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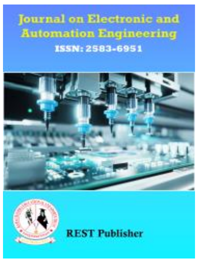

Evolution of Traction Power Systems and DC Electric Traction

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Abstract: *Traction power systems (TPSs) have revolutionized transportation by transitioning from mechanical and steam-based methods to advanced electric systems, enabling efficiency, reliability, and scalability. These systems have played a crucial role in enhancing the performance of railways and urban transit while reducing environmental impact and addressing the growing demand for sustainable mobility. Among the key advancements, Direct Current (DC) electric traction has emerged as a cornerstone technology, offering advantages such as precise speed control, reduced energy losses, and efficient power delivery. DC traction is particularly well-suited for modern transit systems due to its adaptability and compatibility with Renewable Energy (RE) integration, aligning with global sustainability objectives. Despite challenges like infrastructure complexity and maintenance requirements, DC electric traction continues to demonstrate its effectiveness in meeting contemporary transportation needs. This paper explores the evolution and significance of TPSs, focusing on the technological advancements and transformative role of DC electric traction in shaping efficient, sustainable, and future-ready transportation solutions.*

Keywords: *Electric Traction, Direct current, Alternating current, Traction power system.*

1. INTRODUCTION

The core objective of railway power systems is to deliver electric energy to locomotives effectively and economically. Railways play a vital role in modern, high-capacity transportation networks, serving urban and rural areas by moving large numbers of passengers efficiently. Electric traction relies on electric motors to generate the propulsion needed for movement. The inception of electric railways dates back to 1881, pioneered by German engineer Werner von Siemens, while the Italian Railways were the first to implement electric traction. In India, the introduction of electric traction began in 1925 with the operation of the first electric train between Victoria Terminus (Mumbai) and Kurla. Electric traction offers a sustainable alternative to fossil fuels, being energy-efficient, eco-friendly, and free from pollution. This transition in India started with the use of 1500 Volt DC systems, marking a significant milestone in railway electrification [1]. In the current era, energy efficiency has become a key factor influencing the competitive edge of railways in both domestic and global transportation markets. Electrified railways, forming the backbone of advanced transportation systems, are known for their high capacity, cost-effectiveness, low emissions, and operational efficiency [2,3]. With growing economies, the expansion of electrified railway networks is accelerating globally. For instance, projections suggest that by 2035, China’s railway network will span approximately 200,000 kilometres, with 90% electrification. However, the rapid growth of electrified railways has resulted in substantial energy consumption and highlighted challenges related to efficiency and reliability. As the global focus shifts toward carbon neutrality, advancing electrified railways with low-carbon, energy-efficient, and highly reliable systems has become an essential priority. The transition to electric traction is motivated by its distinct advantages over fossil fuel-based systems, applicable across transportation and industrial applications. Primarily, it offers environmental benefits such as eliminating carbon emissions and reducing reliance on fossil fuels, which also results in quieter operations. Economically, it stands out due to lower costs in fuel, operation, and maintenance compared to conventional systems. Electric locomotives demonstrate superior energy conversion efficiency by transforming electrical energy into mechanical energy with high effectiveness. They are adaptable to diverse power sources, including renewable energies like solar and wind, thereby further minimizing environmental impact. Regenerative braking systems enhance efficiency by converting kinetic energy back into electricity, extending operational range and reducing energy wastage. As a result, electric traction emerges as an environmentally friendly, cost-effective, and efficient solution, aligning with global sustainability goals while driving advancements in India's transportation network. In AC TPSs, the network is generally divided into sections separated by neutral zones. Each segment is supplied by a dedicated Traction Sub Station (TSS) using a unilateral power supply approach. This configuration faces significant limitations, such as challenges in achieving a balanced three-phase utility grid, constraints on long-distance power delivery, and restricted support for high-speed locomotive operations [4,5]. Additionally, the segmented design complicates the effective use of Regenerative Braking Energy (REB) from locomotives and limits the seamless incorporation of RE sources. Moreover, electric locomotives, characterized by their high power, nonlinearity, and significant load fluctuations, often induce issues like harmonic distortions, power imbalances and wide-band frequency fluctuations, which have a detrimental impact on the utility grid and the traction network [6, 7, 8]. The innate structural drawbacks of conventional TPS systems make it difficult to meet the future needs of electrified railways, which demand greater RE integration, enhanced system resilience, longer power supply ranges, and superior power quality. This paper focuses on examining the historical progression of traditional TPS, identifying the constraints of current power supply frameworks, and highlighting development objectives. It also offers a thorough review of advanced TPSs and innovative energy supply technologies designed to meet the future demands of electrified rail transit. Additionally, the paper discusses emerging trends and technical challenges in TPSs, aiming to serve as a reference for both theoretical research and practical applications in this field. The following is a summary of this paper's main contributions:

1. A chronological presentation of the evolution of traditional TPSs detailing the evolution, structural features, and the respective strengths and weaknesses of each system.
2. Advanced TPSs suitable for future electrified railways are outlined, including a comparative analysis of power supply capabilities, investment costs, and other attributes, along with recommendations for their appropriate applications.
3. The paper incorporates nearly all recent advancements in TPSs and emerging rail transit energy technologies, providing a valuable resource for researchers seeking a comprehensive reference.

