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Traction power systems for electrified railways: evolution, state of the art, and future trends

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Abstract
Traction power systems (TPSs) play a vital role in the operation of electrified railways. The transformation of conventional railway TPSs to novel structures is not only a trend to promote the development of electrified railways toward high-efficiency and resilience but also an inevitable requirement to achieve carbon neutrality target. On the basis of sorting out the power supply structures of conventional AC and DC modes, this paper first reviews the characteristics of the existing TPSs, such as weak power supply flexibility and low-energy efficiency. Furthermore, the power supply structures of various TPSs for future electrified railways are described in detail, which satisfy longer distance, low-carbon, high-efficiency, high-reliability and high-quality power supply requirements. Meanwhile, the application prospects of different traction modes are discussed from both technical and economic aspects. Eventually, this paper introduces the research progress of mixed-system electrified railways and traction power supply technologies without catenary system, speculates on the future development trends and challenges of TPSs and predicts that TPSs will be based on the continuous power supply mode, employing power electronic equipment and intelligent information technology to construct a railway comprehensive energy system with renewable energy.

Keywords Railway traction power system · Future electrified railway · Flexible continuous power supply · Renewable energy · Integrated energy system

1 Introduction

Electrified railways are the backbone of modern comprehensive transportation systems, with the advantages of large traffic volume, high-efficiency, low pollution and low transportation cost [1–4]. With economic growth, the scale of electrified railways around the world is expanding. Especially in China, it is estimated that by 2035, the Chinese national railway network will reach approximately 200,000 km, of which the proportion of electrified railways will reach 90% [5]. The rapid and high-density development of electrified railways produces huge electric energy consumption [6]. Meanwhile, the disadvantages of low-efficiency and -reliability also increasingly appear. Against the background of achieving carbon neutrality target worldwide, promoting the development of electrified railways with low-carbon, energy-saving and high-reliability is an inevitable trend.

In electrified railways, traction power system (TPS) provides electric locomotives with uninterrupted electric energy from the utility grid and is also the only way for them to obtain power. The performance of electrified railways depends on the power supply modes and structures of TPSs. At present, relatively mature traction power supply standards and structures have formed. Low-voltage DC (0.75, 1.5 and 3 kV) TPSs are usually employed in urban rail transit with medium-power demand and trunk railways in a few countries (e.g., Italy and Spain) [1]. This TPS has the disadvantage of short power supply distance and low utilization rate of regenerative braking energy (RBE). Single-phase AC 25-kV 50/60-Hz TPSs are the most widely used in trunk railways around the world [3]. They play an irreplaceable role in the safe and stable transportation of electrified railways. However, in this AC TPS, the traction network is mostly segmented by neutral sections. Each feeding section is powered by one traction substation (TSS), and the unilateral power supply mode is adopted. This structure has shortcomings in realizing utility grid

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three-phase balance, longer distance power supply of the feeding sections, and higher locomotive speed [7, 8]. Meanwhile, the segmented power supply structure of the traction network is not conducive to the utilization of locomotive REB and convenient access to renewable energy. Moreover, as a high-power power electronic load, electric locomotives have the characteristics of nonlinearity and strong fluctuation, which sometimes brings power quality problems such as wide-band frequency oscillations, harmonics, and imbalances to TPSs and the utility grid [9–11]. The inherent structural characteristics of conventional TPSs limit their ability to satisfy the requirements of future electrified railways for high proportion renewable energy consumption, high-resilience, long-distances and high-quality power supplies.

To address these issues, Serrano-Jiménez et al. [1] compared transformer-based conventional TPSs and converter-based advanced TPSs to construct smart railway systems. References [12, 13] overviewed advanced AC TPSs with static converters, which improve power quality and eliminate neutral sections. Meanwhile, various advanced DC TPS topologies were introduced in [14, 15]. Furthermore, schemes for renewable energy integration in railways were suggested in [16]. References [2, 3, 17, 18] presented available topologies for future railway microgrids integrating distributed energy resources. Combining these perspectives, the development trends of electrified railways can be obtained. In the future designs for electrified railways, one is to apply power electronics, energy storage, renewable energy generation equipment and operation regulation technologies to upgrade existing TPSs, solve their inherent structural problems and improve their operational flexibility and power supply reliability; the other is to employ novel electrified rail transit energy supply technologies to satisfy diversified railway transportation scenarios. The above two paths are implemented in the hope of building intelligent and flexible TPSs that include renewable energy and storage stations to achieve low-carbon, high-reliability and high-efficiency power supply for electrified railways.

Against this background, this paper aims to review the historical evolution of conventional TPSs and analyze the limitations of existing power supply structures and development goals. Then, a comprehensive overview of state-of-the-art TPSs and novel electrified rail transit energy supply technologies adapting to the requirements of future electrified railways is provided. Finally, the future development trends and technical challenges of TPSs are discussed, which are prospected to provide some references for theoretical research and engineering applications of TPSs. The main contributions of this paper are condensed as follows:

(1) The development history of conventional TPSs is deployed in the form of a timeline. The evolution, structural characteristics, and advantages and disadvantages of each TPS are described.
(2) State-of-the-art TPSs that meet the requirements of future electrified railways are summarized. On this basis, we compare the power supply capacity, investment cost and other characteristics of different TPSs in detail, and the applicable lines of each system are suggested.
(3) Almost all the latest TPSs and novel rail transit energy supply technologies are included in this paper, which is expected to provide a comprehensive reference for researchers.
(4) Based on the development requirements of electrified railways, future trends and challenges of TPSs are proposed.

The rest of this paper is organized as follows. Section 2 introduces the early history and evolution of TPSs, as well as their structures under different power supply standards. In addition, future development goals are presented. Sections 3 and 4 depict state-of-the-art TPSs for AC and DC electrified railways, respectively. Novel electrified rail transit energy supply technologies, including mixed-system electrified railways and electrified rail transit energy supply technologies without catenaries, are presented in Sect. 5. Section 6 summarizes future trends and challenges of electrified railways. Finally, Sect. 7 concludes this paper.

2 Evolution of conventional TPSs and future development goals

The first electrified railway in the world was constructed by Siemens and Halsk in 1879 and was powered by a DC 150-V system [1], which is shown in Fig. 1. Benefiting from excellent speed regulation performance, electric locomotives were driven by DC traction motors at the

Fig. 1 The first electrified railway in the world [19]

inception of electrified railways. From the late nineteenth century to the early twentieth century, a low-voltage DC (below 1500 V) system was adopted in tramways, light rail, mine railways, suburban railways, subways, etc. [1, 3]. The locomotives are often fed by a third rail. The low rated voltage of the catenary limits the locomotive power, which leads to the low-voltage DC TPS not satisfying the growing capacity demand of railway transportation.

In the 1920s, Belgium, Italy, Spain, etc., introduced a DC 3-kV TPS [20, 21]. The increase in the traction network rated voltage improves the power supply capacity. Later, it was deployed in trunk railways. However, compared with AC power, DC voltage conversion is more complex, and DC relay protection is more difficult, which limits the development of DC TPS. At present, the rate voltage of electrified railway power supply projects is no higher than DC 3 kV around the world.

Figure 2a depicts the power supply structure of the conventional DC TPS. Transformers and uncontrolled diode rectifiers are deployed in TSSs to implement the AC–DC conversion of electric energy. It has two characteristics:

(1) Since the traction current returns to the negative electrode of the TSS through the rail, current inevitably leaks into the ground through the rail–ground transition resistance to form stray current. The harm of the AC stray current is not prominent, but the DC stray current will cause serious electrochemical corrosion to the buried metal along the railway. Especially for urban rail transit adopted with DC TPS, the underground metal pipeline network is complex, and the harm of DC stray current is particularly notable, which must be treated by certain technical measures.

