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Review

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A review of comprehensive utilization of regenerative braking energy in AC electrified railways

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Abstract: In the context of global decarbonization initiatives and the rapid advancement of electrified railways, the efficient utilization of regenerative braking energy (RBE) has emerged as a critical energy policy in China. RBE not only significantly reduces railway energy consumption, but also offers substantial potential for providing auxiliary services to the power grid, enhancing the coordination, economic efficiency, and stability of both railway and power systems. In this paper, we first analyze RBE utilization strategies, including optimization of train operation scheduling, energy storage technologies, energy sharing mechanisms, and energy feedback configurations. Then, from a macro perspective, the hierarchical structure of the RBE control system is explored. The upper-level energy management system of regenerative braking exhibits development trends based mainly on thresholds, optimization, and learning. Meanwhile, the lower-level converter control system tends to adopt strategies that improve the voltage balance and circulating current performance of the modular multilevel converter-railway power conditioner (MMC-RPC) while reducing computational burden. Finally, based on existing theoretical research and practical engineering applications, rational suggestions are proposed to enhance the utilization efficiency of RBE. These recommendations provide strong support for the efficient utilization of RBE in alternating current electrified railways (ACERs), as well as for technological innovation and economic development.

Key words: Regenerative braking energy; Train operation optimization; Energy storage systems; Energy sharing and feedback; AC electrified railways

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1 Introduction

By the end of 2024, the operational mileage of China's railway system had expanded to 162,000 km, marking significant progress in railway infrastructure development. However, this expansion has been accompanied by a corresponding increase in energy consumption. In 2021, the electricity consumption of China's railways surged to 78.7 billion kWh, establishing it as one of the largest single loads on the power grid. Notably, recoverable regenerative braking energy (RBE) constitutes about 40% of the total traction energy consumption. This immense untapped potential, aligned with China's "Dual Carbon" strategy and escalating railway decarbonization imperatives, necessitates urgent methodological advances in RBE valorization.

While RBE temporarily stored in energy storage systems (ESSs) offers ancillary services enhancing grid resilience, systemic inefficiencies persist: only 15-30% of RBE is used in conventional AC electrified railways (ACERs), constrained by three phase electrical imbalance and harmonic and transient power mismatches. Recent breakthroughs in wide-bandgap power electronics, hybrid ESS topologies, and AI-driven predictive control have catalyzed global RBE research, yet a critical gap remains: the absence of a holistic framework integrating technological innovations with hierarchical control paradigms. To bridge this gap, this review presents a systematic analysis of RBE utilization schemes through dual lenses:

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(1) Critical utilization schemes of RBE—train operational scheduling optimization, multi-form ESS, and advanced feedback configurations;

(2) Control systems of RBE—upper-level energy management systems and lower-level converter control systems.

We systematically analyze current technological approaches and their hierarchical structure and identify emerging development trends to establish theoretical frameworks and practical guidelines for advancing RBE applications in rail transportation systems.

2 Critical Utilization Schemes of RBE

2.1 Utilization Schemes of RBE Based on Optimization of Train Operational Scheduling

Operational scheduling optimization comprises mainly: (1) train trajectory optimization (Sun et al., 2023; Xing et al., 2023) and (2) train schedule optimization (Pan et al., 2020). Trajectory optimization emphasizes the development of a comprehensive multi-parametric optimization framework that incorporates critical infrastructure characteristics, including gradient profiles, tunnel configurations, and sectional speed limits. This approach establishes objective functions aimed at either minimizing total energy consumption or maximizing RBE utilization, ultimately optimizing train velocity profiles. As illustrated in Fig. 1, different train speed profiles correspond to distinct total energy consumption values. Through trajectory optimization, an optimal operational path and combination of operational modes are obtained. It was demonstrated that the speed profile corresponding to trajectory 2 yielded the lowest total energy consumption under the given constraints.

The optimization of train scheduling focuses on the macroscopic regulation and control of the operation distribution across multiple trains. As illustrated in Fig. 2, this approach enhances RBE utilization by maximizing the temporal overlap between the traction and braking modes of adjacent trains (trains i and j) within the same power supply section. This is achieved through strategic adjustments of operational parameters, including tracking the interval between trains and station dwell times, thereby enabling optimal energy transfer from braking trains to those under traction. Such coordinated scheduling significantly improves overall RBE utilization efficiency across the railway grid.

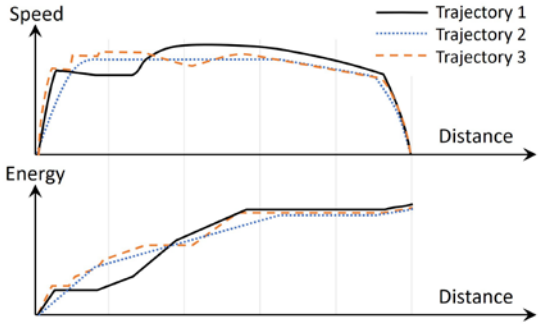

Fig. 1 Schematic diagrams of train trajectories

Enhancing RBE utilization through operational scheduling optimization offers a cost-effective solution that requires no additional energy storage or power regulation devices, making it relatively straightforward to implement. This approach has gained widespread application in urban rail transit systems. However, the optimization model's effectiveness is constrained by multiple limitations, preventing the achievement of maximum RBE utilization potential (Shen et al., 2021). The operational challenges, including severe weather events, vehicle malfunctions, and power supply equipment failures, prevent strict adherence to scheduled operations, resulting in limited maneuverability and reduced operational flexibility (Khodaparastan et al., 2019).

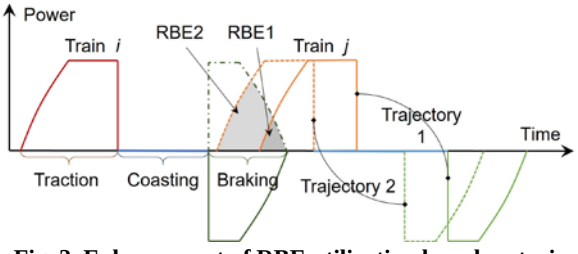

Fig. 2 Enhancement of RBE utilization based on train schedule optimization

2.2 Utilization Schemes of RBE Based on ESSs

ESSs serve as a crucial solution for temporarily storing RBE and subsequently releasing it based on operational demands. The energy storage media for RBE applications include batteries (Yang et al., 2020; Zhang et al., 2022), supercapacitors (Yang et al., 2018), and flywheel energy storage devices (Saeed et al., 2023). Table 1 presents a comprehensive comparison of the performance characteristics of these

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energy storage technologies.

