CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 198

Application of PHM Technology in High-altitude Locomotives

Controls, Automation, Measurement, Monitoring & Predictive Maintenance

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ABSTRACT

The plateau region is characterized by high altitude, low latitude, perilous mountain beaches, rugged terrain, harsh climate, and fragile environment. This imposes extremely high demands on the traction performance, braking performance, durability, and reliability of transport vehicles. Due to its vast area and sparse population, along with a wide range of application fields, the pressure and cost of subsequent maintenance are significantly higher than in plains. PHM, as a comprehensive technology that can enhance system stability, reduce operational costs, and improve economic benefits, has very good prospects in most engineering disciplines. Therefore, utilizing PHM technology to achieve intelligent diagnostic analysis, guide operation and maintenance, and support reliability analysis throughout the entire lifecycle of locomotives is of great significance. Combining the pilot application of PHM in plateau diesel locomotives, the technical system and key technologies of diesel locomotive PHM are summarized from aspects such as demand analysis, overall architecture, physical architecture, functional architecture, and logical architecture.

The overall architecture topology of PHM is divided into five parts: system physical layer, perception layer, data processing layer, tools and functional layer, and application layer. The physical architecture of the PHM system consists of four parts: sensors, data acquisition units, main control units, and operational display terminals. The functional architecture of the PHM system includes major functional modules such as data collection and transmission, data processing, status monitoring, fault prediction, maintenance decision-making, health status assessment, and visualization. It can achieve functions such as status assessment, diagnostic analysis, trend analysis, operation and maintenance, fault dictionary, and report inquiry. The logical architecture of the PHM system is based on the long-term accumulation of data such as state parameters and application information, intelligently cleaning and filtering the data, and defining the state through threshold settings and data processing algorithms.

The pilot application of the PHM system in plateau locomotives focuses on core large components such as diesel engines and locomotive auxiliary systems, exploring the mechanisms of diesel engines, algorithm models, and health diagnosis mechanisms. Based on the frequency of component failures, the severity of component failure risks, and the feasibility at the technical level, the oil system, cooling water system, boost system, exhaust system, auxiliary system, power station, turbocharger, fuel pump, and injector are selected as research objects to construct a diesel engine fault tree model. According to the application data and conditions of plateau locomotives, intelligent PHM technology can provide assurance for fault identification and management as well as maintenance planning.

1 INTRODUCTION

The Qinghai-Tibet Plateau in China, characterized by its high altitude, low latitude, steep mountains, and treacherous terrain, poses significant challenges due to its harsh climate and fragile environment. These factors necessitate stringent requirements for the traction performance, braking performance, durability, and reliability of transportation vehicles. Consequently, the HXN3 plateau diesel locomotive has been developed. This diesel locomotive is specifically designed for passenger and freight transportation on trunk lines in high-altitude and frigid regions. Its technical features, performance applications, and enhancements play a pivotal role in the development of railway transportation in western China. However, the vast and sparsely populated terrain, coupled with the extensive operational span, significantly increases the pressure and cost of subsequent maintenance compared to the plains. PHM (Prognostics and Health Management) is a health management technology that utilizes advanced sensor integration, fault mechanisms, and data-driven algorithms and models to facilitate state evaluation, fault prediction, and diagnostic analysis [1]. As a comprehensive technology capable of enhancing system stability, reducing operational costs, and boosting economic efficiency, it holds great significance in enabling intelligent diagnostic analysis, guiding operation and maintenance, and supporting the whole-life reliability analysis of locomotives on the plateau.

2 PHM TECHNOLOGY OVERVIEW

2.1 PHM Concept

The PHM development process can be broadly categorized into five stages: reliability analysis, fault analysis and prediction, integrated diagnosis and system monitoring, integrated system fault prediction, and health management [2]. The PHM system encompasses key business processes such as status monitoring, fault isolation, performance evaluation, performance prediction, and maintenance decision support.

2.2 PHM Development

PHM Development In recent years, PHM has increasingly been applied across various industries, including shipping, electrical, medical devices, and rail transit. The advancement of modern information technologies in the 21st century, such as testing technology, signal processing, data analysis, and artificial intelligence, has created favorable conditions for the application of PHM technology. Consequently, PHM has emerged as a core technology with broad prospects for both military and civilian use, aiming to enhance the reliability, maintainability, testability, and safety of complex systems, as well as reduce life cycle costs. It is widely applied in various fields [3].