2. LITERATURE REVIEW

Chen and Li et al.,have proposed the concept of combining two or three TSSs and connecting their high-voltage sides to one bus of the buck substation. As a result, a continuous traction substation group TPS is formed. The buck substation is connected to the group's several TSSs via a tree structure. The network of electromagnetic loops does not emerge in this configuration, even when neutral segments in section posts are connected for bilateral power supply. Furthermore, the traction substation's use of a single-phase traction transformer guarantees a steady supply of power for the entire group [9, 10]. Letizia et al., have observed that power quality is a well-established concept in traditional 50/60 Hz AC power systems. Numerous methodologies, algorithms, and measurement techniques related to power quality are included in international standards and are extensively covered in scientific research. It is acknowledged that evaluating Power Quality (PQ) is a useful technique for raising railway systems' performance. Important insights into disruptions produced by DC electric traction have been gained from studies of how common DC fluctuations in railway networks affect the frequency properties of equipment in both AC substations and onboard trains [11]. Kaleybar and Morais et al., have claimed that harmonics produced in AC electric trains are responsible for a significant portion of the active and reactive power. Multiple distortion forms that greatly overlap are characteristics of these railways, which are characterised by a mix of sliding loads under various operating circumstances [12, 13]. Shaposhnikov et al., have provided an illustration of a traction motor controller developed for a metro electric power system. Considering the factors for electric motor design, the subsystem of the subterranean electrical power supply system was modelled. The simulation was created once the electric motor load was calculated. All of the electric motor's power options can be fully utilised to the model for the starting and braking subsystems. After the model was examined, oscillograms of the motor's braking and starting operations were acquired. The underground vehicle component was controlled by the model's implementation of the operator controllers and the subway car rheostat controller features. The driver's controller manages the underground car's power circuits [14]. Lin et al. have constructed a model using finite elements that represents flat damage contact and a rigid-flexible coupled system for fast trains. They examined the effects of single-wheel or double-wheel flats on the wheel-rail dynamics with different positional distributions [15]. According to Wang et al., tire flats significantly increased the force of friction, contact force and stress, and vibrational acceleration at the braking interfaces [16]. According to Ye et al., wheel flats can also cause or exacerbate wheel polygonal wear, and the length of the flats and the vehicle's running speed have a big impact on the damage [17]. Yang et al. developed a wheel-rail dynamics model which included a gearing system and investigated both the time- and frequency-domain impacts of tire flatness on the gear system under changing speed circumstances [18]. According to Wang et al., wheel flats may result in vibrations with high frequencies in gear mesh and longitudinal creep forces [19]. Guo et al. have combined the Miner linear damage theory using vehicle-track linked mechanics to offer an investigation of the vibration effect of wheel flats on motor bearings [20]. Based on their findings, wheel flats would reduce the motor's fatigue life due to the high contact and recurring impact forces. According to Jianwei et al., during traction and braking situations, wheels with flats exhibit stronger dynamic features, however when sliding, the alterations are comparatively small [21].

3. RESEARCH METHODOLOGY

The research methodology for the study of the "Evolution of TPSs and DC Electric Traction" will begin with an extensive literature review to trace the historical development and technological progress of DC electric traction systems. Primary sources such as engineering journals, conference proceedings, technical papers, and industry reports will be examined to identify key advancements, challenges, and innovations in the field over time. The study will focus on understanding the chronological evolution of TPSs, particularly DC electric traction, with an emphasis on design improvements, energy optimization, and operational efficiency. Qualitative analysis will synthesize the historical context and technical advancements, while quantitative analysis will explore data on power consumption, system performance, and efficiency. Case studies of existing and past railway networks will be analysed to evaluate the real-world application and impact of DC traction systems.

