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Review

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Recent advances in traction drive technology for rail transit

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Abstract: The traction drive system is the "heart" of rail transit vehicles. The development of sustainable, secure, economic, reliable, efficient, and comfortable contemporary rail transportation has led to increasingly stringent requirements for traction drive systems. The interest in such systems is constantly growing, supported by advancements such as permanent magnet (PM) motors, advanced electronic devices such as those using silicon carbide (SiC), new-generation insulating materials such as organic silicon, and advanced magnetic materials such as rare-earth magnets and amorphous materials. Progress has also been made in control methods, manufacturing technology, artificial intelligence (AI), and other advanced technologies. In this paper, we briefly review the state-of-the-art critical global trends in rail transit traction drive technology in recent years. Potential areas for research and the main obstacles hindering the development of the next-generation rail transit traction drive systems are also discussed. Finally, we describe some advanced traction drive technologies used in actual engineering applications.

Key words: Rail transit; Traction drive systems; Artificial intelligence

1 Introduction

As rail transit's heart and power source, traction drive technology is the symbol of rail transit renewal. Since Stephenson invented the train, the development of traction drive technology has progressed through several stages: steam, internal combustion, internal combustion electric, DC electric drive, and AC asynchronous electric drive (Loewenthal et al., 1983). The technology continues to evolve and is gradually moving towards permanent magnet (PM) synchronous electric drives (Miller et al., 2007).

As examples of modern high technologies, artificial intelligence, information technology, advanced materials, and advanced manufacturing technology profoundly affect rail transit PM synchronous electric drive technology. Overall, the objectives of the next-generation rail transit traction drive technology are to provide more secure, convenient, efficient, intelligent, economical and easy-to-use systems that have a lower energy consumption.

Considering these objectives, some progress has been made in recent years by governments, academia, and industry in various countries, including the following:

(1) The engineering application of advanced traction motors and systems represented by PM motors has contributed to the security and comfort of vehicles and significantly reduced operating energy consumption (Refaie et al., 2014).

(2) Silicon carbide (SiC) is a representative of the new generation of wide-bandgap (WBG) electronic devices that promote the switching frequency of power devices. They not only significantly reduce the harmonic pollution of the inverter, but also promote the development of new technologies such as electronic transformers (Morya et al., 2019).

(3) Artificial intelligence (AI) represented by autonomous driving technology promotes the intelligence of traction drive systems. This constitutes the core of a new generation of intelligent trains (Flämig, 2016) (Reschka, 2016).

(4) Multi-source and multi-system drive systems for new energy sources continuously improve the performance and environmental friendliness of non-electrified railway trains and support cross re-

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gional operation (Steimel, 2012) (Piraino et al., 2021) (Corbo et al., 2006).

(5) Innovations and breakthroughs in operation and maintenance technology of traction drive systems further improve the efficiency, reliability, and economy of train systems (Xu et al., 2021).

Although these achievements clearly demonstrate the prevalence of advanced technologies in theoretical studies of traction drives, there have been few comprehensive studies of the status of such technologies in engineering applications. It is also important to compare the performance of each engineered application with that of conventional traction drive technology. In this paper, we focus on analyzing and summarizing the engineering applications of these new technologies. We aim to provide a convenient reference for conducting future research on traction drive technologies.

The rest of this article is organized as follows. The new concepts and structures of electric motors and systems are presented in Section 2. Section 3 introduces the application and development of advanced power electronic (PE) devices and systems. In Section 4, the application of AI technology is presented. In Section 5, we discuss multi-source and multi-system drive systems for new energy sources. Section 6 summarizes the current development of traction drive technologies and identifies some challenges for future research.

2 New concepts and structures of electric motors and systems

Since the advent of the first electric locomotive in 1842, the evolution of electric traction technology can be subdivided into three stages: internal combustion electric traction, DC traction, and asynchronous traction. Among these, the AC asynchronous traction motor represented by vector control and direct torque control is currently the mainstream traction motor technology. With their high efficiency, high power density, and excellent controllability, PM motors are considered the next generation of rail transit traction drive technology, and might represent a breakthrough in development. A comparison of their performance with that of induction motors (IMs) is illustrated in Fig. 1.