Battery Energy Storage

Battery energy storage, as the most mature and widely implemented technology in ACERs, includes lead-acid, Ni-Cd, Ni-MH, and Li-ion batteries (Danlami, 2021; Mizobuchi et al., 2022). Lead-acid batteries represent the most prevalent storage solution due to their technological maturity and low cost. However, their application is limited by their large physical volume, poor high-temperature tolerance, and environmental pollution (Liu and Li, 2020). Ni-Cd batteries offer cost-effectiveness and stable performance, with cycle life exceeding 1000 charge-discharge cycles, but their use has been restricted in many countries due to the toxicity of cadmium. Ni-MH batteries, developed as an improvement over Ni-Cd batteries, provide 1.5 to 2 times higher capacity in equivalent sizes, demonstrate environmental friendliness, and are particularly suitable for rapid charge-discharge applications due to their higher current capabilities compared to conventional alkaline batteries (Saeed et al., 2023). Nevertheless, Ni-MH batteries are characterized by higher costs and increased system expenses. Currently, lead-acid and Li-ion batteries dominate ACER applications. While Li-ion batteries offer superior energy density, their implementation is constrained by higher costs (Mizobuchi et al., 2022).

Table 1 Comparison of energy storage media

Types of energy storage	Energy density (Wh/kg)	Power density (W/kg)	Investment cost (CNY/(kWh))	Cycling life (Times)	Self-discharge rate (%)	Response time	Sustainable charge-discharge time
Lead-acid	30-45	35-75	375-3000	500-2000	0.05–0.3	ms	s-10h
Ni-Cd	50–75	75–200	1500-7500	1500–3000	0.2–0.6	ms	min-h
Ni-MH	54–100	400–600	1800-9000	1500–3000	1–2	ms	min-h
Li-ion	100–250	150–2000	1500-9000	1000-5000	0.1–0.3	ms	min-h
Na-S	150–240	150–230	2100-3500	2000–4500	15–20	ms	s-h
Flywheel	5–100	400–1800	7000-35000	>20000	100	s	s-h
Supercapacitor	5–15	5000–18000	2100-14000	>30000	10–20	ms	s-min
SMES	0.5–10	100–10^5	7000-70000	>30000	10–15	ms	ms-s

(Data source: Saeed et al., 2023; Rana et al., 2023; Sahoo et al., 2023; Liu and Li, 2020; Yuan et al., 2024; Takarii et al., 2023; Graber et al., 2022; Berrueta et al.,2019; Ali et al., 2010)

Supercapacitor Energy Storage

Supercapacitors exhibit characteristics, including high power density, rapid dynamic response, and environmental friendliness, making them particularly suitable for applications requiring frequent high-power peaks. Their rapid response capability and fast charging characteristics enable them to be charged during short station stops and by the braking process in operation. However, fundamental limitations in their operational principles and energy density present significant challenges that require resolution. The relatively low voltage output of individual supercapacitor cells necessitates the implementation of series-parallel configurations to achieve medium-to-high voltage and meet large-capacity requirements. This configuration, while addressing voltage and capacity needs, introduces voltage imbalance issues within the capacitor bank, consequently affecting their overall charge-discharge efficiency (Lyu et al., 2019).

Flywheel Energy Storage

Flywheels store energy through the physical conversion between electrical and mechanical energy. The configuration typically comprises several key components: rotor, motor, vacuum chamber, outer casing, bearing system, and thermal management system. Flywheel energy storage can be charged and discharged in multiple cycles, with high energy density and power density. It causes no environmental pollution and has no overly strict requirements for the operating temperature and environment. However, flywheel energy storage technology also has limitations. The flywheel must maintain high-speed rotation in the charged state, resulting in a high self-discharge rate (Saeed et al., 2023) and a relatively low energy density. In addition, the cost of flywheel energy storage is relatively high.

With reference to several typical energy storage

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cases listed in Table 2, and in combination with the operating characteristics of various energy storage media, we found that flywheel and superconducting energy storage are commonly applied to high-power ground-based ESS. Superconducting energy storage is still in the testing stage and has not been commercially implemented. Supercapacitors are frequently used in onboard or ground-based high-power ESSs to regulate the power quality in a short term. Energy storage devices like Li-ion batteries and other storage batteries are often used in onboard or ground-based large-capacity ESSs, which can recover RBE and provide power auxiliary services such as peak shaving and valley filling.

Table 2 Application Cases of Energy Storage in Electrified Railway Trains

ESS type	Vehicle type/Substation	Country	Year	Manufacturer	Operating route	Energy storage method	Power/ Capacity
Onboard ESS	BEMU	UK	1958	Scottish British Railways, Bruce Peebles Ltd and Exide Batteries	Deeside (between Aberdeen and Ballater)	Lead-acid	--
	Lithey-Tramy	Japan	2005	Railway Technical Research Institute (RTRI)	RTRI test line	Li-ion battery	300 kW/ 33.0 kWh
	313 Series EMU	Japan	2005	Central Japan Railway and Toshiba	Nagoya area	Supercapacitor	200 kW/ 0.28 kWh
	Hi-tram	Japan	2007	RTRI	Sapporo municipal	Li-ion battery	600 kW/ 72.0 kWh
	SWIMO light rail	Japan	2007	Kawasaki	Sapporo municipal	Ni-MH battery	250 kW/ 120 kWh
	E995 EMU	Japan	2009	East Japan Railway Company (JR East), Mitsubishi Electric	Utsunomiya	Li-ion battery	163 kWh
	RATP Citadis 402	France	2009	Alstom	Paris T3 line/ Porte d'Italie-Porte de Choisy	Supercapacitor	500 kW/ 1.6 kWh
	Tram	Spain	2013	CAF	Saragossa line	Supercapacitor + Li-ion battery	400 kW/ 16 kWh
	Tram	China	2015	CRRC Zhuzhou Locomotive Co., Ltd.	Huai'an line	Supercapacitor	48.6 kWh
	Class 379 electrostar EMU	UK	2015	Abellio Greater Anglia, Bombardier	Harwich-Manningtree line	Li-ion battery	500 kWh
	Wuhan East Lake Tram	China	2017	CRRC Changchun Railway Vehicles Co., Ltd.	Wuhan East Lake Tram L1, L2, L3 Lines	Supercapacitor	47.6 kWh
	Urbos 100 Tram	UK	2018	CAF	Wolverhampton area	LFP Li-ion battery	400 kW/ 80 kWh
	Talent 3 EMU	Austria/Germany	2018	Alstom and Austrian Federal Railways (OBB)	Vorarlberg, Tyrol, and other regions in Austria; some vehicles also used for international service lines	Li-ion battery	--
	Wuhan "Optics Valley Quantum" Tram	China	2018	CRRC Changchun Railway Vehicles Co., Ltd.	L1: Huazhong University—Fozuling, L2: Tangxun Lake—Optics Valley Botanical Garden	Supercapacitor	47.6 kWh
	Hydrogen Fuel Cell Tram	China	2019	CRRC Qingdao Sifang Co., Ltd.	Foshan Gaoming Line	FCveloCity Fuel Cell	--
	BEMU	Germany	2022	Alstom Transport GmbH and Technische Universität Berlin	Baden-Württemberg line/ Bayern area	Li-ion battery	300 kWh
Ground-based ESS	Itayado	Japan	2007	Hitachi	Seishin – yamate line	Li-ion battery	2000 kW/1000 kW/500 kW
	--	Japan	2011	Kawasaki	Osaka line	Ni-MH battery	205 kWh