Evolution of conventional TPSs and future development goals

The world's first electrified railway, established by Siemens and Halsk in 1879, operated on a 150-volt DC system. Electric trains were initially powered by DC traction motors, offering exceptional speed control. From the late 19th century into the early 20th century, systems utilizing low-voltage DC (under 1500 V) became prevalent in applications such as tramways, light rail systems, mining railroads, suburban trains, and metros. These trains often relied on a third rail for power. However, the limited voltage capacity of the overhead line restricted the locomotive's output, rendering low-voltage DC systems insufficient to meet the rising transportation demands. Over decades of technological progress, standardized Traction Power Supply (TPS) systems have been established across nations: in urban transit, which requires moderate power levels, 750-V or 1.5-kV DC systems are commonly implemented. Figure 1 shows the Conventional DC TPS The traditional DC TPS system's structure is shown in Figure 2a. TSSs employ transformers and diode-based rectifiers to convert AC power to DC.

This system has two notable aspects:

1. Stray currents are created when traction current travels through the rail and returns to the TSS's negative terminal, but some current will unavoidably leak into the ground by the rail's transition resistance. DC stray currents have the potential to cause significant electrochemical damage of underground metal structures along the railway, although AC stray currents are less dangerous. Due to the complex subterranean metal pipeline networks, urban train systems that use DC TPS suffer additional difficulties that must be mitigated by particular technical solutions.

2. Frequent starting and stopping of trains in urban railways generate significant REB. However, much of this energy is wasted as it is dissipated as heat through braking resistors, leading to inefficient energy utilization.

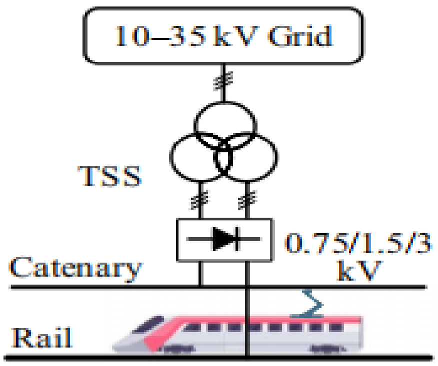

FIGURE 1. Conventional DC TPS

The primary goals of DC TPS are to decrease the harmful effects of DC stray currents, enhance the usage of REB, and raise the proportion of RE. An extensive review of the several advanced DC TPS patterns is given in this part, together with information on the designs, advantages, and limitations. Following that, a thorough comparison is conducted, with particular attention paid to factors such as expenditures on investments, stray current levels, and quality of power, REB utilisation, and electric supply distance.

Energy Feedback and Storage Integrated DC TPS

Figure 2 shows the integrated DC TPS with the energy feedback and storage mechanism. Voltage reduction and comprehensive compensation of power quality are carried out by the main substation. TSSs are equipped with diode rectifiers that extract energy from the medium-voltage loop network of AC 35/10-kV, which then supply DC voltage to the catenary. The REB is fed back into the medium-voltage network for the station's AC load by a Voltage-Source Converter (VSC)-type inverter. Any surplus REB is stored in a storage device for later use.

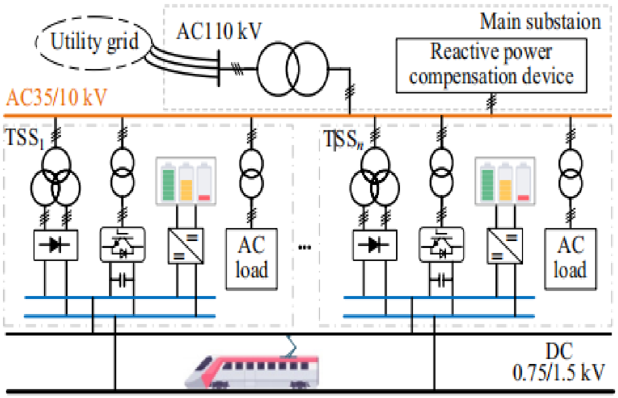

FIGURE 2. Combined DC TPS with energy feedback and storage device

DC autotransformer TPS

The reduction of stray DC currents in the reflux system is crucial for enhancing the operational safety of urban rail transit. Researchers have introduced innovative DC TPSs that actively suppress stray currents. The DC autotransformer TPS, shown in figure 3, is an improvement on the traditional DC TPS that incorporates a negative feeder and 3 port DC power converters. The negative feeder, rail, and catenary are connected to the 3 ports of the DC power converters. A 2× U power supply network is created when the rail-negative feeder voltage and the catenary-rail voltage are equal owing to the voltage regulating device. This design, which is identical to the Auto Transformer (AT) power supply used in AC TPS, is known as the Direct Current Auto transformer (DCAT) TPS. Power supply capability is increased, traction network impedance is decreased, and power supply voltage is increased using this system. However, adding power electronic converters to regulate power flow leads to more complicated system elements and higher prices.