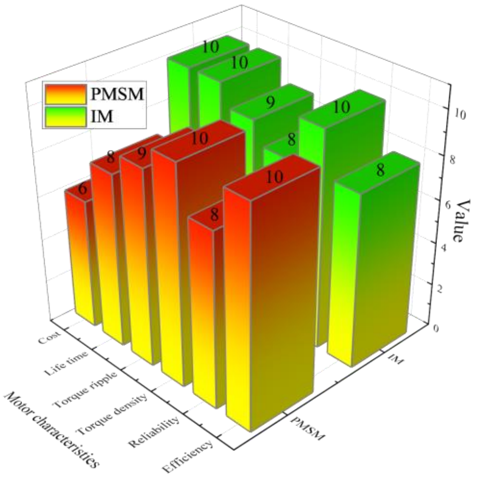

Fig. 1 Performance comparison of IM and PM motors

Prototype PM motors for railway traction were proposed by the Japan Railway Technology Research Institute in 1990 (Matsuoka et al., 2001), followed by Alstom in France, Bombardier in Canada, Siemens in Germany, Skoda in the Czech Republic, and Toshiba in Japan. All of these companies have independently researched traction in experimental trains. A comparison of the performance typical of PM traction motors produced by different manufacturers can be found in Table 1. An AGV high-speed train pulled by a combination of PM and asynchronous motors was manufactured by Alstom (Fig. 2). On April 3, 2007, this train set the world's fastest railroad speed of 574.8 km/h, on the Champagne Ardenne line in France, a record that still stands (Fan et al., 2012). In China, a PM high speed railway started in 2008, somewhat later compared to some European countries. In 2015, CRH380AN PM high speed trains equipped with TQ-600 PM traction motors jointly developed by Zhejiang University and China Railway Rolling Stock Corporation (CRRC) were commissioned on the Great Western Line. Such trains were then used for commercial operation on the Chengdu-Chongqing high-speed railway in 2020. The line experiment indicated that the per capita energy consumption per 100 km could be reduced by 30% compared to the CRH380A. According to reports, the global PM motor market has the potential to increase from $41.2 bn in 2021 to $64.6 bn by 2026. In collaboration with Equipmake, a power-intensive PM motor capable of producing 220 kW at 30,000 rpm, weighing less than

Fig. 2 Automatic Guided Vehicles.

Table 1 Performance parameters of PM traction motors made by various companies. [data source: (Ping and Qingping, 2017), (Peroutka et al., 2009), (Binder et al., 2006), (Zhang et al., 2018)]

Characteristics	Alstom	Škoda	Siemens	Toshiba	Bombardier	CRRC
Structure	Closed	Closed	Closed	Closed	Closed	Closed
Cooling	Natural cooling	Water cooling	Water cooling	Natural cooling	Natural cooling	Natural cooling
Efficiency /%	96	96.6	96.5	97	97.1	
Efficiency improvement/%	3~4	3~4	3	3	3.5	3~5
Noise reduction/dB	3~7	6	15	20	18	10
Traction power/kW	120	46.6	500	356	302	690
Mass/kg	285	335	2300	440	50	
Speed max/(r/min)	3600	196	4000	4500	3500	3700

10 kg, with a power density of 20 kW/kg, was developed by HiETA in March 2020 (Reportlinker, 2021). The development of new technologies for motor design and manufacture will result in continuous technological improvement of PM traction motors.

Currently, considering the cost and scarcity of rare earth components of PMs, traction motor designers have contributed to reducing the magnet volume by moving to motors with less or no magnetism. Moreover, the recyclability of PM material has also been a research focus. In addition, PM direct-drive and flux modulated motors have been proposed to meet higher torque densities.

Produced in Japan in 2007, PM motors with switched reluctance reportedly matched the power density of PM motors (Takano et al., 2010). To further improve the power density of switched reluctance motors, a high-speed synchronous reluctance motor with a carbon fiber wrapped rotor was designed and tested by Grace et al. (2018). This design minimizes flux leakage in the rotor poles compared to conventional synchronous reluctance designs. Then, to allow efficient recycling of the PMs, researchers proposed a new motor structure that does not require glue for holding the PMs in place.