(2) In the application scenario of urban rail transit, abundant regenerative braking energy is generated by the frequent start and stop of locomotives. Nevertheless, a large amount of redundant regenerative braking energy can only be converted into heat energy to be consumed through braking resistance, resulting in energy waste.

Meanwhile, the progress of AC power technology has also contributed to the birth and evolution of AC TPSs. The AC voltage can be transformed through the transformers, which means that a higher rated voltage can be obtained conveniently to accomplish heavy railway transportation tasks in AC TPSs. In 1898, the first three-phase AC supply electrified railway appeared in Germany, and the locomotives were driven by three-phase asynchronous motors. Then, Italy constructed a three-phase AC electrified railway in 1902 [3, 20], and some European countries also deployed this mode. However, in this power supply standard, the complex current collection system of the pantograph and catenary is contrary to the railway transportation requirements for high-speed, stable, safe and reliable operation. This results in the three-phase AC TPS not being applied in trunk railways on a large scale. Most three-phase AC electrified railways constructed in Europe (Sweden, France, Italy, etc.) were eliminated by 1970 [21].

In 1903, ohmic commutation pole shunts were applied to a series-wound commutator motor, which made the locomotives driven by these motors compatible with a single-phase AC power supply. However, under a power frequency of 50 Hz, the commutation spark of the series-wound commutator motor is serious [20, 21]. The voltage frequency must be reduced to ensure safety. After a period of research, the German railway department agreed on common power standards for single-phase AC 15 kV 16.7 Hz in 1912 and later successively employed in Austria, Switzerland, Norway and Sweden [3, 20]. Two main topologies can be found in a single-phase low-frequency AC TPS: centralized and decentralized systems. As shown in Fig. 2b, in the centralized system, TSSs are powered by the railway distribution network that is fed from dedicated railway power plants and/or central substations. In addition, in the decentralized system depicted in Fig. 2c, the catenary is directly connected

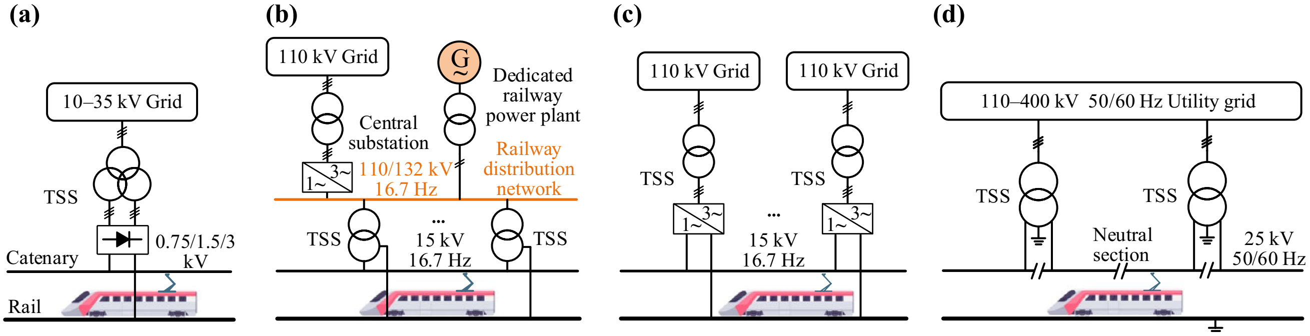

Fig. 2 Conventional DC and AC TPSs: **a** DC TPS; **b** centralized single-phase low-frequency AC TPS; **c** decentralized single-phase low-frequency AC TPS; **d** single-phase power frequency AC TPS

to the utility grid by a rotatory converter deployed in TSSs. Regardless of the topology, from the perspective of electric locomotives, a continuous power supply without neutral sections is realized, and the power quality is guaranteed. However, the rated frequency of the catenary voltage is different from that of the utility grid, which leads to complicated infrastructures and a large primary investment cost in this TPS. For this reason, engineers have desired to use single-phase power frequency AC voltage for TPS.

In the early twentieth century, rotary phase converters were employed in the traction drive system of electric locomotives, which realized a three-phase AC drive under the single-phase AC power supply standard. Hungary first constructed a single-phase AC 16-kV 50-Hz railway in 1932 [20, 21]. During the same period, Germany, the former Soviet Union, etc., tested prototype locomotives driven by rectifying devices and DC motors, which were also powered by single-phase power frequency AC voltage [20–24]. In 1950, a single-phase AC 25-kV 50-Hz testing railway built in France was successful [13, 18]. After that, this TPS was widely applied in trunk electrified railways of France, China, Japan, Russia, India, etc., which was attributed to its superior power supply capacity and simple infrastructure. The power supply structure is shown in Fig. 2d. In this TPS, there is no need for frequency conversion, and the catenary system can directly connect to the three-phase utility grid by traction transformers in TSSs. However, the disadvantages of this traction power supply mode are as follows:

(1) Due to feeding sections powered by different phases, the catenary is divided by numerous neutral sections with lengths of 100–500 m. The existence of neutral sections makes the electric locomotives unable to receive power continuously during high-speed operation. It is necessary to cut off power to pass through the neutral sections relying on inertance, resulting in speed loss of the locomotives. In addition, discontinuous power supply causes mechanical impact and arc between the pantograph and catenary, endangering locomotive operation safety. Moreover, selecting the proper position of neutral sections in some long slope sections and mountain railways with a high proportion of bridges is difficult, and additional investment will be generated for the proper setting of neutral sections in the project.
(2) The traction load is directly connected to the utility grid through an electromagnetic traction transformer. Only two phases of the utility grid are used by the left and right feeding sections, and the load of each feeding section is intermittent and fluctuating, resulting in a serious three-phase voltage imbalance at the grid side of the TSS. Furthermore, the AC/DC conversion of electric locomotive traction drive systems also produces power quality problems, e.g., reactive power and harmonics, and the fines caused by substandard power quality have caused huge economic losses to the railway department.
(3) Each feeding section is an independent power supply unit for the catenary divided by neutral sections. This power supply mode causes a low utilization rate of the regenerative braking energy produced by locomotives. At the same time, feeding sections work independently, which cannot form an effective multisource complementary power supply system.

After more than a century of evolution and development, relatively fixed traction power supply standards have been formed in various countries: in urban rail transit with medium-power demand, 750-V or 1.5-kV DC systems are usually used. In trunk rail transit with high-power demand, aside from a few countries such as Germany and Sweden employing 15-kV 16.7-Hz single-phase low-frequency AC systems, most countries (e.g., China, Japan and France) adopt 25-kV 50/60-Hz single-phase power frequency AC systems. Moreover, in some European countries (e.g., Italy), the 3-kV DC system is still used in trunk railways. Conventional TPSs are the embryonic form and foundation of electrified railways, which provide solid technical support for the enrichment and expansion of the traction power supply theoretical framework. Nevertheless, the structural deficiencies of conventional TPSs have become constraints on the development of electrified railways, which are eager to be improved. To date, the available implementation paths are surveyed as follows:

(1) Break the barriers of neutral sections in the existing segmented traction power network and provide a longer power supply distance to meet the reliable power supply demand under some extreme railway conditions, such as long slope sections (dense neutral sections cause unfeasible speed loss of locomotives), mountain railways with a high proportion of bridges and tunnels or long sea crossing railways (few available locations for traction substations), and railways with extremely weak utility grid (poor power quality).
(2) The efficient utilization of abundant regenerative braking energy generated from electric locomotives is an effective way to save energy and decrease consumption in electrified railways.
(3) Under the carbon neutral vision of the global energy system, clean energy is infiltrating into the railway power supply network on a large scale, and the local consumption of renewable energy is the key path to assist the carbon neutrality target.
(4) Flexible power equipment and intelligent information technologies are widely used in advanced TPSs to con-

struct resilient power supply networks that will realize energy self-consistent and refined management.

