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Editorial

Multi-Level Technological Advancements in Stability and Energy Efficiency of Railway Traction Power Supply Systems

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1. Introduction

Under the twin forces of global energy transition and transportation electrification in the 21st century, the railway system, as an efficient backbone transportation mode, has witnessed the optimization of power supply technology and energy efficiency emerging as a central challenge driving industrial innovation. With the expansion of the high-speed railway network and increased density of rail transit operations, traditional power supply system designs and operational paradigms are confronting unprecedented challenges. Concurrently, there is an increasing demand for enhanced safety, economic viability, and environmental compatibility of power supply systems. The question of how to ensure secure and stable operation of traction power supply systems while improving energy efficiency has become a shared focus in both academic and engineering communities. This paper aims to synthesize recent research advancements in power supply stability and power quality within railway systems, all of which have been published in the Special Issue "Studies in the Energy Efficiency and Power Supply for Railway Systems".

2. Review of New Advances

As a high-density, strongly coupled complex network architecture, railway traction power supply systems encounter multifaceted challenges in both systemic design and operational management, with high-frequency resonance phenomena constituting the predominant technical obstacle. The interplay between distributed parameters inherent in traction systems and nonlinear moving loads induces high-frequency resonance coupled with transient overvoltage events, ultimately precipitating power quality degradation and accelerated equipment aging. These complex system dynamics and their consequential impacts have garnered significant scholarly attention within the global research community [1–4]. The emergence of higher-order harmonic components necessitates rigorous electromagnetic transient modeling of railway traction infrastructure, imposing critical requirements for precise electrical parameter identification and iterative model calibration. As fundamental research in harmonic analysis, ref. [5] implemented algorithmic enhancements to the Sparrow Search Algorithm through Gaussian perturbation integration and Tent chaotic mapping optimization, thereby improving parameter identification accuracy for traction load dynamic models. This methodological innovation effectively addresses the inherent challenges in nonlinear traction load modeling within power systems while enhancing model response fidelity under voltage disturbance conditions. Subsequent to these parametric identification advancements, researchers have achieved comprehensive

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modeling frameworks for railway power supply infrastructures [6] and electric locomotive systems [7,8], enabling sophisticated quantitative analysis of higher-order harmonic propagation characteristics within railway electrical networks [9–12]. Through systematic high-voltage field testing methodologies, ref. [13] conducted rigorous investigations into the influence of catenary distributed parameters on harmonic resonance frequency characteristics in traction power supply systems. The research culminated in the proposal of suppression strategies based on multi-conductor transmission line modeling and chain network theory foundations. Subsequent scholarly work has further elucidated the generation mechanisms, propagation pathways [14], and mitigation techniques [15–18] associated with higher-order harmonics in railway traction systems. Expanding the investigative scope to three-phase power grid interactions, ref. [19] examined harmonic propagation trajectories and transmission mechanisms induced by traction loads. This study implemented quantitative analysis of critical factors affecting low-voltage auxiliary power systems, developed equivalent circuit models for low-voltage load components, and successfully achieved harmonic impedance parameter identification for auxiliary power loads through singular value decomposition methodologies.

Due to its unique transportation characteristics, railway systems impose exceptionally stringent requirements on operational safety, with stability demands extending beyond systemic considerations to component-level reliability. While complex railway power supply systems inherently contain critical vulnerable components, system-level safety optimization cannot entirely eliminate device-level failure risks. Consequently, stability research focusing on specific critical components has gained significant academic attention. As essential elements for power transmission, single-core cables are universally adopted in railway transmission lines to ensure power supply reliability. Extensive research has been conducted on cable protective grounding methodologies. Ref. [20] proposed a grounding configuration where the metallic shielding and armor layers of single-core transmission cables are directly grounded at one terminal while employing universal sheath protection devices at the opposite end. Ref. [21] recommended arranging electromotive forces in an equilateral triangle configuration to mitigate cable induction effects, with the continuous length of cable metallic layers strictly controlled within 3 km. Ref. [22] systematically investigated the structural characteristics, physicochemical properties, and induced potentials of multi-chain single-core cables. Ref. [23] conducted a comprehensive analysis of the generation mechanisms and influencing factors for induced potentials and circulating currents in through-line single-core cables, proposing a simplified engineering application approach. Furthermore, the researchers established sophisticated simulation models using specialized software to analyze sheath-induced potentials and circulating currents in railway through-line single-core cables, enabling quantitative characterization of current and potential characteristics under universal equipment protective grounding configurations.