Motor designers are committed to further improving the torque density of PM motors. An early instance of a PM direct drive solution with Syntegra bogies was proposed by Siemens in 1997 and commissioned in Munich, Germany, in 2007. Compared with traditional traction motors, direct-drive traction motors are 30% smaller, 15 dB quieter, and 3% more efficient (Kolar, 2016). In 2017, the CRRC Nanjing Puzhen Co., Ltd., CRRC Zhuzhou Institute, CRRC Zhuzhou Electric Co., Ltd., and other enterprises jointly developed PM direct drive bogies for metro applications and completed a circuit experiment in Suzhou (Fig. 3). Compared with traditional trains, a reduction of 80 m in the minimum turning radius of direct drive trains can be achieved. The height of the bogies is only 350 mm (Guang-Tong et al., 2021). Flux modulated motors, especially vernier motors, have gained extensive attention from the motor community in recent years due to their high torque density. However, a low power factor and manufacturing difficulties are the main factors limiting their widespread application (Vukotić and Miljavec, 2016).

Fig. 3 Metro direct drive PM motor.

However, most of the above PM motors have been commissioned in low-speed trains, and others are still in the experimental stage. The engineering application of PM motors in high-speed rail traction drive systems faces tremendous obstacles, including the following:

(1) Structure: The mainstream cooling method for high speed train (HST) traction motors is forced internal ventilation. Due to the magnetism of the PM motor's rotor, magnetic dirt is easily absorbed. PM motors must therefore adopt a closed structure, which reduces their heat dissipation. Furthermore, temperature sensitivity is the main factor that significantly increases the complexity of thermal management of PM traction motors.

(2) Control: The main magnetic flux of PM motors is typically considered to be constant. Since the speed of HSTs varies tremendously, the motors' speed range must be strictly regulated. Field weakening control is considered an effective and indispensable approach. However, due to the intensified coupling between the traction motor's rotation speed and the train's operation speed, to meet the security requirements under fault conditions, the field weakening ratio of the PM motors is severely limited. This may complicate the design and optimization of PM motors.

(3). Operating environment: the operation of HSTs involves repeated acceleration and braking, and the motor frequently operates under high overload conditions (Kouroussis et al., 2021). Shock, vibration, and armature reaction may complicate the irreversible demagnetization behavior of motors in long-term service, resulting in difficulties in analysing the whole life cycle reliability and design of the motors. Meanwhile, the output of the inverter is non-sinusoidal due to the immense power and increased frequency of the motors, resulting in increased harmonic loss. This has resulted in demands for more advanced PE devices.

3 Application and development of advanced power electronic (PE) devices and systems

With the development of electric traction technology and power devices, attempts have been made to use advanced power devices in train electric traction. After the thyristor was invented in 1957, an AC traction drive system with vector control as the core was developed. After that, the invention of the insulated gate bipolar transistor (IGBT) promoted the development of asynchronous traction drive technology. Compared with early GTO-based asynchronous drive systems, IGBT-based traction drive systems offer additional features such as higher efficiency. IGBT has become the mainstream traction drive technology for HSTs and heavy-duty freight trains, as well as urban rail transit.

Next, the emergence of the first silicon carbide (SiC) device in 1993 marked the world's entry into the era of four generations of wide bandgap semiconductors (WBG) represented by SiC and gallium nitride (GaN) (Dmitriev et al., 1994). The advantages of WBG semiconductors over silicon (Si) devices include not only wider bandgaps, but also higher breakdown electric fields, thermal conductivity, and electron saturation rates. Furthermore, the on-state resistance of SiC power devices switches is low. The switching frequency is over ten times higher than that of traditional Si-based devices. Reductions of 40%, 71%, and 91% in turn-on and turn-off losses and reverse recovery losses, respectively, can be achieved by SiC MOSFET power devices compared to new IGBT power devices for the same power and voltage level applications. Moreover, the low parasitic capacitance of SiC power devices contributes significantly to achieving high switching frequencies.

Currently, the voltage level of mainstream commercial devices is reported to be in the range of 600-1700 V for SiC PE devices (She et al., 2017), and 600 V for GaN devices. GaN devices may be the preferred choice with higher performance. A new generation of GaN based CoolGaN™ devices for modular power supplies with 2% higher efficiency and 40% lower loss was launched by Infineon in 2020 (Moser et al., 2021). Next-generation 650 V and 600 V GaN field-effect transistors with fast switching, 2.2 MHz integrated gate drivers that double the power density, and achieve 99% efficiency were proposed by Texas Instruments in November 2020 (Bindra, 2021). In February 2021, Nexperia introduced the AEC-Q101 half-bridge package extension LFPAK56D MOSFET product with 60% lower parasitic inductance and clearly improved thermal performance (Nexperia, 2021). Considering the key parameters such as junction temperature detection to support intelligent operation and fault diagnosis, the sensors are integrated into the chip. This shows that SiC and GaN devices are evolving toward intelligence. The latest XM3 full SiC power modules (Fig. 4), with built-in voltage sensing and an integrated temperature sensor at the low-side switch position, were released by Wolfspeed in 2019 (Feurtado et al., 2019).

