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Overview of Key Technological Innovations in the New Generation of Intelligent Heavy-Haul Electric Locomotives

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Abstract

In order to better meet the demand for 20000-ton heavy-haul freight transportation on the Shuohuang Railway, key technology research and prototype development of a new generation of intelligent heavy-haul electric locomotives have been carried out. This paper mainly presents the main performance parameters of the locomotive, focusing on seven technological innovations including new generation electric transmission technology, heavy-haul direct drive bogies, cooling technology, and intelligent technology. The breakthrough of key technologies and the application of new systems in the new generation of intelligent heavy-haul electric locomotives have promoted the comprehensive improvement of key performance of heavy-haul electric locomotives, achieving the goal of intelligent, efficient, green, and safe operation of locomotives.

Keywords: heavy-haul electric locomotive, intelligence, technological innovation, integrated cooling, direct drive bogie, 20000-ton heavy-haul freight transportation

1 Introduction

The Shuohuang Railway is a major corridor for China's "West-to-East Coal Transportation" strategy. With a total length of 594 km, it currently has an annual transport capacity of 350 million tons[1], playing a vital role in ensuring national energy supply. To better adapt to the operational needs of 20,000-ton heavy-haul freight trains on the Shuohuang line, the company has focused on intelligent heavy-haul railway transportation innovation. Aiming for higher efficiency, intelligence, green performance, and safety[2], it has actively explored the development of new intelligent heavy-haul rail equipment and technologies. A new generation of intelligent heavy-haul electric locomotives with generational characteristics is currently under development, with the goal of establishing a new technological benchmark and platform for future heavy-haul electric locomotives.

2 Main Performance Parameters of the Locomotive

The new intelligent heavy-haul electric locomotive is the world's most powerful permanent magnet direct-drive heavy-haul electric locomotive, jointly developed by Guoneng Shuohuang Railway Company (leading the project) and CRRC Zhuzhou Locomotive Co., Ltd., among other organizations. Based on the principles of standardization, modularization and platformization, and with the overall design objectives of "high efficiency, intelligence, environmental friendliness and safety," the locomotive achieves a comprehensive performance enhancement through the adoption of new-generation electric drive technologies represented by permanent magnet direct-drive, silicon carbide (SiC) converter technology and integrated cooling systems, as well as intelligent technologies such as Time-Sensitive Networking (TSN), intelligent driving, and intelligent operation and maintenance.

The traction and braking characteristic curves are shown in Figure 1. A comparison of key technical indicators with existing eight-axle locomotives is presented in Table 1.

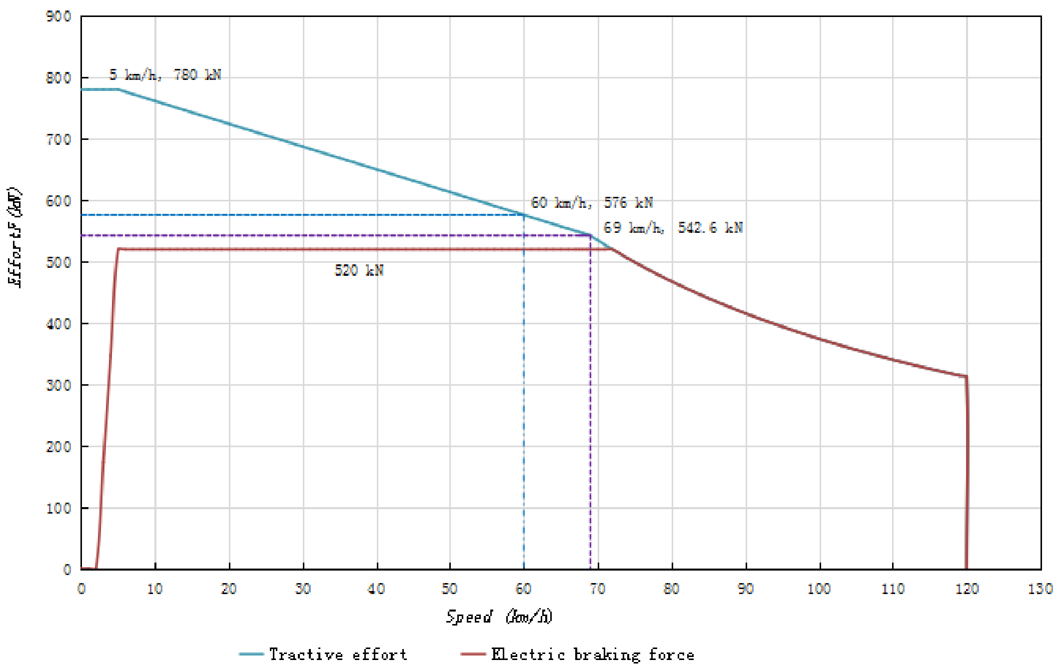


Figure 1: Traction braking characteristic curve.