Furthermore, for fundamental equipment like transformers and circuit breakers, failures arise from the long-term complexity inherent in electrical devices and their operating environments [24]. Consequently, transformer failures manifest diverse symptoms, and the relationship between fault symptoms and mechanisms is complex, making fault diagnosis particularly challenging. Transformer faults can be categorized into electrical, thermal, and mechanical types. However, mechanical faults typically manifest as electrical or thermal faults; thus, in most cases, transformer failures can be simplified into discharge faults and overheating faults [25]. Ref. [26] utilized concentrations of hydrogen, ethane, ethylene, and acetylene as inputs, collected diverse sample data types, and achieved reliable transformer fault identification through BP neural networks. Ref. [27] developed an expert system for transformer diagnosis based on expert knowledge, detailing its system architecture. This system offers simplicity and reliability, providing novel approaches and tools for practical

diagnostic challenges. Ref. [28] employed fuzzy sets and fault tree algorithms, using fault tree analysis as the diagnostic foundation to identify fault locations and establishing a fuzzy set diagnostic model to enhance accuracy. Ref. [29] integrated real-time electrical equipment information with fault diagnosis using IoT-based multi-data fusion technology. Subsequently, it implemented transformer fault diagnosis via a BP neural network algorithm optimized by particle swarm optimization. By optimizing feature subsets with PSO, this study established a fault diagnosis model for vacuum circuit breakers, achieving effective circuit breaker fault diagnosis.

Building upon stable system operation, research on power quality and energy utilization in railway traction power supply systems has progressively advanced.

Regarding power quality, conventional power quality management devices struggle to simultaneously achieve harmonic suppression, power factor correction, inertia enhancement, and negative-sequence component elimination [30,31]. Although previous studies have implemented dynamic reactive power compensation through specialized connection transformers and reactive components [32], the compensation effectiveness remains limited. However, with the proposal and development of MMC-RPC systems [33,34], diverse control methodologies have been applied to RPC devices to achieve enhanced power quality management. The authors of [35] adopted an integrated control strategy combining voltage–current double closed-loop control with hysteresis comparison for conventional RPCs. In [36], the MMC-RPC employed a phase-locked-loop-free direct power control strategy, demonstrating rapid power response and robust stability. In [37], virtual synchronous generator control was implemented to provide improved inertia and damping support. Ref. [38] introduced adaptive virtual synchronous generator control to dynamically emulate the external characteristics of synchronous generators under varying operating conditions, achieving optimized inertia and damping control. Concurrently, a differential flatness control strategy was applied in the inner loop to ensure stable control of the MMC-RPC.

To improve energy efficiency, modern trains are equipped with regenerative braking systems, which capture the kinetic energy from braking and convert it into electrical power that can be used by other motor trains. Therefore, timetables make an important impact on train regenerative braking utilization. An optimal timetable is able to provide a means of reducing energy consumption by reaching the full potential of train regenerative braking systems. A large number of scholars have presented different methods to model railway operations and develop optimal running strategies to improve operational efficiency. Zhi developed a common train timetabling mathematical model, which can calculate the most appropriate timetable according to different objectives, including robustness and dwell time [39]. Most of the previous timetable optimization research outcomes are based on simulations without trial tests or practical verifications. For example, Xin has developed scheduling rules to improve the train overlapping time but has not identified the impact on the regenerative braking energy utilization [40]. Montrone has used two simulation tools, namely modeFRONTIER and Opentrack, to calculate and validate the train energy consumption results [41]. Due to environmental and human disturbances, such as high passenger boarding and alighting rates in peak-time hours, system failures, etc., trains may perform differently compared with their modelling and simulation results [42]. Therefore, ref. [43] establishes a train kinematic model based on Newton's laws and the Davis equation and employs a genetic algorithm to optimize service intervals with the objective of maximizing regenerative braking energy utilization. The optimized timetable is generated through this approach. For the first time, the optimized timetable is applied to an actual metro line, and real-world operational data collected via the Onboard Train Monitoring Recorder demonstrate the algorithm's effectiveness, as evidenced by a 4.1% increase in regenerative energy utilization and a 2.2% reduction in total energy consump-

tion. This practical implementation bridges the gap between theoretical simulations and real-world applications.

3. Conclusions

Modern railway power supply systems constitute complex integrated systems requiring coordinated operation and mutual interaction across multiple hierarchical levels. Research on the stability and energy efficiency of such intricate systems inherently spans multiple system layers, encompassing component-level stability optimization at the micro scale to system-wide harmonic suppression at the macro scale. Furthermore, the railway power supply domain demonstrates increasing multidisciplinary convergence, extending from advancements in conventional electrical engineering theories to the integration of artificial intelligence technologies.

These systemic challenges demand multidimensional breakthroughs spanning fundamental theories, control strategies, and engineering implementations. The research presented in this Special Issue provides a focused response to these requirements. Analysis of studies published in this Special Issue, titled "Energy Efficiency and Power Supply in Railway Systems", reveals both innovative reinterpretations of classical issues and proactive explorations of emerging challenges. Progress in these domains not only equips the industry with technical toolkits to address current operational constraints but also outlines potential evolutionary trajectories toward digitalization, resilience, and decarbonization in future railway energy systems. The featured articles present substantive, knowledge-enhancing research that expands scholarly understanding while stimulating further scientific inquiry.

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