Fig. 4 XM3 Full Silicon Carbide Power Modules.

The development of new PE devices with WBG semiconductors increases the operating frequency and significantly reduces the size and weight of passive devices, such as filter reactors and capacitors. It also improves waveform quality and control performance and promotes the development of new technologies, such as traction transformers and power electronic transformers (PET).

WBG semiconductors have the potential to further contribute to the development of traction inverters. A 1500 V DC traction inverter adopting full SiC power modules was launched by the Mitsubishi Electric Corporation in 2013. This device reduces switching losses by 55% compared to a conventional inverter with an IGBT power module (Fabre et al., 2012). Japan's JR company successfully developed the N700S HST using the Mitsubishi SiC-MOSFET in 2017, and conducted a line experiment in March 2018. The total mass of its electrical traction equipment can be reduced by 20%, and with the complete absence of a traction converter can be reduced by about 30% (Sato et al., 2020). In 2017, SiC MOSFET-based traction inverters were installed by Bombardier on the Green line of the Stockholm metro system in Sweden for three months of passenger operation. A 51% increase in power density and a 22% weight reduction were achieved compared to the use of conventional inverters (Lindahl et al., 2018). A full SiC traction inverter based on 3300 V-grade high-voltage and high-power SiC MOSFETs was developed by the CNR Zhuzhou Institute with Shenzhen Metro, and commissioned on the Shenzhen Metro Line 1 in 2021. More than 65,000 cumulative passenger kilometers were travelled in five months, with a reduction of over 10% in annual total energy consumption, a noise reduction of over 5 dB, and a temperature rise reduction of over 40 °C.

The first single-phase 200 V/3kVA PET was launched by the Kyushu Electric Power Company in Japan in 1996. This reduced the overall volume by 1/3 and mass by 4/5, with an operating efficiency of 90% (Harada et al., 1996). A 5-kHz PET-based traction drive was developed and tested by SMA on a locomotive operated by ALSTOM in 2003 (Hugo et al., 2007). A 1.2-MVA rated PET-based traction drive was commissioned in a 15 kV/16.7 Hz traction network in 2011, improving efficiency by 2-4%, to 96%. This locomotive has operated securely for over 13,000 km in Geneva, Switzerland for two years (Zhao et al., 2013). With the surge in progress in power semiconductor devices in the field of PE, PETs composed of power semiconductor devices have been successively rolled out. An intelligent substation PET that can be connected to the power grid was developed in succession by the FREEDM system center. The cascade-less connection makes the topology much simpler. The prototype efficiency can reach up to 97% with a 15 kV/20 SiC IGBT diode module for the high-voltage stage, and a 1200 V/100 SiC MOSFET diode module for the low-voltage stage (Hatua et al., 2011). In China, under the support of the National Key Research and Development Program, the world's first PET prototype for a 25-kV traction grid system was developed and commissioned by the CRRC Zhuzhou Electric Locomotive Research Institute Co., Ltd. in 2020 (Fig. 5). The system realizes a weight reduction of 15%, volume reduction of 20%, and an efficiency improvement of 2%. The CRRC believes that the SiC-based PET will be installed in locomotives within 3 to 5 years, and the introduction of AI will guarantee its operational reliability.

Fig. 5 CRRC Zhuzhou Electric Locomotive PET prototype.

4 Application of artificial intelligence technology

4.1 Autonomous driving

One of the critical fields of application of AI is autonomous driving. The autonomous driving technology of rail transit has generally matured considerably earlier than that of autonomous vehicles. The first autonomous metro line was opened in 1983 in Lille, France. Subsequently, autonomous driving technology has been applied to urban rail transit systems such as maglev, metros, and urban rail. An autonomous driving high-speed maglev line has operated securely for 20 years in Shanghai, China (Tan et al., 2016). The world's first fully autonomous train conducted by the German Federal Railways and Siemens was opened in Hamburg, Germany, in October 2021. Real-time traffic situation information is transmitted by radio, and the transportation volume can be increased by 30% (Designboom, 2021). In 2021, Alstom proposed to achieve the highest level of automation on regional railway lines by 2023, with an expected 30% increase in transportation volume and a 45% reduction in energy consumption (Alstom, 2021).