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Haijima	Japan	2013	JR East	Ome line	Li-ion battery	76 kWh
Okegawa	Japan	2014	JR East	Takasaki line	Li-ion battery	137 kWh
Westlake/MacArthur Park	USA	2014	VYCON and LAMETRO	LA metro red line	Flywheel	2 MW/ 8.33 kWh
Wannianquan Road/Yan'an 3rd Road Station	China	2017	CRRC	Qingdao Metro Line 3	Flywheel/ Supercapacitor	1 MW
Anayama	Japan	2018	JR East and RTRI	Chuo Main line	Flywheel	29 kWh
Guangyangcheng Station	China	2019	CRRC Changchun Railway Vehicles Co., Ltd., Beijing Metro Rolling Stock Equipment Co., Ltd.	Beijing Metro Fangshan Line	Flywheel	1 MW/ 11 kWh
Handan-Changzhi Railway Hebei Xingu Traction Substation	China	2021	Dunshi Magnetic Energy Technology Co. (Flywheel Energy Storage System)	Handan-Changzhi Railway	Flywheel	--
Beijing-Shanghai Railway Sanjie Traction Substation	China	2023	CRRC Qingdao Sifang Rolling Stock Research Institute Co., Ltd.	Beijing-Shanghai Railway	Supercapacitor	11.6 kWh
--	China	2023	CRRC Qingdao Sifang Co., Ltd.	Wuhan "Optics Valley Photon" SkyRail / Jiufeng Mountain-Longquan Mountain Line	Flywheel	--
Hainan Railway Cross-Sea Train Mobile Energy Storage Station	China	2024	China Railway Guangzhou Group Co., Ltd.	Hainan Railway Cross-Sea Train Line, Crossing Qiongzhou Strait	Li-ion battery	400 kW/ 645 kWh

(Data sources: Murray-Smith, 2019; Ogasawara, 2010; Fedele et al., 2021; Ogasawara, 2008; Moskowitz and Cohuau, 2010; Lin, 2021; Filograno, 2012; Li et al., 2015; Reynaud et al., 2018; Ding and Wu, 2024; Boev et al., 2023; Chen et al., 2020; Abad, 2016; Chen et al., 2020; Swanson et al., 2015; Xin et al., 2019)

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2.3 Utilization Schemes of RBE Based on Energy Feedback Technology

Due to the single-phase nature of ACER loads, the single-phase RBE generated by locomotives, when directly fed back into the public grid, can lead to three-phase imbalances, misoperation of relay protectors, harmonic injection, and voltage elevation issues (Thorne et al., 2019). Currently, to ensure the quality of energy feedback in traction power supply systems, the solutions can be categorized into two main types: (1) Optimization of the power supply system's own structure. By using balanced transformers to optimize the system's structure, negative sequence currents can be suppressed, although the compensation functionality is singular and the suppression capability is limited. Expanding the traction grid involves numerous issues such as planning, site selection, and land occupation. A through-type co-phase power supply can fundamentally resolve power quality issues such as a negative sequence. (2) Installation of external compensation devices. These include passive filters (PFs), static var compensators (SVCs), static synchronous compensators (STATCOMs), active power filters (APFs), and railway power conditioners (RPCs).

Energy Sharing of RBE

RPCs show better comprehensive compensation performance, port extensibility, system controllability, and flexibility than other compensation devices (Li et al., 2023). They are widely applied in the feedback and sharing of RBE. Traditional RPCs use a two-level voltage source converter (Ma et al., 2020), which connects two adjacent power supply sections through the secondary side of a transformer. This back-to-back connection enables the RPC to transfer RBE between two supply arms within the same traction substation, balancing active power while compensating for reactive power, thereby creating opportunities to improve the utilization rate of RBE (Ma et al., 2023). Currently, the most mature topology is

the full-bridge two-level converter-based RPC (FT-RPC) (Chen et al., 2024). Additionally, as shown in Fig. 3, there are other configurations such as the half-bridge two-level converter-based RPC (HT-RPC) (Ma et al., 2013) and the two-phase three-wire converter-based RPC (TW-RPC) (Wu et al., 2012).

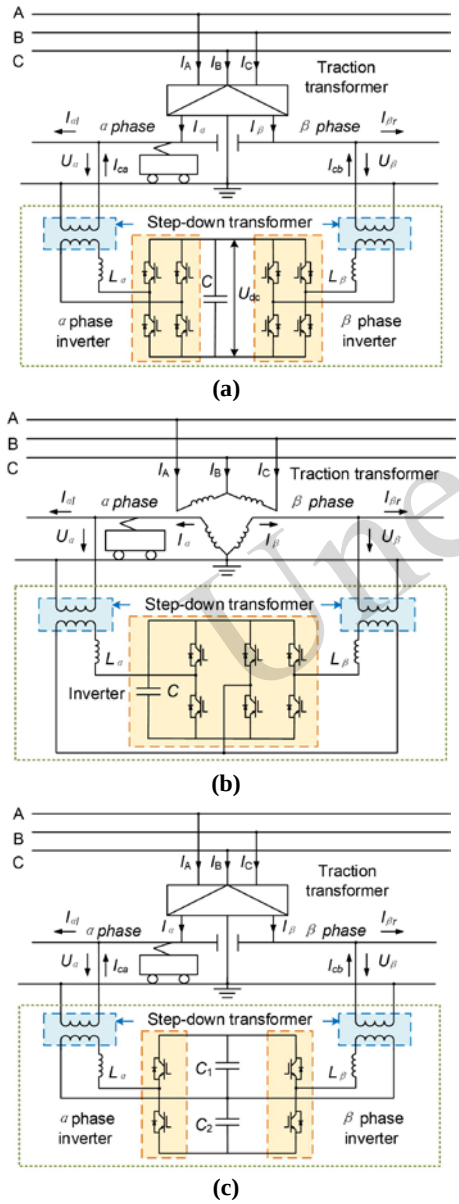

Fig. 3. A railway power conditioner (RPC) and its derived topological configurations. (a) FT-RPC; (b) HT-RPC; (c) TW-RPC