In summary, the historical evolution of conventional TPSs, the disadvantages of current mainstream TPSs and future development goals are briefly depicted in Fig. 3 with a timeline.

3 AC traction power systems in state of the art

This section introduces various topologies of state-of-the-art AC TPSs in detail, including their structures, advantages disadvantages, and engineering cases. Then, a comprehensive comparison is conducted in terms of the number of neutral sections, power supply distance, power quality, regenerative breaking energy utilization, investment cost, etc. Finally, the applicable lines of each TPS are depicted.

3.1 Power routing TPS

Based on the scheme of applying railway power conditioners (RPCs) to control power quality [25–28], References [29–32] proposed constructing a power routing TPS, which is shown in Fig. 4. In this TPS, RPCs are installed in TSSs and section posts (SPs) of existing single-phase power frequency AC TPSs [33]. An RPC consists of a back-to-back single-phase four-quadrant converter whose AC terminals are connected to the adjacent feeding sections. The RPCs can transfer active and reactive power between two feeding sections, which realizes their power routing. Apart from RPC, power redistribution between two feeding sections can also be implemented by a three-phase voltage source converter (VSC) [34].

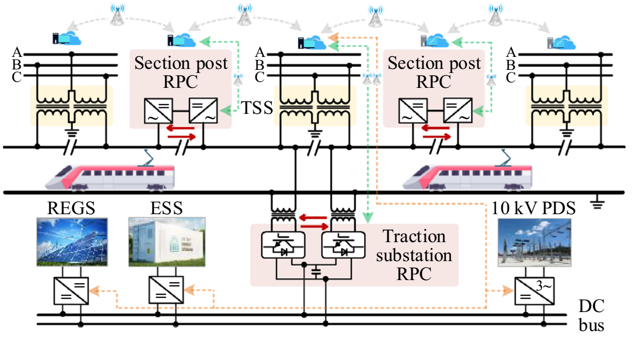

Fig. 4 RPC-type power routing TPS

In this structure, different feeding sections are no longer separate individuals, and the coordinated energy supply of multiple TSSs is implemented by utilizing the power routing equipment and hierarchical energy control strategy [35, 36]. As a result, regenerative braking energy (RBE) can be transferred and utilized between locomotives operating in different feeding sections; simultaneously, the negative sequence current injected into the three-phase utility grid will be reduced, benefiting from the power balance of different feeding sections. Additionally, RPCs can compensate for the reactive power and suppress the voltage fluctuation to a certain extent. Furthermore, renewable energy generation stations (REGSs), energy storage stations (ESSs) and railway 10-kV power distribution systems (PDSs) can be interconnected through power routing equipment DC buses to form a railway integrated energy system, which can construct a resilient TPS with interconnected feeding sections and achieve efficient acceptance of renewable energy [37, 38].

Another advantage of this TPS is that power routing equipment does not affect the original structure of the conventional TPS and can also adapt to different types of traction transformers. Thus, this scheme is applicable to the reconstruction of existing TPSs with a relatively small cost. Additionally, the failure exit of the power routing equipment does not interrupt the power supply of the system; therefore, the reliability of the system can be guaranteed. However, the shortcoming of this TPS is that the number of neutral sections has not decreased. Table 1 depicts some

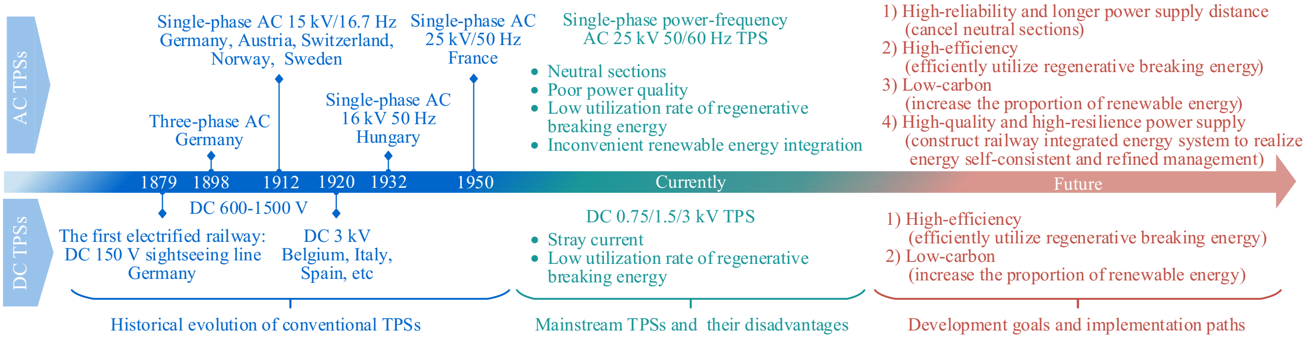

Fig. 3 The historical evolution of conventional TPSs, disadvantages of current mainstream TPSs, and future development goals

Table 1 RPC engineering cases

Country	Line/traction substation	Power routing device
Japan	Shinkansen line	TSS and SP RPC
China	Hunan Shimen traction substation	TSS RPC
	Shanghai Nanxiang traction substation	
	Datong–Qinhuangdao railway	SP RPC
	Lanzhou–Lianyungang railway	

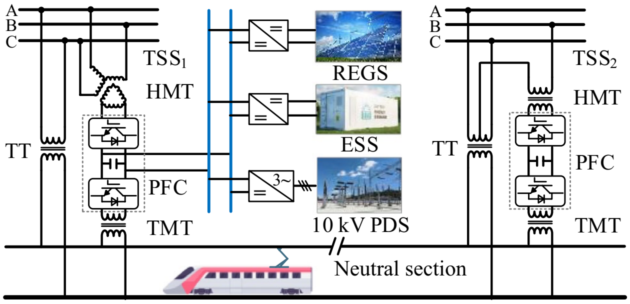

Fig. 5 Combined co-phase TPS

engineering cases of RPCs in Japan and China, which have obtained good results.

3.2 Combined co-phase TPS

References [39–43] proposed a combined co-phase TPS, which employs an electromagnetic transformer and electronic transformer in TSSs. Figure 5 shows the TSS structure of a combined co-phase TPS, which is composed of a single-phase traction transformer (TT), a high-voltage matching transformer (HMT), a power flow converter (PFC), and a traction matching transformer (TMT). The PFC is used to dynamically compensate for the negative sequence current at the grid side of the traction transformer to realize the symmetrical transformation from three-phase AC to single-phase AC in the TSS [44–47]. At the same time, the system can be connected to the railway integrated energy system through the DC link of the PFC [48].

According to the different wiring forms of HTMs, they can be divided into single/three phase combined co-phase power supply scheme and single phase combined co-phase power supply scheme, which are depicted in TSS$_1$ and TSS$_2$ of Fig. 5, respectively. The single-/three-phase scheme is suitable for the upgrading and reconstruction of existing TSSs using V/v and V/x traction transformers, while the single-phase scheme is suitable for new projects because of its simpler structure and higher equipment utilization rate [49, 50]. Both schemes have been put into engineering application in China over the past decade. The cases are listed in Table 2.