3 CURRENT STATUS AND DEMAND ANALYSIS OF LOCOMOTIVE OPERATIONS ON PLATEAUS

The HXN3 plateau locomotive is utilized in the hub areas of Golmud, Lhasa, and Xining, primarily handling passenger and freight transportation on the main lines of the Golmud Section of the Qinghai-Tibet Railway, the Lari Railway, and the Lalin Railway. Additionally, it is tasked with traction of small-scale transfer trains along the Ning-Dalian Railway, the Shuanghuang Railway, and around Xining. However, due to the harsh environmental conditions of the plateau, such as low air pressure, significant temperature variations, tunnels, and long, steep slopes, there are increased potential safety hazards associated with the components during operation. Currently, regular maintenance and bulk replacements are employed to address this issue, requiring significant investments in manpower, materials, and financial resources to ensure reliable locomotive operations. Nevertheless, traditional preventive maintenance methods are increasingly demonstrating shortcomings and drawbacks. On one hand, the current regular maintenance model relies on mechanical wear theory, determining repair timing based on the failure starting point of the mechanical failure rate curve, which can easily lead to issues such as neglect of maintenance and over-maintenance. On the other hand, the plateau region is vast and sparsely populated, with weak rescue capabilities, making maintenance and rescue operations extremely inconvenient. This results in high operational and maintenance costs, as well as poor timeliness in fault handling. Therefore, it is urgent for us to enhance operational and maintenance efficiency, reduce costs, and ensure the reliability and uptime of locomotives.

Engineering application technology analysis indicates that PHM technology can predict and manage potential future risks in systems, reduce maintenance support costs, enhance mission efficiency, and ensure safer and more reliable operation of machinery and equipment. Based on the fundamental theory, system architecture, and related key technologies of PHM, guided by the issues of product neglect and over-maintenance in traditional locomotive maintenance management, and starting from the rail transit equipment industry's demand for proactive maintenance and health management of locomotives, a PHM system design scheme is proposed with the high-altitude locomotive as the application background. The ultimate goal is to enhance data monitoring and intelligent diagnostic capabilities to aid maintenance.

4 PHM FRAME DESIGN OF HIGH-PLACE LOCOMOTIVE

4.1 Overall structure

The overall architecture topology of PHM is divided into five parts: system physical layer, sensing layer, data processing layer, tool and function layer, and application layer. The system physical layer determines the research object, its physical structure tree BOM diagram, and FMEA decomposition. The sensing layer provides reliable data monitoring through data acquisition. The data processing layer processes data through various methods such as data receiving, storage, cleaning, and pretreatment [4]. Combined with segmentation, feature extraction, association analysis, machine learning, and other methods, software such as R engine, Python, Matlab, and Spark are used to carry out FTA analysis, early warning rules, mechanism models, and algorithm model implementations. Ultimately, this achieves functions such as status monitoring, status early warning, fault diagnosis, statistical analysis, maintenance strategy, fault prediction, health evaluation, and data visualization, as shown in Figure 1.

Figure 1. Overall architecture of PHM

4.2 Physical Architecture

Considering the impact of insufficient ground technical support due to long-distance cross-bureau traffic, PHM technology employs a vehicle-mounted approach for plateau locomotives to ensure timely fault prediction and health management. The design principle of the vehicle-mounted PHM system emphasizes separation from the locomotive control system, refraining from participating in decisions such as locomotive speed regulation and safety protection, while enabling universal portability. The physical architecture of the PHM system, depicted in Figure 2, comprises sensors, a data acquisition unit, a master control unit, and an operation display terminal. The locomotive is equipped with high-precision sensors that are resistant to interference and vibration, providing precise status data such as temperature and pressure. These sensors are connected to the data acquisition unit via a wire harness, enabling rapid signal processing and transmission to the master control unit, which is a high-performance industrial control computer equipped with communication, database, and AI service modules. The communication module responds to the connection and database status of each PHM unit, while the database module stores and transmits data. The AI service module handles data cleaning, feature extraction, correlation analysis, machine learning, and other processes. The operation display terminal allows for real-time monitoring of parameter status and facilitates visual human-computer interaction.

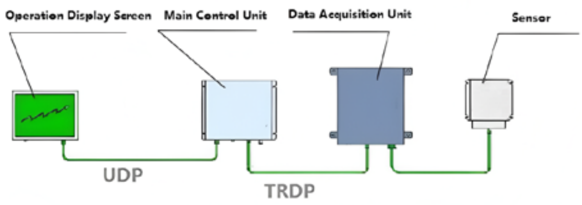

Figure 2. PHM Physical Architecture Model

4.3 Function Architecture

The PHM system's functional architecture comprises key modules such as data acquisition and transmission, data processing, condition monitoring, fault prediction, maintenance decision-making, health state assessment, and visualization. These modules enable functions like condition assessment, diagnostic analysis, trend analysis, operation and maintenance, fault dictionary, and report query, as illustrated in Figure 3. The PHM system's functionalities are realized through four software programs: the system program, computing program, back-end data interface program, and front-end display program. The system program offers a reliable operational environment, while the computing program handles data acquisition and transmission, edge intelligence, and fault warning. Data acquisition includes communication debugging and monitoring, allowing for acquisition and measurement configurations for the collected data. Edge intelligence encompasses core PHM functions. Its methods for data segmentation, preprocessing, feature extraction, and AI application provide rule-based early warnings, life-cycle statistics, and out-of-limit alarms, enabling intelligent fault handling. Fault early warning involves functional output, providing early warnings and fault time feedback for health assessment and fault prediction. The back-end interface program utilizes the Node.js runtime environment to offer a flexible data interface. The front-end display employs the VUE architecture to provide a human-computer interaction interface.