An autonomous train control system consists of an automatic train protection system, automatic train operating system, and automatic train supervision system (Fig. 6). This arrangement realizes data interconnection and intercommunication through wireless transmission modules (Brenna et al., 2016). However, rail transit autonomous driving technology is still in the embryonic stage, with the communication signal system as the core to ensure operational safety. Furthermore, the potential ability to improve system safety, comfort, economy, and operational efficiency through autonomous driving has not been fully explored.

Essentially, a rail transit system is a displacement control system, which can be considered a position control system of the motor under an adhesive constraint. The comprehensive incorporation of AI to optimize the whole process of displacement control by optimizing the speed profile might achieve the following aims: 1) reducing point-to-point operating energy consumption; 2) reducing the maximum acceleration and impulse to improve comfort; 3) improving the average speed and reducing the point-to-point operating time; 4) realizing the blocking of the moving section using the centralized control of the training group, on the one hand, improving the security, and on the other hand, reducing the operation interval and increasing the transportation volume.

In recent years, the China Railway Corporation has led research on intelligent trains and has trialled autonomous driving HSTs on the Beijing-Zhangjiakou Line. Nevertheless, fully intelligent driving is yet to be achieved. The significant step is that HSTs are a typical security-critical and colossal system. The dilemma is that it is difficult to implement large-scale operation of lines without a long-term reliability assessment, and the system’s reliability cannot be comprehensively verified without a large-scale line operation assessment. Therefore, a whole-line whole-process global semi-physical simulation tech- nology, covering all application scenarios and fault conditions, has become an essential approach to cope with this problem. In this regard, the conditions are available with the development of PE.

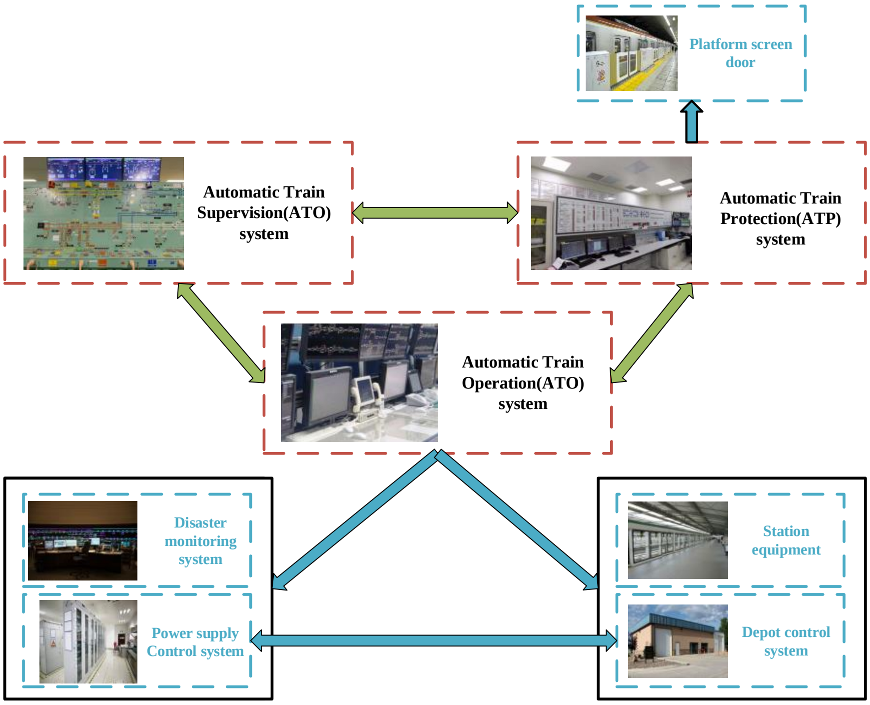

Fig. 6 Automatic train control system

4.2 Intelligent operation and maintenance of traction drives

With the formation of high-speed railway networks and the large-scale application of HSTs and other transportation equipment, operation and maintenance costs have gradually become a pivotal factor affecting transportation economy. Meanwhile, the quality of operation and maintenance directly affects the reliability and security of transportation. The efficiency of operation and maintenance determines equipment availability. Conventionally, railway operation and maintenance units have adopted a maintenance strategy based on maintenance mechanism and classification. The introduction of intelligent technology to realize the reliability of a maintenance strategy based on equipment operation status and risk management can not only scientifically manage operation and maintenance costs, but also effectively improve security and reliability.