While RPCs can balance the active power load between two supply arms and compensate for the reactive power and harmonics of the traction load, they cannot address the issue of phase separation. The presence of phase separation restricts the utilization of RBE to the local supply arm, preventing its sharing and use across the entire line. To overcome this limitation, a three-phase to single-phase active compensation system based on a balanced transformer and an active power compensator (APC) has been proposed (Dai et al., 2012). In this configuration, one phase of the balanced transformer supplies power to the traction network, while the other phase is connected to the active compensation device, achieving three-phase balance (Fig. 4).

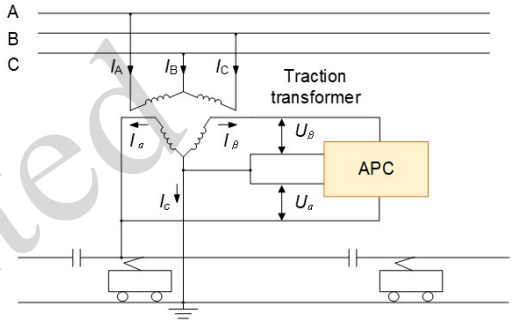

Fig. 4 Three-phase to Single-phase Power Supply System Based on APC

This type of co-phase power supply technology, based on compensation devices, combines power electronic converters with balanced transformers to deliver power to the traction grid. By controlling the power electronic converters, it is possible to mitigate power quality issues at the output of the substation feeding the traction grid (Mousavi et al., 2015). While this co-phase power supply system can eliminate the neutral sections within the substation, it cannot remove the neutral sections across the entire traction network, thus failing to achieve a fully continuous co-phase power supply (Wang et al., 2015; Chen et al., 2016).

Another type of advanced co-phase power supply system uses a power flow converter. The rectifier unit of the power electronic device is coupled to the grid via a transformer, while the inverter unit is connected to the traction grid for power interaction. The traditional traction power supply system (Fig. 5(a)) relies on multiple traction transformers connected to different phases (A, B, C) of the three-phase grid, inherently creating "phase separation" sections where trains must coast through powerless segments, leading to disruptive power fluctuations and speed losses.

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In stark contrast, the advanced through-type co-phase system Fig. 5(b) replaces these transformers with Advanced Co-Phase Power Supply Equipment (ACPSE) units (Shu et al., 2011). These have an AC-DC-AC energy feedback structure which dynamically adjusts the output voltage's amplitude, phase, and frequency via closed-loop inverter control. This establishes a continuous, single-phase power transmission path across the entire traction network that seamlessly interconnects phases A, B, and C without interruption, effectively eliminating the problematic phase separation sections and their associated power fluctuations. The electrical topologies include neutral-point clamped, flying capacitor, cascaded H-bridge, and modular multilevel converter (MMC) structures.

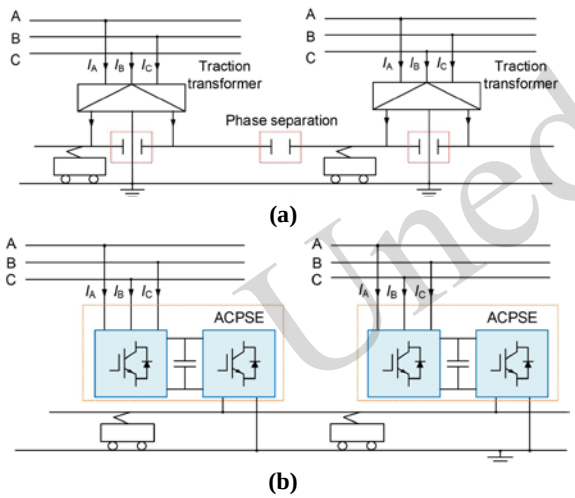

Fig. 5 Schematic diagrams of the structure of traction power supply systems. (a) Traditional Traction Power Supply System; (b) Through-type co-phase power supply system

Based on existing co-phase power supply schemes and combined with the analysis of actual engineering cases presented in Table 3, we aimed to evaluate the current utilization level of RBE and understand the development trends of ACER. In China, the co-phase power supply solution based on balanced transformers and APC is widely adopted. This can effectively prevent the amplification of harmonics by parallel capacitor banks, and parallel SVCs can significantly reduce harmonic fluctuations during power supply voltage fluctuations and flicker. Although there have been many theoretical studies of through-type co-phase power supply technology, it has not yet been implemented in engineering applications.

Table 3 Typical co-phase power supply engineering cases

Co-phase power supply scheme	Time	Country	Operation routes and characteristics
APC Transmission mode of RBE: single-phase interval of a single traction substation.	2010	China	Chengdu-Kunming Railway Line (Meishan Traction Substation)
	2014	China	Shanyu substation in Shanxi Province.
	2019	China	Wenzhou suburban railway line S1 Using APC to eliminate the electrical phase separation at the traction substation. The traction transformer and the negative sequence device are independent of each other.
	2021	China	Guangzhou metro lines 18 and 22 A 10 MVA, 25 kV AC co-phase power supply system is deployed along the railway line, using automatic phase-transition technology for seamless power delivery.
RPC Transmission mode of RBE: adjacent sections of traction substation.	1996	Japan	Shinkansen
	2002	Japan	Tohoku Shinkansen Capacity of co-phase power supply device is 20 MVA/60 kV
	2014	Japan	Ushiku Section Post

(Data source: Han et al., 2013; Wu, 2021; Morimoto et al., 2002; Uzuka et al., 2005; Hayashiya et al., 2016)

The feedback structure of RBE

The direct feeding mode of RBE through the overhead contact line has significant advantages over energy storage solutions in terms of energy efficiency. In the current technical approach, traction loads within the supply arm preferentially absorb braking energy, while any surplus energy is transmitted in reverse through the contact line to adjacent traction substations (Ronanki and Williamson, 2018). This effectively supports the power supply and distribution needs of station facilities and auxiliary equipment.