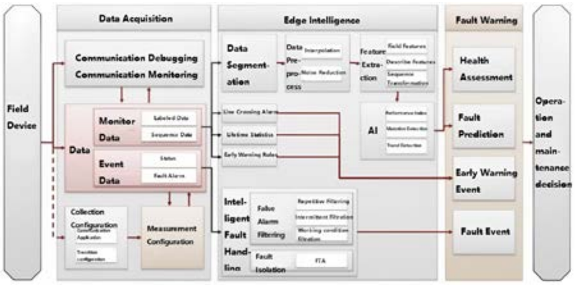

Figure 3. PHM System Functional Architecture Diagram

4.4 Logical Architecture

Based on long-term accumulated state parameters, operational information, and other data, the PHM system intelligently cleans and filters the data. Threshold setting and data processing algorithms can be utilized for state definition, as illustrated in Fig. 4. By integrating the FTA fault analysis model, logical coherence is achieved, and an algorithm model with learning capabilities is established to extract fault symptom information. Based on the operation and maintenance decision model, timely and reliable operational and maintenance suggestions are provided, ultimately leading to the generation of state and fault diagnosis reports to aid in maintenance. The failure mechanism model is a complex system built upon parameter fusion diagnosis and fault tree analysis methods. The data-driven model consists of trend analysis and statistical calculations, specifically utilized for failure prediction and lifespan estimation.

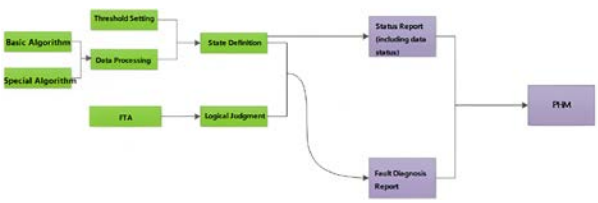

Figure 4. PHM System Logic Architecture

5 APPLICATION EFFECT OF PHM FOR PLATEAU LOCOMOTIVE

The pilot application of the PHM system on the HXN3 plateau locomotive uses the core large components, namely the diesel engine and locomotive auxiliary system, as initial examples to explore the diesel engine's mechanism, algorithm models, and health diagnosis mechanisms. Based on the frequency of component faults, their hazard levels, and technical feasibility, we selected the engine oil system, cooling water system, supercharging system, exhaust system, auxiliary system, power unit, supercharger, fuel injection pump, and injector as the research objects to construct a diesel engine fault tree model. A fault tree is a graphical representation of logical cause-and-effect relationships composed of various events and logic gates, enabling the direct identification of the underlying causes of faults [5]. Given that diesel engines are complex power machinery, their diagnostic parameters corresponding to fault modes may result in a combinatorial explosion problem. Therefore, we employ a multi-parameter fusion diagnosis method to identify the root cause of faults. The PHM system performs preprocessing on raw data, including data cleaning, interpolation, smoothing, and noise reduction, followed by feature extraction and data screening, to provide high-quality data for performance modeling. We have established a deductive failure analysis method for each parameter, moving from alarm to cause, describing the system's alarms, fault causes, and the relationship between alarms and various fault causes in a tree structure diagram. This detailed reasoning analysis process aids in assessing whether system state indicators are normal. Ultimately, a state and fault diagnosis report is generated to guide operation and maintenance.

As shown in Fig. 5, taking the oil system as an example, during the operation of HXN3 plateau locomotive, the faults with low frequency and great influence include insufficient oil volume, oil dilution, blocking of oil filter, leakage of oil pipeline, poor operation of oil pump, poor operation of relief valve, poor oil cooling, poor lubrication of supercharger, etc. For the above faults, abnormal identification can be realized by combining such parameters as engine oil inlet pressure, engine oil inlet temperature, supercharger engine oil inlet pressure and engine oil pump outlet pressure. Each operating parameter has mutual influence, so FTA model shall be established for each parameter. Take the inlet pressure of engine oil as an example. When the inlet pressure of engine oil is abnormal, it will directly cause the power reduction or emergency stop of locomotive. The causes may be from the three subsystems of engine oil system, electrical system and auxiliary system. Therefore, this parameter will appear in multiple fault trees. However, different system faults have different severity levels and different fault handling timeliness. For example, in case of communication loss fault in the electrical system, which causes the transmission failure of the oil inlet pressure signal, it can be handled by power-off and reset in time. However, in case of poor operation of the oil pump or insufficient oil volume, the problem can only be solved by the return section and cannot be solved online in time. Therefore, in order to find out the fault cause in time and handle it quickly, PHM system is required to conduct comprehensive model research and judgment, and combine with multi-parameter fusion algorithm to finally obtain the fault identification result. Based on the diesel engine mechanism and years of maintenance experience, it is necessary to diagnose the outlet pressure, oil temperature and high temperature water temperature parameters of the oil pump when determining the cause of the inlet pressure failure.