For a traction drive system, the core of intelligent operation and maintenance is predominantly the philosophical perception of equipment status, followed by the prediction and estimation of faults and risks. This forms the basis of the operation and maintenance strategy.

The CRRC has achieved state observations based on electrical signals for pivotal components such as converters, electromagnetic motor systems, bearings, gearboxes, and transformers, through systematic research in the last few years. The accuracy and efficiency of the state of perception are clearly improved by integrating with traditional signals such as temperature and vibration. Scholars from Beijing Jiaotong University proposed a risk-chain-based system safety guarantee approach. A comprehensive experimental system for the intrinsic safety of rail transportation equipment was presented to further enhance the safety and reliability of the train traction drive system (Hao et al., 2020).

4.3 Autonomous-rail transit development

Autonomous-rail transit is another prominent example of traction drive intelligence. The CRRC Zhuzhou Electric Locomotive Research Institute Co., Ltd. released a new rail transit vehicle and system integrated with ground transportation autonomous rail rapid transit (ART) on June 2, 2017 (Fig. 7). A virtual

Fig. 7 The ALSTOM Prima H4 multi-power source locomotive.

track following control technology independently manufactured by CRRC was adopted, which recognizes a virtual track line on the road through various onboard sensors, and can precisely control the train to travel on the established virtual track. A 100% low floor structure and PM drive system were used. Meanwhile, a flexible grouping mode of high-speed rail was adopted to adjust the capacity according to the change of passenger flow. Because ART does not rely on rails, the construction period of ART is less than one year, with a cost reduction of around 10~20 times compared to metros. The minimum turning radius of the three-group ART is 5 m smaller than that of direct-drive trains. Furthermore, it has the zero-emission and pollution-free characteristics of rail trains such as light rail and metros, and supports multiple power supply methods (Lawrie, 2020).

5 Multi-source and multi-system drive systems for new energy sources

Due to the divergent development histories of rail transit systems in various countries, there are various incompatible power supply systems (Fig. 8). Moreover, there are also divergent pivotal parameters such as the gauge, catenary height, catenary form, and speed limit under the same power supply system. Furthermore, there are plenty of non-electrified railways in domestic and international use due to transportation volume and environmental constraints. Compatibility with divergent traction drive modes and power systems is also a significant issue to be addressed urgently.

Multi-source power locomotives are common and considered as a standard solution for rail transit systems to address the interconnection between electrified and non-electrified railways. The first multi-source traction drive locomotive named "Green Goat" was developed by the Canadian Railways in 2002. It was deployed in the Illinois Railway system (Cousineau and Magazine, 2006), reducing emissions by 80%. The H4 type multi-source electric locomotive manufactured in France by ALSTOM in 2018 (Fig. 8) can operate at a speed of 120 km/h. It can operate under the hybrid power of a lithium battery plus a diesel engine in the section without a contact network, and can also switch between "grid + diesel engine" or "grid + lithium battery" in the section with a contact network. This locomotive consumes 15% less energy than conventional locomotives and reduces carbon emissions by 6,000 tons per year (Lopez-Ibarra et al., 2019). In China, the Larin Line, the first electrified railway in Tibet, was opened in June 2021. The CRRC Puzhen built the "Fuxing" plateau double-source Electric Multiple Units (EMU), which operate through the Larin Line non-electrified and electrified railways.

In view of the problem of incompatible power supply systems in various rail transit systems, a universal multi-system electric locomotive is an efficient and effective approach. Such a locomotive would be compatible with various traction power supply systems and various rail gauges. Siemens launched the Eurosprinter series of multi-system locomotives in the 1990s, and its third generation Locomotive Rh121