A combined co-phase power supply device can realize a high-quality power supply by compensating for the negative sequence current and taking into account reactive power and harmonic compensation. Moreover, the combined co-phase power supply takes the traction transformer as the main power supply equipment and the PFC as the auxiliary power supply equipment. In this way, a good balance between technology and economy can be obtained by optimizing the co-phase compensation device capacity. Additionally, the co-phase power supply device also provides an interface for renewable energy generation stations and energy storage stations. However, the combined co-phase TPS does not realize the complete decoupling of the traction network and the three-phase utility grid, which results in the impact of the traction load on the utility grid not being avoided. On the other hand, neutral sections installed in section posts still cannot be cancelled. In the future, novel bilateral power supply technology will be applied in combined co-phase TPS. Then, a continuous co-phase power supply without neutral sections can be realized.

3.3 Traction substation group continuous TPS

As mentioned in section III-B, to further implement the bilateral power supply mode, the feeding sections on both sides of the section post need to be connected. However, the three-phase utility grid in some countries (e.g., China) adopts the management mode of "high-voltage loop network, low-voltage disconnection, and tree structure power supply." An electromagnetic loop network may be formed while the section post between two adjacent traction

Table 2 Combined co-phase traction power supply engineering

Time	Traction substation/line	Power supply device
2010	Meishan traction substation [40]	Co-phase power supply device
2014	Shayu traction substation [41]	Single-/three-phase combined co-phase power supply device
2019	Wenzhou intercity railway S1 [48]	Single-phase combined co-phase power supply device
2021	Guangzhou metro line 18	Single-phase combined co-phase power supply

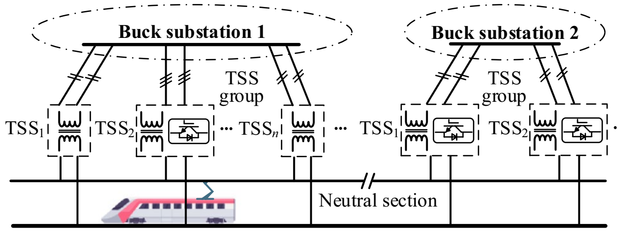

Fig. 6 Traction substation group continuous TPS

substations is simply connected, to form a bilateral power supply mode, and the high-voltage side of two traction substations draws power from different superior substation buses. In this instance, the power flow originally flowing through the utility grid will penetrate the traction network, which will have negative effects on the dispatching and management of the utility grid. To avoid this problem, Refs. [51, 52] proposed combining two or three TSSs into a group, and the high-voltage side of the TSSs in this group is connected to the same bus of the buck substation, forming the traction substation group continuous TPS, as shown in Fig. 6. A tree structure is formed between the buck substation and several TSSs in the group. In a group, even if the neutral sections installed in section posts are connected to realize bilateral power supply, the electromagnetic loop network will not be formed. At the same time, the traction substation adopts a single-phase traction transformer, which can further realize the continuous power supply in a traction substation group.

For each traction substation group, a continuous power supply is realized, which greatly reduces the number of neutral sections. This TPS is suitable for some extreme railway conditions, such as long slope sections (dense neutral sections cause unfeasible speed loss of locomotives) and railways with extremely weak utility grid (few available external power). However, all TSSs in a group are powered from the same phase bus of the buck substation, greatly aggravating the three-phase voltage imbalance of the buck substation. Thus, it is necessary to select a main TSS in the traction substation group and install a comprehensive compensation device to achieve centralized power quality control. Another option could be to install a compensation device in each TSS for decentralized power quality control [53–55].

3.4 Flexible continuous TPS

In a flexible continuous TPS, as shown in Fig. 7, the full line of the catenary is connected without neutral sections. The catenary is powered by TSSs employing the power electronic transformer (PET). The PET is composed of a three-phase rectifier and a single-phase inverter, which can control the output voltage amplitude and phase to the unified voltage of the full-line traction network. In this way, the neutral sections can be completely eliminated, and power quality issues such as negative sequence current, reactive power and harmonics can be solved [56, 57].

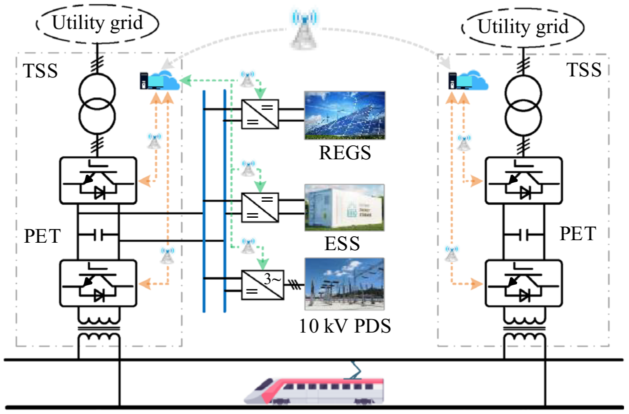

Fig. 7 Flexible continuous TPS

In the flexible continuous power supply mode, the locomotives are simultaneously powered by multiple TSSs, which enhances the power supply capacity compared with the unilateral power supply mode. As PETs can decouple the traction network and utility grid, the adverse impact of the traction load on the utility grid is effectively reduced [58, 59]. In addition, TSSs, renewable energy generation stations, energy storage stations and railway power distribution systems can effectively form a railway integrated energy system [60–64]. Thus, self-consistent railway energy management is realized, and a resilient TPS is erected. In light of the above advantages, this is an ideal power supply mode, especially for high-speed and heavy-haul railways. Many countries have carried out engineering applications. Table 3 summarizes the deployment time of the first flexible continuous TPS project in different countries. Nevertheless, in this TPS, the traction load power is fully borne by the power electronic transformers. The reliability of the system needs to be further improved in the face of strong impact traction loads. The primary investment cost of high-capacity and high-voltage PETs is high.

3.5 HVDC-feeder flexible continuous TPS

Swedish scholars propose to use a ± 60-kV high-voltage DC (HVDC) feeder to form an HVDC-feeder flexible continuous TPS, as shown in Fig. 8 [66, 67]. In this system, a double-layer power supply pattern is formed. The main substations (MSSs) are set in the system for rectification, and then, the electric energy is transmitted to each TSS through the dedicated railway HVDC-feeder. Compared with the HVAC distribution line, the application of an HVDC-feeder can reduce the total distribution loss of the system. Moreover, the DC distribution line provides a good interface for the distributed

Table 3 Flexible continuous traction power supply engineering

Time	Country	Line	Power supply device
1994	Germany	Nuremberg railway	Three-phase 50 Hz–single-phase 16.7 Hz
2004	Japan	Tokaido Shinkansen [65]	Three-phase 50 Hz–single-phase 60 Hz
2014	Australia	Queensland railway	Three-phase 50 Hz–single-phase 50 Hz
2022	China	Beijing Daxing International Airport line	Three-phase 50 Hz–single-phase 50 Hz

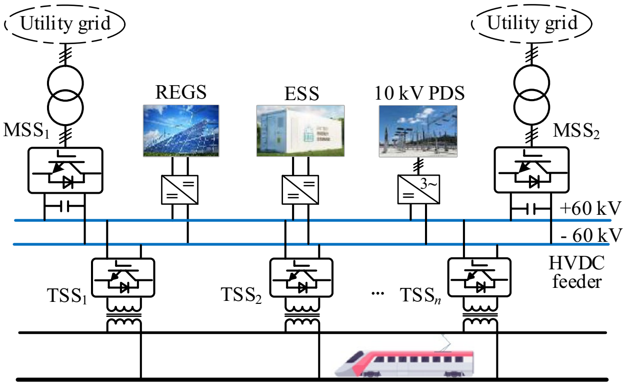

Fig. 8 HVDC-feeder flexible continuous TPS

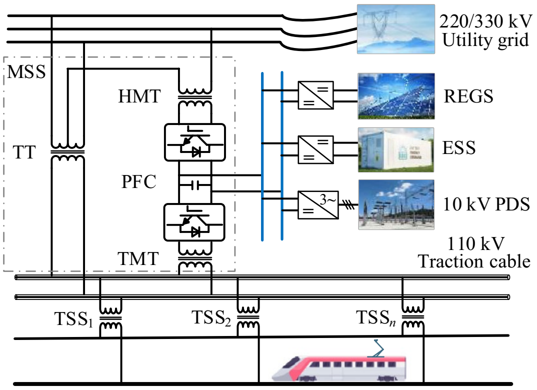

Fig. 9 Cable continuous TPS

renewable energy generation stations along the railway [68, 69]. In traction substations, a VSC is used to invert and output a single-phase AC voltage for the catenary.