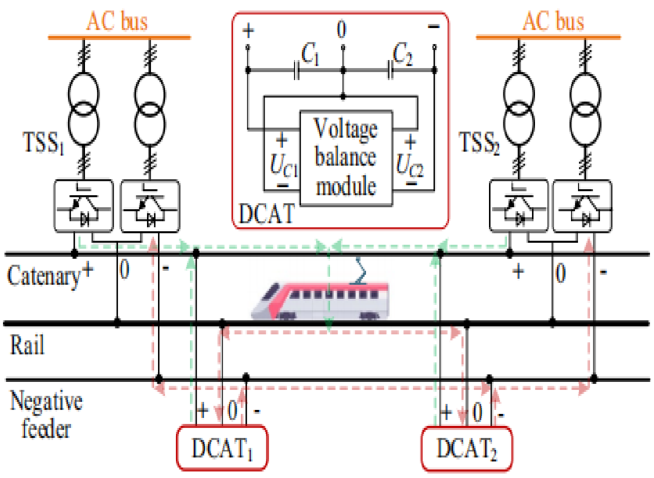

FIGURE 3. DC autotransformer TPS

Mixed-system electrified railway

The power supply standards and voltage levels of TPS for electrified rail transit have evolved over time, influenced by factors such as service requirements, power supply distances, and construction conditions. Mainline railways with high-power trains and long-distance transit usually use AC TPSs. These systems are often powered by 15 kV/16.7 Hz, 25 kV/60 Hz, and 25 kV/50 Hz power supplies. DC TPSs, on the other hand, are better suited for urban rail transit that uses specifications like DC 750 V, 3 and 1.5 kV and has lower power requirements and shorter travel distances. The effectiveness of passenger and freight transit is hampered by the isolation of railways with disparate power supply standards, which restricts electric locomotives from moving among different networks. A key challenge in developing mixed-system electrified railways lies in the design and production of locomotives capable of integrating both AC and DC traction drive systems. Figure 4 shows the mixed-system TPS.

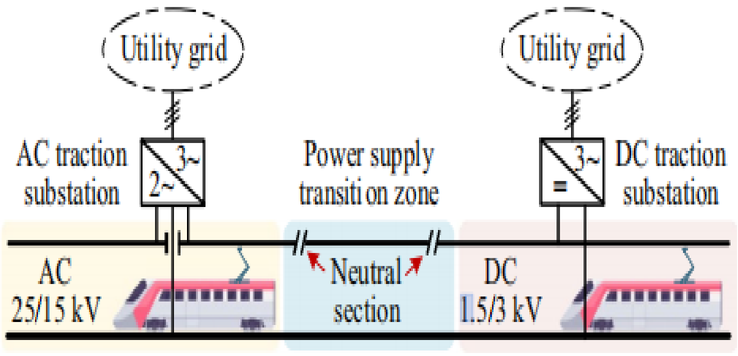

FIGURE 4. Mixed-system TPS

4. RESULT AND DISCUSSION

A significant tendency in TPS development is the move towards electronic kinds, where electrical power equipment plays a major role in power flow control, integration of energy from renewable sources, and connecting different traction systems. There is still need for enhancements to the power electrical devices handle high voltage and power. It is anticipated that the voltage and current endurance of future wide-bandgap of power electronic devices will be greatly increased, thereby increasing the reliability of power electronic converters and reducing power consumption. This, in turn, lowers both equipment investment and operational costs, accelerating the adoption of electronic-type TPSs. Challenges for the flexible medium-voltage DC TPS include high investment costs and the need for modifications to the locomotive traction drive system. However, it offers substantial improvements in power supply distance and capacity compared to other power supply structures, making it better able to meet the high-power requirements of heavy-duty and high-speed railways. Furthermore, it offers benefits in terms of resilient power supply and incorporation of RE. The standard DC TPS develops into the DC autotransformer and the negative resistance TPSs converter by adding a third wire and several electrical power converters along the railway. The system's variable power flow regulation greatly helps to decrease stray currents, despite its greater complexity. Moreover, the flexible power supply mode facilitates efficient recovery of REB.

5. CONCLUSION

Traditional AC 25-kV 50/60-Hz TPS and DC 0.75/1.5/3-kV are still the major systems in electrified railroads, despite of advancements over the past century. Considering the challenges identified in current TPS designs, the future goals for the construction of electrical railways are outlined. The latest advancements in AC and DC TPSs, which address the requirements of future railways, are reviewed, along with a comparative analysis of their strengths and weaknesses. In addition, alternative solutions, such as hybrid electrified railways, superconducting cable TPS, and catenary-free power supply technologies for electrified rail transit, are introduced. The adoption of power electronics, energy storage, and RE sources to build sustainable, efficient, and reliable TPSs is expected to be a crucial trend moving forward. Furthermore, the exploration of TPSs that operate without catenaries remains a key area of development. Lastly, the challenges and critical technologies necessary for the advancement of electrified railways are summarized.

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