the train station and locomotive depot, but this method is time-consuming and the labour cost is high and it cannot realize on-line insulation fault monitoring during traction motor operation.

Based on the multifeature fusion theory and machine learning, Ref. [126] proposed a new electrical signal diagnosis method, realized fault detection and identification through nonimmersion on-line monitoring and diagnosis method and machine learning method, and carried out
a series of traction motor insulation fault simulation experiments. The test is shown in Fig. 7, so as to realize on-line condition monitoring and fault early warning of a high-speed train traction system. For the first time in the industry, the interturn short circuit state assessment technology of a traction motor based on electrical signal has been proposed, which has overcome the technical problem of on-line identification of early insulation deterioration of motor. The technology has been applied to CR EMUs and a metro line in batch, and played a positive role. For example, in January 2020, the interturn insulation fault of traction motor of 04 EMU of a high-speed train was successfully warned. It was about 40 minutes earlier than the grounding fault alarm, as shown in Fig. 8.

6. Conclusions and outlook

The traction system is the key component of the train, and it is also the most reliable component in the current train equipment. The reliability of the traction system is related to the normal operation of the train. At present, the maintenance technology and application research of traction system key components have been carried out at home and abroad, from the early reliability-centred maintenance to the current condition-based maintenance, and fault prediction and health management technology. In summary, with the development of foreign high-speed railways for decades, the traction system components have been fully studied from aspects of design, operation, maintenance, reliability and service life, and a relatively mature condition-based maintenance technology system and management mode have been formed, which greatly reduces the maintenance cost of the whole train life cycle. At present, the world’s largest high-speed railway transportation network has been formed through stages of introduction, digestion, absorption and re-innovation in China. The train traction system has been completely independent from scratch. The research on reliability evaluation, lifetime prediction and condition monitoring of traction system needs to be further deepened and improved. The research results and development trends at home and abroad are summarized as follows.

(1) The cost of train life-cycle maintenance needs to be further reduced. In the current modes of planned maintenance and fault maintenance, due to the lack of monitoring information on vehicle operation status and the ability of real-time fault early warning and prediction, the ability of safety assurance is insufficient. The replacement of parts in planned maintenance leads to the waste of transitional maintenance, and the lack of fault early warning ability leads to the...
failure of timely maintenance. The whole life-cycle maintenance cost of the whole train is more than twice the price when the vehicle is purchased.

(2) Transformation of maintenance technology. With the development of high-speed train technology, the current mode based on planned maintenance and fault maintenance cannot meet the needs of current high-speed train operation. It is urgent to bring changes to vehicle maintenance technology through the application of new technology. The maintenance mode changes from traditional fault maintenance and planned maintenance to condition-based maintenance, so as to effectively reduce the failure rate and improve train safety and maintenance level, reduce the inventory of spare parts, reduce human cost and reduce maintenance costs.

(3) Realization of state maintenance and precise maintenance. The future maintenance of the traction system of high-speed trains mainly focuses on the maintenance work based on maintenance plan and existing faults, optimization of maintenance strategy and realization of status assessment and life prediction combined with fault mechanism and big data analysis, and state maintenance to achieve accurate maintenance and cost reduction.

(4) Establish a comprehensive intelligent operation and maintenance system. Through more comprehensive condition detection, more early fault detection and more accurate diagnosis and prediction, the optimal maintenance strategy and maintenance business are determined, and the comprehensive intelligent operation and maintenance system of train multidisciplinary intelligent operation and maintenance are realized.

Conflict of interest statement
None declared.

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