In this TPS, the neutral sections are completely eliminated. Compared with electromagnetic transformers, PETs have a stronger support capacity for bus voltage, which also results in high primary investment cost. At the same time, the TPS realizes isolation between the utility grid and the traction network through the two-stage transformation of electric energy, greatly reducing the impact of the traction load on the utility grid.

3.6 Cable continuous TPS

Based on the combined co-phase TPS, Refs. [70, 71] presented the cable continuous TPS, which also forms a double-layer power supply pattern. As shown in Fig. 9, the main substation is set up to convert the three-phase 220-kV/330-kV voltage into single-phase 110-kV voltage, and then, the power is transmitted to each TSS through the dedicated railway traction cable. Due to the use of single-phase traction transformers, neutral sections installed at the exit of TSSs are no longer needed. Additionally, all TSSs are powered by the same main substation, which can realize a continuous power supply within the full-line catenary.

The power transmission capacity of the cable is stronger than that of the overhead line. Applying the cable to the traction network can extend the distance of the power supply section without neutral sections. However, under the influence of the cable capacitance effect, the voltage rise of the catenary is relatively obvious without one locomotive operating in the system. In this situation, reactive power compensation is necessary. While considering the negative sequence and harmonic current compensation, the co-phase compensation device can be set in the main substation to conduct the centralized control of power quality. The master–slave power supply relationship also brings reliability problems. The outage of the main substation will affect multiple subordinate TSSs. Additionally, a high-voltage cable distribution line must be constructed in cable continuous TPS, which requires a large investment cost.

3.7 Summary and discussion

The aforementioned AC TPSs have different advantages and disadvantages in terms of power supply capacity, power quality, economy, etc. Table 4 presents a comprehensive comparison of the above six AC TPSs. Simultaneously, the applicable lines for each TPS are given.

For the number of neutral sections, the flexible continuous TPS and HVDC-feeder TPS can realize a full-line continuous power supply without neutral sections. In the cable continuous TPS and traction substation group continuous TPS, only the neutral sections at the group connection are reserved. The combined co-phase power supply can cancel

Table 4 Comparison of different AC TPSs

TPS type	The number of neutral sections	Power distance	Power quality	Construction difficulty	Infrastructure cost	Advantages	Disadvantages	Applicable line
Power routing TPS	Numerous	Medium	Compensation required	Low	Low	Minor structure changes, high-reliability	The number of neutral sections dose not decrease	Reconstruction of existing lines
Combined co-phase TPS	Less	Medium	Compensation required	Medium	Medium	Reduce neutral sections by half	Neutral sections installed in section post has not been removed	New and existing line reconstruction/urban rail transit
Traction substation group continuous TPS	Little	Long	Compensation required	Medium	Medium	Reduce most of neutral sections	Power quality compensation is required	Long slope sections/railways with extremely weak utility grid
Flexible continuous TPS	None	Long	No need compensation	High	High	No neutral sections and realizes isolation between traction network and utility grid	Power electronic system, high cost	High-speed railway/heavy-haul railway/urban rail transit
HVDC-feeder flexible continuous TPS	None	Long	No need compensation	High	High	HVDC-feeder has lower power transmission loss, no neutral sections	High cost, and each traction substation is highly dependent on the main substation	High-speed railway/heavy-haul railway/extreme railway conditions
Cable continuous TPS	Little	Long	Compensation required	Medium	Medium	Reduce most of neutral sections	Each traction substation is highly dependent on the main substation, and traction cable has a high cost	Extreme railway conditions

the neutral sections located at the exit of TSSs, while the power routing TPS does not reduce the neutral sections of the conventional single-phase power frequency AC TPS.

In terms of the power supply distance, the power routing TPS and combined co-phase TPS belong to the unilateral power supply mode, and the power supply distance has not increased. Under the AT power supply mode, the power supply distance of a single feeding section of the traction substation can reach 25–30 km. The other four power supply structures adopt the bilateral power supply mode; thus, the power supply distance of the single feeding section has improved.

As with power quality, flexible continuous TPS and HVDC-feeder TPS realize isolation between the traction network and the utility grid through AC–DC–AC power conversion, so the traction load has little interference on the utility grid. The other four power supply structures deploy active and reactive power compensation devices to comprehensively control the power quality. After the improvement, power quality indicators such as three-phase unbalance, reactive power and harmonics can conform to the state standards.

In terms of construction difficulty and infrastructure investment, flexible continuous TPS and HVDC-feeder TPS employ power electronic transformers for power supply, so the construction difficulty and cost are high. Combined co-phase TPS, traction substation group continuous TPS and cable continuous TPS adopt the combination of electromagnetic transformer and power electronic transformer, with medium construction difficulty and cost. Moreover, the power routing TPS has the smallest cost in power electronic converters and lowest construction difficulty.

4 DC traction power systems in state of the art

In DC TPSs, the main development goals include increasing the proportion of renewable energy and the utilization of RBE, reducing the adverse effects of DC stray current. Thus, this section gives a particular introduction of various topologies of state-of-the-art DC TPSs, including their structures, advantages and disadvantages. Then, a comprehensive comparison is conducted in terms of power supply distance, power quality, regenerative breaking energy utilization, stray current level, investment cost, etc. Finally, the applicable lines of each TPS are depicted.

4.1 Combined DC TPS with energy feedback and storage device

The combined DC TPS with energy feedback and storage device is shown in Fig. 10. The main substation implements voltage step-down and power quality comprehensive compensation. The diode rectifiers installed in TSSs draw power from the AC 35/10-kV medium-voltage loop network and then provide DC voltage to the catenary. The VSC-type inverter feedback device feeds regenerative breaking energy back to the medium-voltage ring network for station AC load [72, 73]. Moreover, the rest of the regenerative braking energy will be reused by a storage device [74, 75].

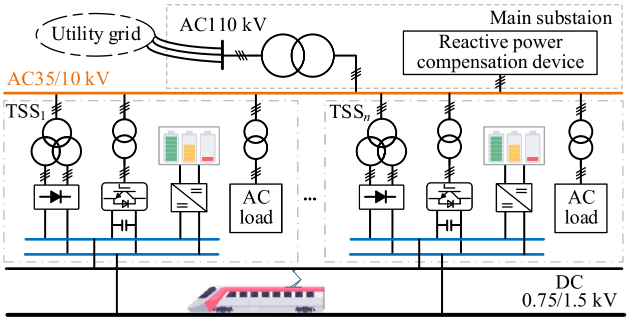

Fig. 10 Combined DC TPS with energy feedback and storage device

In this TPS, the utilization of abundant regenerative braking energy is realized. The energy consumption of the locomotives is reduced, which benefits from removing the on-board braking resistance. These measures raise the level of energy conservation and emission reduction. Currently, energy feedback devices have mature technology, low cost and small equipment volume. It has been used in many projects [76–80] and has gradually become an essential part of urban rail transit TPS [81]. However, the cost of energy storage equipment is high, and its volume is too large, which is not conducive to installation in places with limited space, such as subways. In the future, VSCs will gradually replace conventional diode rectifiers to construct a flexible DC TPS [82, 83].