3 Key Technological Innovation

3.1 New-Generation Electric Drive Technology

The new locomotive adopts a new-generation electric drive system featuring lightweight transformers, high-power SiC-based converters, and fully sealed water-cooled permanent magnet direct-drive traction motors. As SiC devices offer higher voltage ratings, lower power losses, better thermal performance and higher switching frequencies[3]. A system-level matching technology based on kHz-level switching frequency has been developed, enabling miniaturization, lightweight design, environmental friendliness, and high efficiency. Compared to traditional silicon-based systems, SiC converters increase power density by over 25%, reduce harmonics by more than 60%, improve traction efficiency by 1%, and auxiliary efficiency by 2%. The prototype is shown in Figure 2.

Parameter	Guoneng 8-Axle Locomotive	New Intelligent Heavy-Haul Locomotive	Remarks
Axle arrangement	2(B0-B0)	2(B0-B0)	
Max operating speed (km/h)	120	120	
Axle load (t)	25	25	
Starting tractive effort (kN)	760	780	Single-axis starting traction increased by 2.63%
Continuous speed (km/h)	65	60	Continuous application range expanded by 5 km/h
Continuous tractive effort (kN)	532	576	Single-axis continuous traction force s increased by 8.27%
Electric braking force (kN)	461	520	Single-axis electric braking force increased by 12.80%
Max wheel-rim power (kW)	9600	10 400	Single-axis power increased by 100 kW
Efficiency	85%	90%	Increase by 5 percentage points

Table 1: Comparison of Key Technical Parameter.

Through systematic research on key technologies such as high torque-density design, electromagnetic topology, integrated thermal management and direct-drive mechanical architecture, a fully enclosed, multi-pole permanent-magnet direct-drive

(PMDD) traction motor with record-specific torque density has been realized for the first time.

Figure 2: Silicon carbide traction converter and high-frequency auxiliary converter.

The thermal-management challenges inherent to high torque-density PMDD machines operating at high protection levels have been solved; the physical prototype is shown in Figure 3. Overall design targets: specific torque density ≥ 15 N·m kg^{-1}, protection rating ≥ IP 55, average winding temperature rise ≤ 150 K, efficiency ≥ 0.96. Low-speed, high-torque insulated-bearing module: calculated bearing life ≥ 2 million km. Prototype performance: continuous output power ≥ 1300 kW, starting torque ≥ 60000 N·m, rated torque ≥ 43000 N·m.

Figure 3: Permanent magnet direct drive traction motor.

3.2 Heavy-Haul Direct-Drive Bogie Technology

The new-generation intelligent heavy-haul electric locomotive is equipped with a direct-drive bogie—the world's first 27 t axle-load direct-drive bogie certified for high-power heavy-haul freight service (Figure 4). A disc-type diaphragm coupling transmits torque directly from the permanent-magnet motor, eliminating the conventional gearbox and its associated efficiency losses while eradicating chronic gearbox failures such as oil leakage, pinion-shaft fracture, and bolt loosening. The drive unit is elastically suspended under the frame, cutting unsprung mass by 30% and yielding lower wheel-rail dynamic loads and extended wheel and drive-train life. Moreover, compared with traditional gearbox bogies, the major-overhaul interval for the drive line is doubled from 1.2 million km to 2.4 million km, and maintenance access is significantly simplified.

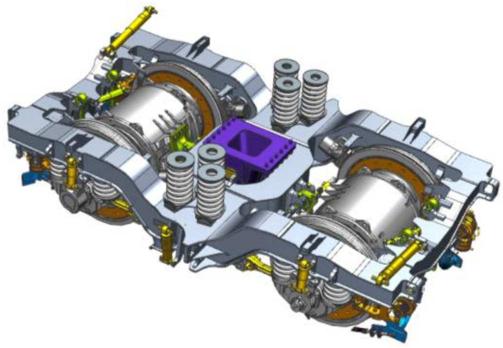


Figure 4: Direct drive bogie.

3.3 Cooling Technology Innovation

By exploiting the outlet-temperature gradient of the cooling media for the traction converter, traction motor, and traction transformer, this project has developed an integrated cooling system that combines the heat-rejection functions of all major electro-mechanical components. The resulting system-level architecture is illustrated in Figure 5.