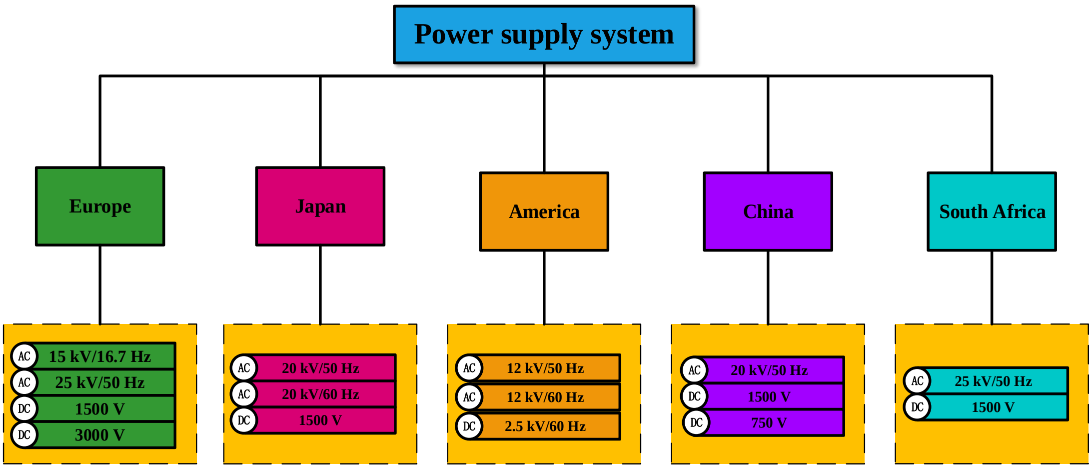

Fig. 8 Main area power supply system and voltage level.

was delivered to the Austrian Federal Railways in 2005. This locomotive is compatible with four European power supply systems and achieves speeds of up to 230 kph (Bakran et al., 2014). The PRIMA 3U15 electric locomotive manufactured by Alstom in 2004 features three pantographs suitable for operation at 15 kV/16.7 Hz AC, 25 kV/50 Hz AC and 1.5 kV DC, and is compatible with the German, French and Swiss rail networks (Chapas and Barat, 2004). Developed by CRRC, the 400-kph transnational interconnectivity high-speed EMU rolled off the production line of the CRRC Tangshan Co., Ltd. in October 2020 (Fig. 9). The train adopts an AC25 kV/50 Hz and DC3000 V dual-system power supply while using 400 kph high-speed variable gauge bogies and built-in axle box bogies. This train can operate continuously at -50 °C at 400 km/h. It will realize cross-domain operation with variable gauge and multi-stream systems between China and Europe in the future.

5.1 Application of new energy technologies

In recent years, with the enhancement of low-carbon environmental protection requirements, clean energy and new energy-saving technologies in non-electrified lines have gradually attracted increasing interest.

Fig. 9 The 400-kph cross-border interconnection high-speed EMU.

A hydrogen fuel cell hybrid switching locomotive weighing 127 tons with a transient power of more than 1 MW, and a continuous fuel cell power of 250 kW was developed by a North American team (Miller, et al., 2007). The ¥ 4 bn HYBARI hydrogen hybrid train developed by Toshiba for trial operation in Japan in 2022, which can travel about 140 km per charge, is expected to come into service in 2030. In November 2021, a hydrogen fuel cell hybrid locomotive manufactured by the CRRC Datong Locomotive and Rolling Stock Co., Ltd was deployed in the 627-km coal transport railway line in the Inner Mongolia Autonomous Region of China. This vehicle can operate for 24.5 h with a continuous power of 700 kW, and a maximum traction load of 5,000 t on straight tracks. Moreover, a hydrogen fuel cell hybrid locomotive with a continuous power of 2,000 kW has been developed.

Biofuels are also a significant direction for renewable energy development and utilization. Since the 1970s, many countries have paid increasing attention to the development of biofuels, and have achieved remarkable results (Tang et al., 2019). We believe that biofuels will be the new path to low-carbon transportation. They have huge potential to reduce the carbon emissions of rail transportation. However, the use of biofuels in rail transportation is still in the laboratory stage.

5.2 Application of energy storage technologies

Improving the utilization efficiency of regenerative braking energy feedback traction drive systems is a focus of attention in the field of rail transit. In contrast to the feedback to the transformer substation, a braking energy storage system in braking energy recycling can effectively improve the quality of electric energy. This application is particularly attractive for urban rail transit and in remote mountainous areas with weak electric networks.

Battery energy storage was applied in the Berlin metros in Germany during the early 1990s (Jiang et al., 2014). Subsequently, the Gigacell battery module of Kawasaki Heavy Industries was commissioned in light rail lines in Japan and the USA to absorb the energy generated by braking trains (Banham-Hall et al., 2012).