4.2 Flexible medium-voltage DC TPS

At present, some countries in Europe, America and Asia have DC 3-kV railways, and DC 3-kV trunk railway lines account for more than 90% of the total railway mileage in Italy [84]. The contradiction between the large traction current and the temperature rise of the catenary cable is serious in the low-voltage DC TPS, which limits its application to high-speed and heavy-haul railways. It is only applied to railways with speeds below 200 km/h. To give full play to the advantages of the DC TPS and obtain comparable capacity with the AC TPS, scholars in France, Italy and Spain pointed out that the rate voltage of DC TPS will increase to 7.5–24 kV in the future [85–87]. Power supply distance, power supply voltage and other indicators reflecting the power supply capacity of the system are quantitatively calculated in [85, 86]. Gómez-Expósito et al. [88] proposed

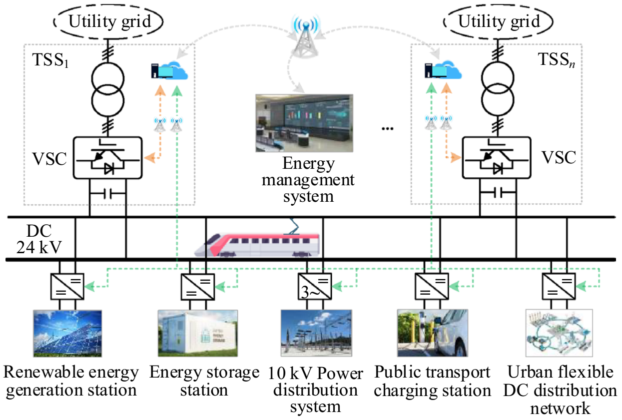

Fig. 11 Twenty-four-kV flexible DC TPS

a 24-kV flexible DC TPS, which is shown in Fig. 11. The VSC is adopted to convert three-phase AC to 24-kV DC in TSSs. For the high-voltage and high-power application of traction power supply, they [88] recommended that the modular multilevel converter (MMC) topology should be used as the traction substation converter.

In the 24-kV flexible DC TPS, the traction network conductor has no skin effect and no reactance voltage drop; thus, the traction network impedance is lower, and the power supply distance is longer than that of the AC TPS under the same voltage level. The power supply distance of the traction substation in the system usually increases to 100–160 km (the distance between two traction substations). Therefore, the number of TSSs decreased significantly, which is beneficial to lines with few available locations for traction substations (such as mountain railways with a high proportion of bridges and tunnels or long sea crossing railways). Additionally, the DC continuous traction network provides a natural interface for distributed renewable energy generation stations and the interconnection of other power supply networks. With the DC catenary as the bus, the system can also be interconnected with the public transport charging station and the urban flexible DC distribution network. Under the unified control of the energy management system, a resilient DC railway microgrid structure with the DC catenary as the bus is formed [89–94]. Moreover, the DC system is more simplified at the controller, with only one dimension of voltage. However, as a new voltage standard is adopted, the traction drive system of locomotives operating in this TPS needs a major change [95, 96].

4.3 DC autotransformer TPS

Effectively reducing the DC stray current of the reflux system is important to further improve the operational safety of urban rail transit. Some scholars have proposed novel DC TPSs to realize active suppression of stray current. References [97–99] add the negative feeder and three-port DC power converters to the conventional DC TPS, forming the DC autotransformer TPS, as shown in Fig. 12. The three ports of DC power converters are connected to the catenary, rail and negative feeder. The voltage balance module controls the catenary–rail voltage to be equal to the rail–negative feeder voltage to form a $2 \times U$ power supply circuit. Because the topology of the power supply system is similar to the AT power supply mode in AC TPS, this system is also called the direct current autotransformer (DCAT) TPS.

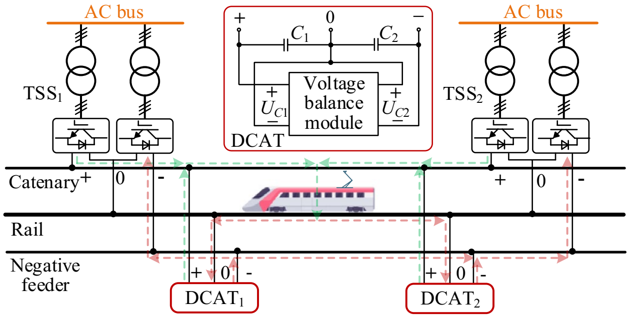

Fig. 12 DC autotransformer TPS

This power supply topology changes the power flow distribution of the traction network. In the long circuit, the traction current is transmitted through the catenary–overhead negative feeder circuit, fundamentally reducing the traction return current flowing through the rail and the stray current [100–102]. The power flow path under ideal conditions is depicted in Fig. 12 with dotted lines. The system improves the power supply voltage and reduces the traction network impedance, which further enhances the power supply capability. At the same time, adding power electronic converters for power flow control means increasing the investment cost and complex system equipment.

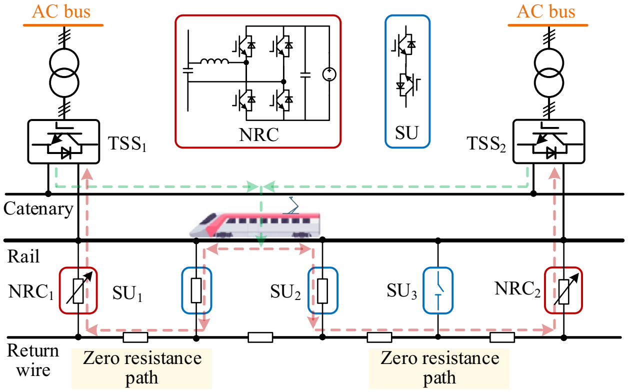

Fig. 13 Negative resistance converter TPS

4.4 Negative resistance converter TPS

Figure 13 shows the topology of the negative resistance converter DC TPS, which was presented in [103, 104]. First, return wire is added to the conventional DC TPS. Then, power converters composed of fully controlled power electronic devices are installed between the rail and the return wire to change the power flow distribution of the traction return current. As a result, part of the traction current flowing through the rail is transferred to the overhead return wire, which reduces return current leakage into the earth.

In Fig. 13, the negative resistance converter (NRC) forms a negative output resistance by controlling the voltage and current of the port, which will offset the positive resistance on the return wire to form a zero-resistance path. The switch units (SUs) along the railway control their own opening and closing according to the locomotive's position and cooperate with the NRC to form a zero-resistance path for the traction return current. Dotted lines represent the power flow path under ideal conditions in Fig. 13. The traction current returns to the traction substation through the zero-resistance path instead of the rail. However, introducing the locomotive's position variable into the control system will greatly increase the cost and complexity of the software and hardware of the control system.

4.5 Summary and discussion

Table 5 provides a comprehensive comparison of DC TPSs discussed in section IV A–D. The adaptive railway lines of different systems are given.

Under the premise of not changing the structure of the conventional DC TPS, the first DC TPS can realize the effective utilization of regenerative braking energy by adding inverter feedback and energy storage devices in TSSs. Compared with the other three power supply structures, the investment cost is smaller, and the practicality is higher.

The flexible medium-voltage DC TPS faces challenges such as high investment and the reconstruction of the locomotive traction drive system. However, compared with the other three power supply structures, the flexible medium-voltage DC TPS has significantly improved power supply distance and capacity, which is more suitable for high-power locomotive loads of high-speed and heavy-haul railways. At the same time, it has more advantages in realizing renewable energy consumption and resilient power supply.