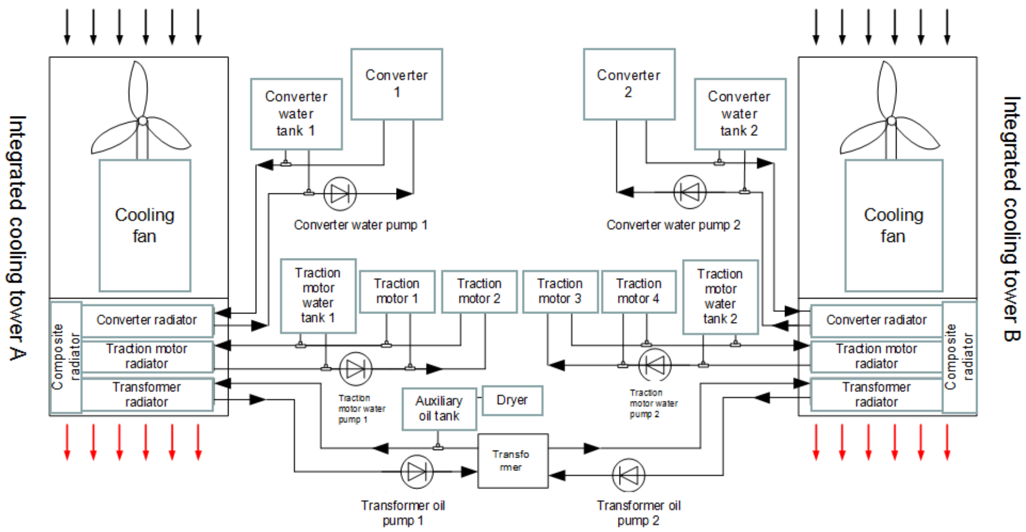


Figure 5: Schematic diagram of the integrated cooling system.

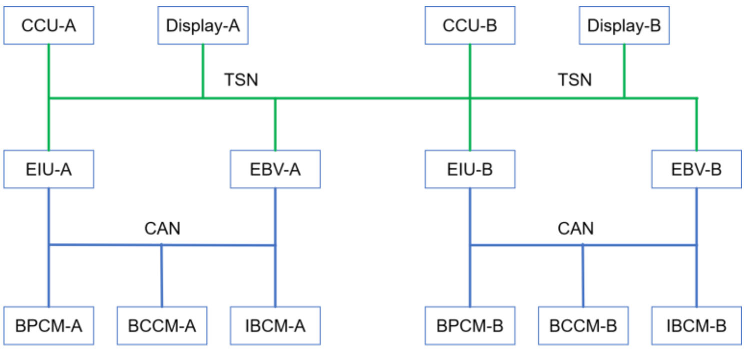
3.4 Driver Cab Technology Innovation

The cab of the new-generation intelligent heavy-haul electric locomotive is equipped with AI-based human–machine interaction capabilities, including video playback, voice alarms, face recognition, voice control, behavior recognition, and a head-up display. These functions satisfy the driver's operational needs under complex conditions and enhance both convenience and safety. An intelligent centralized controller governs the HVAC, heated floor, foot-warmer and knee-warmer units, creating a comfortable working environment. The cab layout and hardware have been optimized and integrated; an innovative single display combines traction, braking, and monitoring screens to ensure uninterrupted information flow and coordinated operation of the entire digital-intelligence system, providing robust support for safe and efficient locomotive operation. The new-generation intelligent cab is shown in Figure 6.

Figure 6: The new generation of intelligent driver's cab.

3.5 Braking System Redundancy Technology

To satisfy the operational requirements of 20 000 t long-combined heavy-haul trains and sustained downhill grades, the new-generation intelligent heavy-haul electric locomotive implements a fully redundant braking-control architecture based on the DK-3 brake valve[4], encompassing both system-level and module-level redundancy; the network topology is shown in Figure 7. The locomotive is formed by two permanently coupled sections; the brake system integrates train-pipe, equalizing-pipe, and Ethernet reconfiguration, enabling mutual connectivity and interchangeability between the two sections. Either section can be appointed master, yielding a dual-section fully redundant control system. Internally, the brake valve tolerates single-module failures: remaining modules automatically assume the functions of the failed unit. Redundant modules include train-pipe control, brake-cylinder control, and independent brake control. This comprehensive redundancy significantly increases the availability of the brake-control system and the overall safety of heavy-haul train operations.



CCU—Central Control Unit; EIU—Electrical Interface Unit; EBV—Electronic Brake Valve; BPCM—Brake Pipe Control Module; BCCM—Brake Cylinder Control Module; IBCM—Independent Brake Control Module.

Figure 7: Fully redundant control network topology.