There is also an independent station feedback-based RBE recovery technology (Fig. 6). RBE

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harvested from rolling stock can be efficiently cascaded from the 27.5-kV traction substation down to the 10-kV railway power supply network. This strategic energy transfer fulfills critical station demands—including lighting, HVAC systems, and auxiliary equipment—across the rail network. Beyond station self-consumption, the feedback energy has full grid compliance, adhering to strict interconnection standards for voltage, frequency, and harmonic distortion when reinjected into the railway grid. Pivotal to this architecture are independent station feedback devices, whose electrical topology universally uses an AC-DC-AC conversion structure. This configuration ensures precise controllability of intermediate DC-link voltage, enabling dual functionality: it not only stabilizes feedback quality but also facilitates power delivery to adjacent DC distribution networks (e.g., municipal grids near stations). While inverter-based feedback technology provides a pathway for RBE transmission to the grid, maintaining rigorous synchronization—specifically stabilizing voltage magnitude and frequency of reverse-fed energy under dynamic load conditions—remains a persistent engineering challenge impacting system stability and grid acceptance.

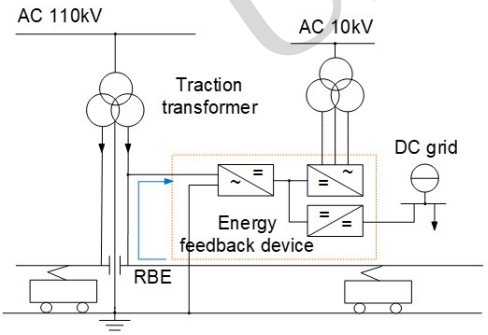

Fig. 6 Independent station feedback RBE recovery

The use of RBE in electrified railways faces globally recognized challenges, including three-phase imbalance and harmonic distortion when fed back to public grids—issues that necessitate standardized mitigation approaches. Internationally adopted solutions center on AC-DC-AC converter topologies and RPCs, with Japan's Shinkansen implementing 20 MVA RPC systems for cross-arm energy sharing. While through-type co-phase supply emerges as the universal technical direction for eliminating phase separation, its implementation shows national divergence: China prioritizes transformer-APC hybrid systems (e.g., on the Chengdu-Kunming Railway), whereas Japan's RPC-focused strategy encounters cost barriers during power scaling. Notably, China's independent station feedback architecture uniquely enables 10-kV rail grid absorption. These distinct pathways underscore engineering constraints that must be resolved to advance through-type co-phase supply system deployment globally.

2.4 Comprehensive utilization

When the RBE generated cannot be absorbed by traction trains within the same supply arm, a combined solution integrating energy storage and energy feedback technology is proposed. The aim is to avoid the simultaneous direct feedback of RBE from multiple trains to the contact grid, which could otherwise elevate the voltage. This hybrid approach not only enables the storage and reuse of braking energy but also plays a role in peak shaving and valley filling for the power grid, thereby enhancing the flexibility of energy feedback technology.

MMC Based on Energy Storage Structure

In recent years, due to its characteristics of high efficiency, low distortion, high reliability and high flexibility in medium-high voltage and high-power systems (Wang et al., 2024), the MMC has been extensively studied in traction power supply systems that integrate energy storage and energy feedback technologies. A typical four-branch MMC-based traction power supply structure is illustrated in Fig. 7 (Präger et al., 2022).

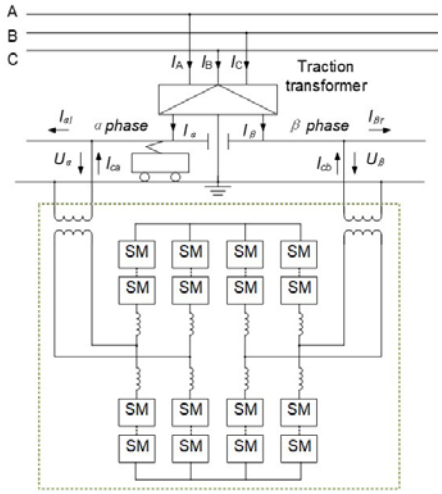

Fig. 7 Traction power supply structure of a typical four-branch modular multilevel converter (MMC)

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Sub-module (SM) topologies can be categorized as half-bridge, full-bridge, or double-clamped structures, and structures incorporating energy storage devices have been widely proposed. Various SM topologies have been proposed (Ronanki and Williamson, 2018). Fig. 8(e) shows a structure that integrates supercapacitors into the SM. This avoids the direct series connection of supercapacitors, enhancing the system's fault tolerance and enabling distributed state-of-charge balancing. Also, the use of low-blocking-voltage devices allows for the generation of high-quality waveforms and improved efficiency. However, this structure increases the complexity of drive control and system costs.

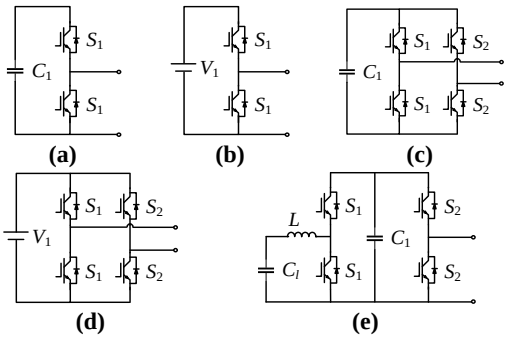

Fig. 8 Sub-module topology structures. (a) Half-bridge structure; (b) Half-bridge structure with battery unit; (c) Full-bridge structure; (d) Full-bridge structure with battery unit; (e) SM with energy storage device

Table 4 Comparison of critical utilization schemes of RBE

Category		Advantages	Disadvantages	Cost	Efficiency	Application
Train operational scheduling optimization		- Easy to implement	- Many constraints - Poor flexibility during emergencies	Lowest	Relatively low	Commonly applied in train operation
ESS	Battery	- Mature technology - Diverse types (high flexibility)	- Limited storage duration - Safety risks and environmental pollution	Low	Relatively high	On-board/ground energy storage
	Supercapacitor	- Fast response - Long cycle life - Environmentally friendly	- Voltage imbalance	Relatively high	High	On-board/ground high-power energy storage
	Flywheel	- Fast response - Long cycle life - Environmentally friendly	- High self-discharge rate - Relatively low energy density	Relatively high	High	Ground-based high-power energy storage
Energy Feedback	Energy Sharing	- Mature technology - Enables energy transfer between feeding sections	- Cannot fully eliminate neutral sections - Relatively simple functions	Relatively low	Relatively high	Widely used in RBE sharing
	Feedback structure	- Surplus energy can be reversely transmitted	- High difficulty in controlling reverse voltage/frequency	Relatively high	Relatively high	Widely used in RBE feedback
Comprehensive utilization	MMC Based on Energy Storage	- High fault tolerance - High power quality	- Complex drive control	Relatively high	High	Traction Power Supply System
	Overall Structure	- Full-line energy transmission - Continuous power through neutral sections	- Complex system structure - High technical requirements	High	High	Traction Power Supply System