A flywheel energy storage device application in the traction power supply system was tested in the London metros in 2000. A Power-Bridge flywheel energy storage system manufactured by the German company Piller was deployed in Hanover, Germany, in 2004 (Faraji et al., 2017). A 3-MW flywheel energy storage system was commissioned in the Los Angeles Red Line, USA, in 2012 (Gee and Dunn, 2014). Developed by Rotonix, the Onmifly^{TM} high-energy carbon-fiber flywheel energy storage system was installed in a metro system in 2014, with a maximum output of 1 MW from a single machine, storing 12 kWh of electricity with a footprint of only 0.84 m^2 (Rotonix, 2014). Manufactured by the Dunshi Magnetic Energy Technology Co., Ltd., a 2-MW carbon-fiber maglev high-speed flywheel array GTR was successfully deployed in the Fangshan Line of the Beijing metro in July 2019.

Alstom's supercapacitor energy storage system, STEEM, was installed in the T3 line of the Paris tram, saving energy an average of 16% in 2009 (Moskowitz and Cohuau, 2010). The world's first supercapacitor energy storage bus line opened in Ningbo, China, in July 2015. Storing about 2 kWh and reducing grid power consumption by 20-30%, a supercapacitor from Maxwell Technologies was adopted by Bombardier's EnerGstor brake energy recovery system (Lamedica et al., 2022).

However, there are still plenty of drawbacks of these energy storage methods, which can widely be summarized as follows: 1) The battery life is much lower than the locomotive life. 2) Flywheel energy storage is less economical and requires extensive regular maintenance. 3) The cost required to regenerate braking energy using a single supercapacitor train is high.

To address these shortcomings, researchers have focused their attention on hybrid energy storage systems combining divergent energy storage methods, for example, combining batteries with supercapacitors to improve the energy density and power density of the system (De La Torre et al., 2014). This also means that the traditional traction drive system design technology in the face of design requirements and constraints cannot achieve high-performance rail transportation. Therefore, improving and optimizing advanced traction motor and PE technology, realizing autonomous driving HSTs, and establishing the full application of AI are considered the new development trends for rail transit traction drive technology.

6 Conclusions

The traction drive system is considered to be a well-established technology, but train operating speeds are increasing, and requirements for operation security, economy, and comfort are becoming increasingly stringent. Fortunately, the surge of progress in motor, PE, and information technology provides new technical support for improving the performance of traction drive systems. More progress on the development of traction drive technology for rail transit is expected in the coming years.

In general, we believe that: 1) There is a general trend that traditional asynchronous drive systems will be replaced by advanced motor technologies represented by PM motors; 2) The large-scale application of the new generation of traction converters with the new generation of WBG PE devices as the core will further improve the power supply quality and power density of traction drive systems; 3) The combination of AI technology and modern traction drive technology will promote intelligent driving, intelligent operation and the development of new transportation modes, thereby improving the efficiency and quality of transportation; 4) The combination of clean energy represented by hydrogen energy, modern control technology and advanced energy storage technology will promote energy conservation and emission reduction on non-electrified and cross domain railway operations.

There are still plenty of obstacles to overcome to achieve these objectives. A key issue is concerns about the reliability and safety of the new technology. As well as the world's largest high speed railroad network and the most complete high-speed railroad industry chain, China has the world's largest research and development team working on rail transportation technology. This team has the responsibility and capability to make crucial contributions to the development of new generation rail transportation traction drive technologies.

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Author contributions

Ji-en MA designed the research. Bo-wen XU and Jia-bo SHOU processed the corresponding data. Chao LUO wrote the first draft of the manuscript. Xing LIU and Lin QIU helped to organize the manuscript. You-tong FANG revised and edited the final version.

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中文概要

题　目：轨道交通牵引传动技术新进展

牵引传动技术是轨道交通的心脏和动力来源，也是轨道交通的断代标志。从史蒂芬森发明火车以来，轨道交通的牵引传动技术经历了蒸汽、内燃、内燃电动、直流电传动、交流异步电传动等几个阶段，正在逐步向永磁同步电传动演进。

作为现代高新技术的集成展现，智能化、信息化技术和先进材料、先进制造技术都深刻影响着轨道交通牵引传动技术的发展。总体来讲，未来的轨道交通技术将会朝着更安全、更便捷、更舒适、更节能、更环保、更智慧、更经济的方向发展，牵引传动技术必须为上述目标服务。

近年来，围绕上述目标各国政府、学界和产业界进行了持续的努力，取得了一些进展，重点体现在：1）新概念和新结构的电机及其系统；2）先进电力电子器件及系统的应用与发展；3）以牵引传动系统为核心的无人驾驶技术与智慧列车；4）面向新能源的多源、多制式驱动系统；5）高效率、高可靠、低成本的牵引传动系统运维技术。

关键词：轨道交通；牵引传动系统；研究进展