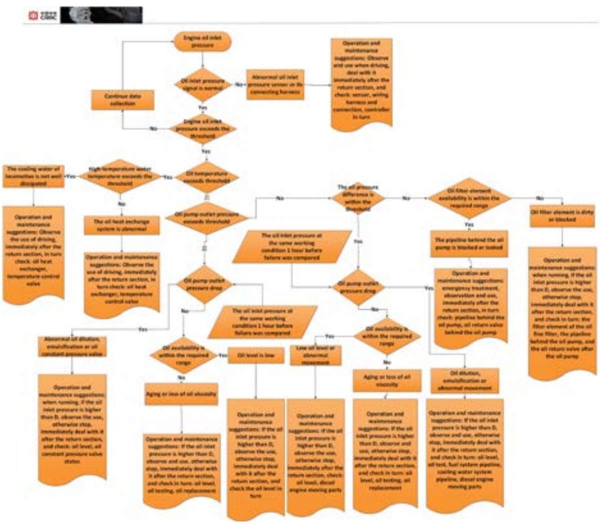

Figure 5. Oil Inlet Pressure FTA Model

When the oil inlet pressure exceeds the threshold range, first judge whether the sensor and its harness are abnormal, i.e. whether the electrical system is normal. If the electrical system is normal, it is considered that the oil inlet pressure is valid operating data, and the abnormality is caused by the diesel engine oil system or the locomotive auxiliary system. Then judge whether the oil temperature and high temperature water temperature are too high. If both are too high, it is considered that the fault is caused by poor cooling of cooling water. If only the engine oil temperature is high and the high temperature water temperature is normal, it is considered that the engine oil heat exchange system is poor. However, if both temperatures are normal, it is necessary to judge whether the outlet pressure of the oil pump exceeds the range. If the outlet pressure of the oil pump also exceeds the normal threshold range, it is necessary to judge whether the outlet pressure of the oil pump is caused by the sudden drop. If there is a sudden drop, it is considered that the oil dilution, emulsification or the constant pressure valve of the oil are abnormal, otherwise, it is considered that the oil level is abnormal, the oil product of the oil drops or the oil pump is abnormal. If the outlet pressure of the oil pump is normal, it is necessary to judge whether the inlet pressure of the oil has sudden drop abnormality. If there is, it is considered that the pipeline leaks or the motion pair is abnormal. If there is no abnormality, it is considered that the oil level is low, the oil product drops or the oil filter element is blocked. Through the above logic diagnosis process, the root cause of abnormal oil inlet pressure can be obtained, and corresponding operation and maintenance suggestions can be provided according to the fault source, so as to realize the complete closed-loop of state evaluation, fault diagnosis and maintenance strategy.

The PHM design applied to HXN3 plateau locomotive comprehensively considers the technical realizability, cost and value relationship, and selects 43 sensing data for processing and logical judgment. PHM technology includes 83 state levels, 69 sets of integrated diagnosis logic, comprehensive examination of locomotive operation health status, and timely response and diagnosis of abnormal conditions. The PHM system feeds back the fault information for many times during the operation process, including speed sensor fault, abnormal fuel pressure, branch pipe exhaust temperature weakening, etc. Combined with the maintenance strategy to eliminate the fault, it does not affect the train operation, and reduces the false alarm of locomotive and the risk of mechanical failure. PHM system automatically generates status diagnosis report every day, obtains locomotive health indexes in time, carries out targeted maintenance, reduces workload of service group personnel, effectively avoids insufficient maintenance and excessive maintenance, improves locomotive operation and maintenance efficiency and attendance rate, and reduces operation cost.

6 CONCLUSIONS

As the application extension and extension of locomotive operation and maintenance system, PHM system realizes the integration of state evaluation, fault diagnosis and operation&maintenance strategy. Taking HXN3 plateau locomotive as application background, combined with relevant theoretical system of fault prediction and health management technology, the overall architecture, physical architecture, functional architecture and logical architecture of

PHM system for diesel locomotive are proposed. Based on the application of plateau locomotive, the intelligent PHM technology has been able to provide guarantee for identification and management of fault occurrence, planning and maintenance, and support for improving the reliability of diesel locomotive.

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