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Overall Structure of the Traction Power Supply System

The comprehensive solution achieves the recovery and reuse of RBE by coordinating multiple distributed power flow controllers to regulate the power flow across several adjacent traction substations. The traction power supply scheme (Fig. 9) combining energy storage and energy feedback technology enables the transmission of RBE across the entire ACER line (Lu et al., 2020; Chen et al., 2021; Brenna et al., 2019). This allows trains to pass through phase separation sections without power interruption. Meanwhile, the energy storage devices

installed at traction substations provide peak shaving and valley filling services, offering auxiliary power support.

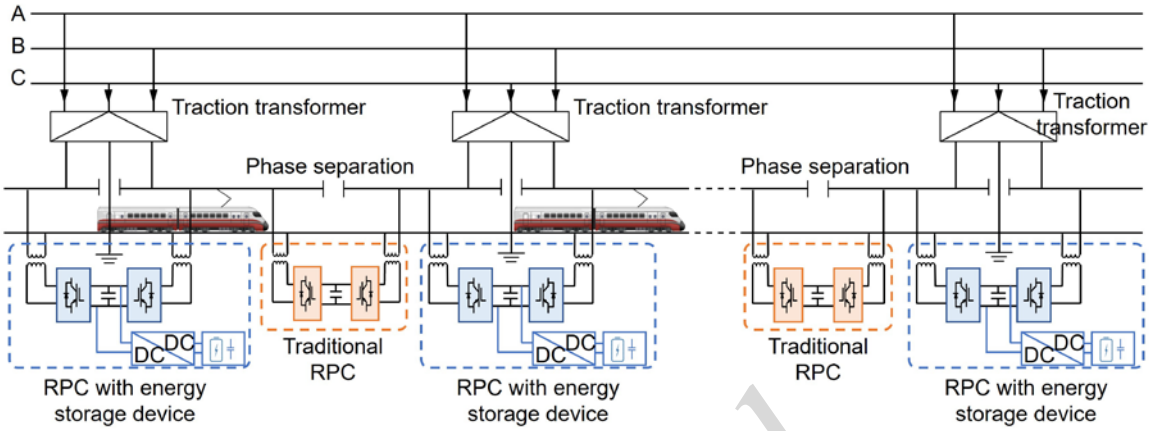

Fig. 9. Traction power supply structure for the comprehensive utilization of RBE

The traction power supply structure for the comprehensive utilization of RBE uses power flow controllers at traction substations and phase separation points to connect all power supply areas within the operational line. The inherent back-to-back structure of a traditional RPC makes it an ideal choice for realizing intelligent electrical infrastructure. This structure installs RPCs with energy storage devices at traction substations and traditional RPCs at phase separation points, enabling the collection of most RBE and further improving its utilization rate.

Building upon the detailed exposition of operational principles and system architectures for critical utilization schemes of RBE in the preceding sections, we conducted a systematic comparative analysis to evaluate their relative merits. Table 4 presents a multidimensional framework contrasting four predominant approaches: train operational scheduling optimization, ESS, energy feedback, and comprehensive utilization. This analysis systematically evaluated critical dimensions including the advantages, disadvantages, costs, efficiency and scope of application.

Table 5 Economic analysis of critical utilization schemes of RBE

Technical solutions		Investment cost	Payback Period (years)
Train operational scheduling optimization		¥0.5–1.0 million / line section	2–3
ESS	Battery	¥500–9000 / kWh	4–6
	Supercapacitor	¥2100–14000 / kWh	5–7
	Flywheel	¥7000–35000 / kWh	8–10
Energy Feedback	Energy Sharing	¥0.8–1.2 million / station	3–4
	Feedback structure	Converter: ¥2500–3500 / kW Grid retrofitting: ¥2.0 million / station	2–3
Comprehensive utilization		Converter: ¥4000–5000 / kW Grid retrofitting: ¥2.0 million / station	6–8

(Data source: Xing et al., 2023; Rana et al., 2023; Sahoo et al., 2023; Liu and Li, 2020; Fedele et al., 2021; Xin et al., 2019; Li et al., 2023; Dai et al., 2012; Ronanki and Williamson, 2018; Lu et al., 2020)

Furthermore, to facilitate comparative economic analysis of the solutions, Table 5 presents the capital investment and payback period for four critical RBE utilization schemes. Scheduling optimization achieves the shortest payback period (2–3 years) with minimal capital investment (¥0.5–1.0 million per line section), typically reducing traction energy consumption by 7%–12%. Among energy storage technologies, Li-ion batteries have emerged as promising solutions, with costs declining annually due to technological advances and economies of scale. Supercapacitors show economic viability in high-frequency scenarios through their exceptional cycle life. Energy feedback configurations (converters: ¥2,500/kW +

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grid retrofitting: ¥2.0 million per station) have a payback period of 2–3 years while enhancing energy absorption rates, representing a strategic long-term investment. Comprehensive utilization systems, despite requiring the highest initial investment, deliver great lifetime economic returns.

Based on the comprehensive analysis of RBE utilization technologies, the integrated energy storage-feedback solution represents a universal advancement for RBE utilization, with MMC sub-modules incorporating supercapacitors demonstrating global potential in fault tolerance and waveform optimization. Country-specific implementations reveal divergences: China prioritizes distributed power flow controllers for multi-substation coordination to leverage its extensive ACER networks, whereas European projects (e.g., Germany's EnerGtra project) focus on modular MMC designs for cross-border interoperability, constrained by regional grid standards and subsidy frameworks.

3 The RBE Control System

In the ACER system, the electrical topology of the railway traction system has an important impact on the utilization of RBE, but an effective control system is also a key factor. During the operation of the train, the operating modes are frequently switched, resulting in obvious fluctuations in the load power. In this context, it is necessary to implement efficient control over the power flow, based on the real-time load status of the two supply arms of the traction substation and the state of charge (SOC) of the ESS.