3.6 Heavy-Haul Train Coupling Technology

Owing to their exceptional length and mass, heavy-haul trains are intrinsically difficult to control; imprecise regulation of tractive or braking effort frequently introduces large longitudinal forces that damage car-body structures, in severe cases, trigger coupler failure or derailment, jeopardizing both safety and operational stability. Consequently, the new-generation intelligent heavy-haul electric locomotive incorporates a newly optimized coupler and a high-capacity silicone-elastomer buffer, illustrated in Figure 8.

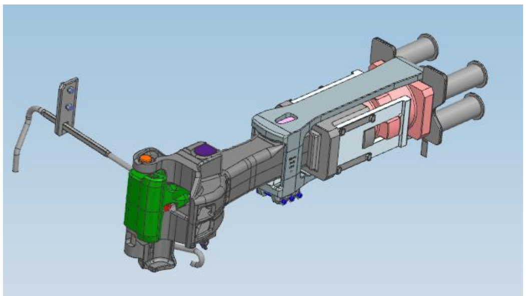


Figure 8: New intelligent heavy-duty locomotive hooking and retarding system.

Starting from the Type 100 coupler, the hook body has been structurally refined and cast from E+ grade steel—an upgrade that raises both load-carrying capacity and service life. A lower anti-jump stop, added to the Type 100 profile, eliminates the disengagement that occasionally occurs on intermediate locomotives within long, heavy-haul consists.

The buffer is the QKX120 unit, which surpasses the preceding QKX100 in every critical metric: sealing concept, mass balance, initial pressure, maximum resisting force and total energy absorption. The silicone-elastomer core now incorporates an enhanced dynamic seal, markedly improving reliability and fatigue life under heavy-haul duty.

3.7 Intelligent Technology Innovation

The new-generation intelligent heavy-haul electric locomotive implements a full-stack intelligence architecture that spans perception, transmission, diagnosis, control, and interaction. A cloud–edge–end cooperative network enables system-wide monitoring and intelligent management of the locomotive; the architecture is illustrated in Figure 9.

The train-level network is built on Time-Sensitive Networking (TSN) Ethernet, delivering high reliability, ultra-low latency and minimal jitter with a usable bandwidth of 1000 Mb/s. This robust backbone guarantees deterministic communication, computation and closed-loop control across all on-board systems. An autonomous-driving layer provides full-scale automatic train operation, raising the average running speed by 2~3 km/h while cutting energy consumption by 2%~3%. A next-generation human-machine interface-featuring a single, large-format display and far-field voice interaction-makes driver-locomotive dialogue more intuitive and efficient. For predictive maintenance, the eight mission-critical subsystems are equipped with embedded Prognostics and Health Management (PHM) algorithms[5]; diagnostic alerts are streamed to the wayside in real time, through a hardware-firewalled channel that preserves cyber-security integrity.

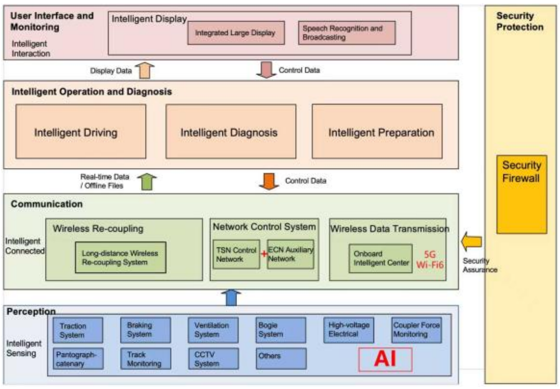


Figure 9: Intelligent architecture of the new type of intelligent heavy-duty locomotive.

4 Conclusion

This paper presents the research advances made by Shuohuang Railway Co., Ltd. in the key technologies of the new-generation intelligent heavy-haul electric locomotive and documents their implementation in system architecture, critical-component design, simulation and experimental validation. By integrating next-generation high-efficiency traction technologies, silicon-carbide converters, water-cooled permanent-magnet motors, direct-drive bogies and a unified cooling system, the locomotive achieves higher traction efficiency, lower harmonic currents, and reduced acoustic emissions. By studying health-management algorithms, autonomous-driving functions and an intelligent cab, we provide a solid foundation for the onboard deployment of smart driving, real-time monitoring and digital-cab systems. These innovations decrease the maintenance burden on subsystems and components, ease crew workload and improve ride comfort and stability, collectively advancing the locomotive's level of intelligence.

In summary, by mastering cutting-edge technologies and introducing new products, Shuohuang Railway Co., Ltd. has achieved a comprehensive upgrade in the key performance of heavy-haul electric locomotives. This advance effectively addresses the current challenges of high operating costs and low transport efficiency in heavy-haul traction and provides strong support for the evolution of heavy-haul locomotives toward intelligent, efficient, green and safe operation.

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