The third wire and several power electronic converters distributed along the railway are added to the conventional DC TPS, forming the DC autotransformer and negative resistance converter TPSs. The system equipment is more complex. However, flexible control of power flow will be beneficial for stray current suppression. Furthermore, the regenerative braking energy recovery is convenient in the flexible power supply mode.

5 Novel electrified rail transit energy supply technologies

This section introduces mixed-system electrified railways, superconducting cable TPS and some novel electrified rail transit energy supply technologies without catenaries, which can satisfy some extreme railway conditions and special application scenarios.

Table 5 Comparison of different DC TPSs

TPS type	Power supply distance	Complexity of devices	Stray current level	Disadvantages	Applicable line
Combined DC TPS with energy feedback and storage device	Short	Simple	High	The utilization rate of regenerative braking energy depends on the capacity of inverter feedback and energy storage device	Urban rail transit
Flexible medium-voltage DC TPS	Long	Simple	Low	High investment cost, immature technical system and large reconstruction in locomotive traction drive system	High-speed and heavy-haul railways
DC autotransformer TPS	Medium	Complex	Low	Increase investment cost in negative feeder and DCAT and additional land occupation	Urban rail transit and high-speed railway
Negative resistance converter TPS	Short	Complex	Low	Increase investment cost in return wire and converters and additional land occupation	Urban rail transit

5.1 Mixed-system electrified railway

Throughout the history of TPSs for electrified rail transit, the power supply standard and voltage level of TPSs changed with the service objects, power supply distance, construction conditions and other factors [20, 21]. AC TPSs are usually applied to trunk railways with high-power locomotives and long transportation distances. The power supply standard mainly includes 25 kV/50 Hz, 25 kV/60 Hz and 15 kV/16.7 Hz. DC TPSs are usually applied to urban rail transit with lower power requirements and shorter transportation distances, including DC 750 V, 1.5 kV and 3 kV. Railways with different power supply standards operate independently of each other, and electric locomotives cannot operate across various power supply systems, which limits passenger travel and freight transport efficiency.

To realize the cross-region running of electric locomotives under different power supply standard TPSs, a power supply transition zone is set between the conventional AC and DC traction networks to construct a mixed-system TPS [105–108], which is depicted in Fig. 14. In this system, the structural change in the traction network is relatively small. The key point in developing mixed-system electrified railways is the design and manufacture of mixed-system electric locomotives, which integrate AC and DC traction drive systems into the same electric locomotive.

The demand for economic and trade exchanges between different countries in Europe is large, but the railway power supply standards in various countries are diversified [21]. To guarantee uninterrupted railway transportation, the development of European mixed-system electric locomotives is at the forefront of the world. Table 6 shows mixed-system electric locomotive platforms of different countries.

5.2 Superconducting cable TPS

France and Japan have been conducting studies and tests to achieve a superconducting feeder cable system applicable to actual railway lines [109–112]. As shown in Fig. 15, in this TPS, the superconducting cable is placed parallel to the catenary and connected to the TSSs without changing the existing structure of TPS. The introduction of superconducting cables to TPS will greatly reduce the voltage drop and is expected to realize some advantages, such as reduction of transmission loss and TSS numbers, as well as rail potential stray current suppression. However, because of the zero-resistance characteristic, the fault current is enormous after short circuit in superconducting feeder cable system. Moreover, small voltage difference between TSSs will generate a large circulating current, which is also a critical issue [113, 114].

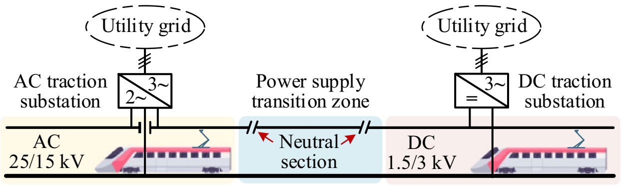

Fig. 14 Mixed-system TPS

Table 6 Mixed-system electric locomotive platforms

Country	Company	Mixed-system electric locomotive
Germany	Siemens	Eurosprinter-series
French	Alston	PRIMA-series
Canada	Bombardier	TRAXX-series
China	CRRC Co., Ltd.	20E-series and 22E-series

5.3 Electrified rail transit energy supply technologies without overhead catenary system

Presently, the pantograph–catenary sliding contact power supply mode is popularly adopted in TPSs. Nevertheless, abnormal phenomena of the pantograph–catenary system often occur during locomotive operation, which are attributed to the complex system structure. Meanwhile, the analysis of wave propagation theory indicates that when a flexible overhead catenary system is used for the power supply, the upper limit of the locomotive speed is approximately 700 km/h [115]. Hence, the pantograph–catenary contact current collection mode cannot satisfy the application requirements of higher speed rail transit in the future. Moreover, in urban rail transit, it is not convenient to install overhead catenary systems on crowded city streets. In recent years, a few power supply technologies without catenary systems have been developed, which are briefly introduced as follows.

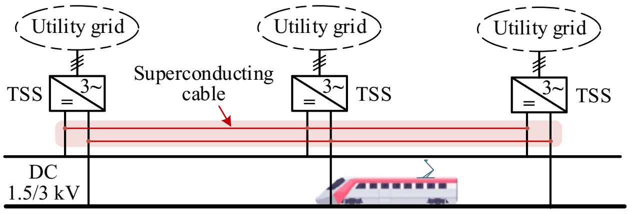

Fig. 15 Superconducting cable TPS

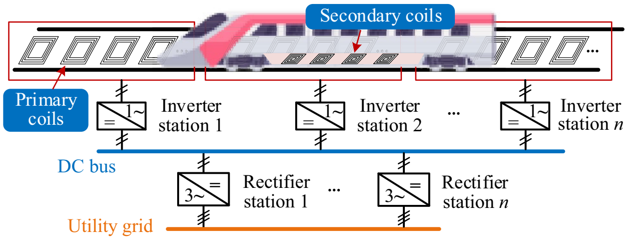

Fig. 16 Rail transit with the WPT system

5.3.1 Rail transit with the wireless power transmission system

Scientific research teams from many countries in the world have been committed to applying WPT technology to the field of rail transit power supply [116–119]. As shown in Fig. 16, the system consists of rectifier stations, inverter stations, primary coils arranged on the rails and secondary coils installed in the locomotives. Power was obtained by electromagnetic coupling of the WPT systems. Table 7 lists some typical rail transit with WPT system cases publicly reported in the literature. Overall, only a few cases of rail transit high-power WPT systems have been applied. In the future, the large-scale application of rail transit WPT systems still has many problems that need to be solved:

(a) Power improvement [116]: The locomotive power is usually 8–20 MW in high-speed and heavy-haul railways. With this power demand, the WPT system needs to increase transmission power to satisfy it. However, a narrow locomotive bottom space also makes it difficult to achieve power improvement of the WPT system.
(b) Steady power supply [117]: Different from WPT applications of consumer electronics and electric vehicle charging, in rail transit WPT systems, the electric energy receiving end (locomotive) is in a state of rapid movement. Therefore, it is also a huge challenge to solve the static offset and the stability of power transmission during the rapid movement of the receiving end.
(c) Efficiency improvement [118, 119]: In the application of a high-power rail transit power supply, the efficiency of the WPT system has dramatic effects on the system operation economy.

5.3.2 Hydrogen energy rail transit

Currently, diesel locomotives are mainly used in application scenarios in which it is inconvenient to obtain electric energy through the catenary, such as shunting locomotives, rescue locomotives, engineering maintenance locomotives, and transportation tasks in some nonelectrified sections. Compared with diesel locomotives that consume fossil fuels, hydrogen fuel cell locomotives have the advantages of zero carbon emissions and high-energy utilization efficiency and operate without catenary systems. Developing hydrogen fuel cell locomotives to replace diesel locomotives is an effective way of constructing green and low-carbon rail transit [120–125]. In the future, the large-scale market application of hydrogen fuel cell locomotives depends on the progress of hydrogen production, hydrogen storage and other related supporting technologies. The application in high-speed and heavy-haul railways depends on the further improvement of the power density of the locomotive hydrogen fuel cell system.