Currently, the ACER systems adopt mainly a dual-layer control strategy (Fig. 10). The upper layer is the energy management system, responsible for formulating power allocation and scheduling strategies from a macro perspective based on factors such as the overall operating status of the ACER system, train distribution, and power supply requirements. It provides instructions and targets for the lower layer's specific control tasks. The lower layer is the converter control layer, tasked mainly with executing the upper layer's instructions. Through precise control of the converters, it achieves real-time regulation of the traction grid's power, ensuring efficient utilization of RBE under various operating modes, maintaining system stability, and guaranteeing power quality.

3.1 Upper-layer Energy Management System

The energy management layer determines the energy flow between the ESS and the traction power supply system, which is jointly determined by the power of the power supply arms on both sides, the charging and discharging strategy of the ESS, and the power distribution strategy. Currently, energy management control can be divided into three main types: threshold-based (Liu et al., 2021; Liang et al., 2019), optimization-based (Lin et al., 2019; Yousaf et al., 2023), and learning-based (Shang et al., 2020; Liu et al., 2024) systems, as shown in Fig. 11 (Hu et al., 2022).

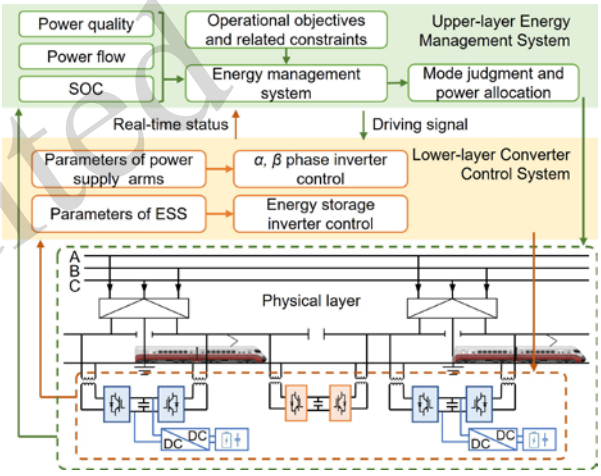

Fig. 10. Structure of the dual -layer control system of ACERs

Threshold-based energy management scheme

Threshold-based energy management classifies the operating modes of the ESS according to the energy flow characteristics on both sides of the traction supply arm. These operating modes can be switched based on predefined key parameters such as grid voltage and SOC thresholds, enabling charge/discharge operations or power distribution. This strategy is characterized by its simplicity of implementation and rapid response, meeting the basic energy management requirements of the system.

To ensure the safety and stability of battery operation in ESS, the fixed SOC charge/discharge threshold strategy (Yamanoi et al., 2006) prevents overcharging or over-discharging caused by imbalances during repeated charge/discharge cycles. When the ESS is in standby mode, the SOC is maintained within a specific threshold range, and small-current

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charge/discharge operations are performed to avoid the battery operating under extreme conditions. However, unnecessary charge/discharge processes during this period can reduce the lifespan of the battery (Liu et al., 2024). By constructing a correlation model between charge/discharge critical parameters and RBE (Lee et al., 2011), combined with iterative optimization to solve for the optimal threshold, the results indicate that no-load voltage random disturbances and dynamic loads from multiple trains form strong coupling constraints, causing the energy-threshold mapping relationship to exhibit significant time-varying characteristics. In other words, the inherent voltage fluctuation range of traction substations and the randomness of train departure density make fixed threshold control strategies unable to achieve an optimal dynamic energy efficiency configuration.

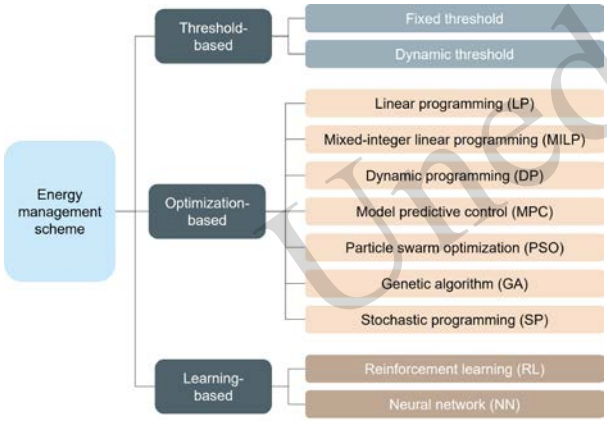

Fig. 11. RBE management systems

To address the limitations of fixed threshold strategies, numerous studies have focused on dynamic threshold adjustment methods. Dynamic threshold-based energy management schemes can more accurately track the operating modes of energy storage devices, enhancing the energy-saving effects of the storage system under the same capacity configuration (Konishi et al., 2014). A hysteresis control strategy based on SOC zoning achieves dynamic energy balance by dynamically adjusting the start-stop voltage thresholds of energy storage units. By calculating SOC reference values based on train speed and other information (Ciccarelli and Iannuzzi, 2012; Ciccarelli et al., 2012, 2014) and using a three-loop control to make the actual SOC follow the desired value, this strategy enables more precise regulation of the ESS's SOC to adapt to different train operating conditions. However, this strategy faces a conflict between SOC tracking accuracy and power coordination requirements. On the one hand, the delayed response characteristics of energy storage units can weaken their real-time support capability for traction loads. In scenarios involving multiple trains operating collaboratively, the time-varying characteristics of the traction power supply network and the dynamic hysteresis effects of energy storage devices are coupled, resulting in strongly nonlinear characteristics during the supercapacitor charging process. On the other hand, random fluctuations in train states caused by operational plan adjustments, the dynamic characteristics of the traction network, and the response delays of the ESS itself introduce multiple sources of interference that complicate the prediction of energy replenishment for the storage system.

Optimization-based energy management scheme

The optimization-based energy management scheme involves constructing mathematical models with objective functions such as minimizing system energy consumption, maximizing RBE utilization, and optimizing power supply stability. It also considers various constraints, such as battery charge/discharge power and device capacity limits, and uses optimization algorithms to derive the optimal energy flow scheme. This strategy can more precisely adapt to complex and variable system operating conditions, achieving efficient energy utilization and system performance optimization. However, it often faces challenges such as high computational complexity and strong dependence on system parameters.