5.3.3 Novel third rail power supply technologies

Italy introduced a “Tramwave” system for trams or light metros [126, 127]. The contact rail is laid on the ground, and rail space can be shared with urban traffic vehicles. French Alston developed a ground power supply system called “APS” for “Citadis” trams [128–130]. These two systems provide power to locomotives by the specific third rail rather than the overhead catenary system, reducing interference with urban landscapes.

5.3.4 Other types of rail transit without catenary systems

In addition to the abovementioned systems, some advanced energy supply technologies for locomotives are also notable. References [131–133] research maglev trains, which can break the velocity limit caused by wheel/rail contact. Additionally, the combination of maglev trains and vacuum-sealed tubing will form an ultrahigh-speed ground transportation mode that is faster than 1000 km/h. Moreover, with

Table 7 Rail transit WPT systems

Time	Country	R&D units	Products
1997	New Zealand and Germany	University of Auckland and Wampfler AG company	Fixed rail sightseeing vehicle
2009	Canada [117]	Bombardier	RPRIMOVE-series trams (100–500 kW)
2015	Korea [116]	Korea Railway Research Institute	High-speed train (818 kW)
2021	China	Southwest Jiaotong University and CRRC Co., Ltd.	Tram (500 kW)

the development of controllable nuclear fusion technology, micronuclear power plants are expected to be applied to electric locomotives in the future. In this way, external power sources are no longer needed for locomotives.

6 Development trends and challenges of future electrified railways

To satisfy the power supply requirements of future electrified railways under various extreme conditions, one is actively promoting existing TPSs to constantly develop in the trends of electronic-type, continuous-type, improving the power supply reliability and resilience. At the same time, a high proportion of renewable energy consumption is an inevitable requirement for the sustainable development of the energy system. TPSs will accelerate the construction of distributed renewable energy generation stations and achieve low-carbon electrified railways. As a result, resilient TPSs will be constructed by integration with REGSs, ESSs and railway 10-kV DPSs. Furthermore, mixed-system electrified railways, superconducting cable TPS, WPT systems, hydrogen fuel cell locomotives and other electrified rail transit energy supply technologies without catenaries, including the "Tramwave" system, "APS" system, maglev rail transit and nuclear-powered locomotives, can be employed as supplements.

Under the requirements of the above development trends, the challenges and key technologies faced by constructing new TPSs are as follows:

(1) One of the major development trends of TPSs is electronic-type. Power flow control, renewable energy access and interconnection of different traction network architectures all rely on a large amount of power electronic equipment. At present, the comprehensive cost performance of power electronic devices with high voltage and power needs to be improved. With the application of next generation wide bandgap power electronic devices, the voltage and current withstand level of the devices will be improved significantly, enabling the power electronic converter to obtain higher reliability and lower power consumption. Thus, the equipment investment and operating costs are reduced, which vigorously boosts the process of electronic-type TPSs.

(2) The second notable development trend of TPSs is continuous-type power supply. From the perspective of improving the power supply distance, the continuous power supply of full-line traction network will eventually be realized. However, that will inevitably pose a huge challenge to traction network protective relaying. In the new TPSs, the sectioning protection, state measurement and control technology of the traction network are crucial for the accurate location of the fault and power outage range reduction after the fault. Moreover, the ability of power electronic devices to withstand impulse voltage and current is weak, which contradicts the characteristics of strong fluctuation and impact of traction loads. The protection of power electronic power supply devices in TSSs also has certain particularity and complexity. Therefore, it is necessary to construct a device-station-system level cooperative protection scheme to ensure the reliability and security of the power supply.

(3) In the new TPSs, the boundary between power sources and loads is no longer obvious. The power converters, energy storage stations and locomotives constantly switch between source and load conditions. The power

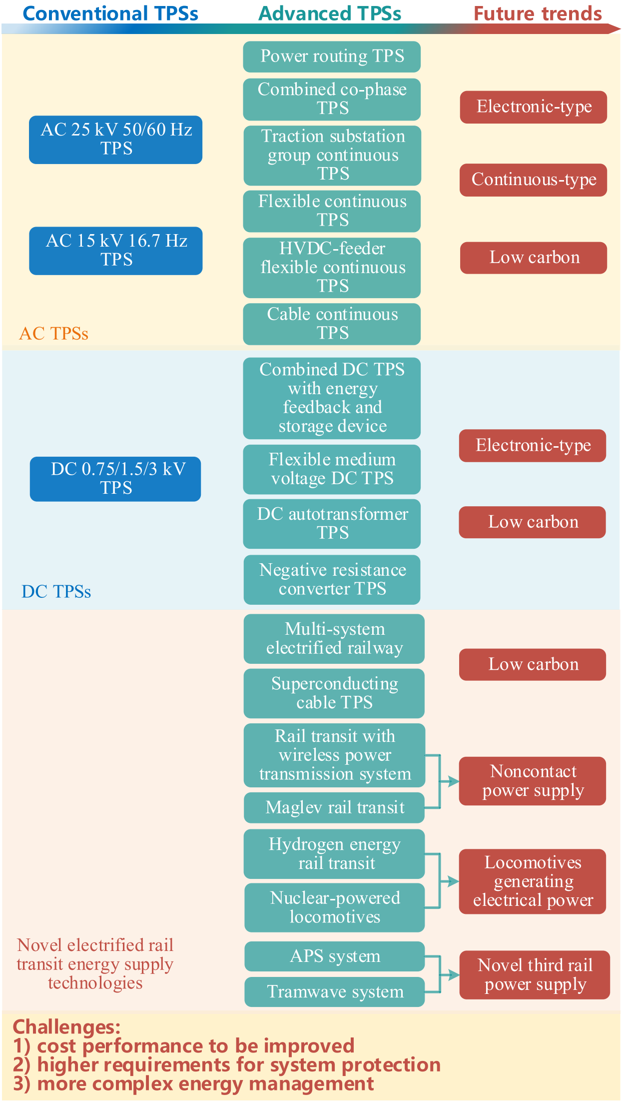

Fig. 17 Development trends and challenges of TPSs

of the renewable energy generation station and the railway 10-kV power distribution system also have randomness. Therefore, it is also a key technology to build a multilevel energy management strategy of "converter-traction station-system" to dispatch the railway integrated energy system to meet the balance of power adaptively, safely and efficiently.

In summary, Fig. 17 displays the kinds of TPSs introduced in this paper. Furthermore, their development trends and challenges are summarized briefly.

7 Conclusion

This paper overviews the historical evolution of electrified railways and reveals that the development of TPSs is closely related to locomotive traction drive systems. Through more than one century of development, conventional DC 0.75/1.5/3-kV TPS and AC 25-kV 50/60-Hz TPS dominate electrified railways at present. Then, based on issues exposed from existing TPSs, future development goals of electrified railways are presented. State-of-the-art AC and DC TPSs satisfying the requirements of future electrified railways are described. Meanwhile, comprehensive comparisons of their advantages and disadvantages are discussed. Moreover, mixed-system electrified railways, superconducting cable TPS, and electrified rail transit energy power supply technologies without catenaries are introduced as supplements. In the future, applying power electronics, energy storage and renewable energy generation equipment to construct low-carbon, high-efficiency and high-reliability TPSs is an inevitable trend. In addition, traction power supply technologies without catenaries are also an important development direction. Finally, the challenges and key technologies are summarized.

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