To address the optimization of braking resistor energy consumption, some scholars have proposed energy management strategies for ESSs based on dynamic programming (DP) (Bilbao et al., 2014). Others have explored multi-objective collaborative optimization of ESSs using mixed-integer linear programming (MILP) (Beer et al., 2012). Additionally, for dual-train cooperative operation scenarios, some researchers have transformed the energy storage optimization problem into a variational problem and derived analytical solutions using the Euler-Lagrange equation (Iannuzzi et al., 2012). Note that although these methods have made theoretical progress, DP and MILP models generally face efficiency bottle-

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necks due to high-dimensional state spaces and are prone to being trapped in local optima. On the other hand, existing modeling methods have inherent limitations in real-time control response speeds, making it difficult to meet the online regulation requirements under dynamic operating modes.

An energy management strategy based on model predictive control (MPC) enables online control. In this process, the first step is to predict the load demand within a specific time horizon. Then, an objective function is constructed to minimize system costs over that time horizon, followed by optimizing the optimal control sequence. Some scholars have used MPC to minimize operational costs (Song et al., 2019; Sun et al, 2016), while also quantifying the profitability of both retired Li-ion batteries and new battery ESS. They found that the prediction accuracy and prediction horizon significantly impact the performance of MPC. Additionally, uncertainties in the prediction process, such as weather changes and load demand, can affect the performance of optimized operations. Even with the feedback correction mechanism of rolling optimization, these effects cannot be entirely eliminated (Reniers et al., 2018).

Learning-based energy management scheme

With the progress of computing power and data storage technology, machine learning algorithms have witnessed rapid development. The data-driven intelligent control paradigm is opening up new paths in the field of energy efficiency optimization for rail transit, providing a new perspective for research on energy-saving technologies. By using learning algorithms to mine and train a large amount of historical data, the optimal control output can be obtained without relying on an accurate mathematical model of the system. Currently, the applications of learning-based energy control focus mainly on reinforcement learning (RL) and neural networks (NNs).

RL-based energy management systems can achieve model-free real-time online operation. The core idea is to enable the agent to perform actions with the highest rewards through dynamic interaction with the environment. For instance, an RL learning scheme based on enhanced Monte Carlo tree search and domain knowledge can be used to solve multi-period stochastic optimization problems for dynamic scheduling of battery storage in microgrids. Deep reinforcement learning (DRL) for online sequential decision-making (Wang et al., 2023) can derive dynamic power allocation strategies, effectively protecting energy storage components while improving convergence speed and reducing energy consumption. RL-based control methods for optimizing hybrid ESSs show more stable system output power than traditional optimization algorithms, with smoother bus voltage and current transitions, thereby enhancing grid reliability. A multi-agent structure based on the Q-learning framework can learn actions through interaction with the environment (Lee and Choi, 2019), coordinating with each other to maximize cumulative rewards. Multi-agent RL has attracted significant attention due to its ability to achieve higher levels of reliability, economic efficiency, and scalability through collaboration among agents.

An NN-based energy management system can simulate different behaviors and fit complex nonlinear functions by adjusting the weights of the multi-layer network. It can train the operation rules of energy storage offline according to historical data and then apply them online. The online energy management controller, designed based on the optimal power distribution of the NN, shows excellent performance in terms of energy consumption and battery life management. Compared with threshold-based energy management, it can extend battery life by more than 60% (Shen and Khaligh, 2015). Some scholars have proposed a control system based on the artificial rabbits optimized neural network (ARONN) (Sandeep and Satyajit, 2023). By planning the actual power accessible on the shared common bus to design a power regulator, the ARONN ensures the balance between production and consumption in the power demand and maintains a stable DC bus voltage.

To explore the impact of real-time fluctuations caused by uncertain loads or sources on the reliability of the energy management system, some scholars have also proposed an online energy management strategy based on a long short-term memory (LSTM) network and a deep deterministic policy gradient (DDPG) algorithm (Ying et al., 2023). This has the advantages of a small tracking error, model-free control, and continuous action control. The online operation strategy based on the branching dueling Q-network (BDQ) can operate the distributed battery ESS under uncertain conditions (Shuai et al., 2021). It can realize the linear increase in the output quantity of the neural network with the number of distributed

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energy storage batteries, and overcomes the curse of dimensionality caused by the charging and discharging decisions of a multiple battery ESS.

In conclusion, the main advantage of the learning-based energy management system is that there is no need to establish complex mathematical models, especially those related to the battery dynamics in the ESS. With the development of intelligent algorithms and computing power, the learning-based energy management scheme has broad prospects. However, issues such as its lack of physical meaning and the high standards for the quantity and quality of data should not be underestimated.

Synthesizing the preceding analysis, Table 6 delivers a systematic cross-comparison of the three principal strategies implemented in upper-layer energy management: threshold-based, optimization-based and learning-based systems.

Table 6 Comparison of upper-layer energy management systems

Type	Advantages	Disadvantages	Application
Threshold-based management	- Simple implementation. - Fast response.	- Fixed thresholds: unnecessary charging/discharging accelerates battery aging. - Dynamic thresholds: trade-off between SOC tracking precision and power coordination.	Basic energy management in ACER systems.
Optimization-based energy management	- Adapts to complex operating conditions and multi-objective scenarios.	- High computational complexity, prone to local optima.	Optimal energy scheduling for complex scenarios.
Learning-based energy management	- No need for precise mathematical models - Enables real-time operation; and supports offline training.	- Lacks physical interpretability. - High demands on data volume, quality, and computing power.	Intelligent energy management, energy systems affected by multi factor coupling

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3.2 Lower-layer Converter Control System

The converter control system is the lower execution layer in the energy control system. The overall performance of the converter depends not only on its own electrical topology, but also on the choice of control method.

For the converter, the traditional control method is the dual-loop proportional integral (PI) control. The outer voltage loop is used to establish a stable DC-side voltage and provide a reference value for the inner current loop, while the inner current loop is responsible for tracking and controlling the real-time output current of the α and β phase converters. This traditional PI control has a simple structure and is easy to implement. However, due to the resonance of the grid-connected system, the harmonic content will increase, and the PI control is effective only for tracking direct current values, with a significant problem of the second harmonic ripple (Chen et al., 2022). In contrast, a proportional-resonant (PR) controller can effectively overcome this deficiency and compensate for harmonics at specific frequencies (Shen et al., 2010). Nevertheless, each resonant controller can compensate for only one type of harmonic. Therefore, some scholars have proposed a PI-repetitive controller to improve the harmonic suppression ability in various frequency bands (Qing et al., 2023). A controller with this composite structure can effectively improve the system's robustness, but also increases the complexity of the system. The parallel connection of too many controllers increases the design difficulty and response time.

In addition, to achieve energy sharing in the traction power supply system, the interconnected converter is a key interface between the traction substation and auxiliary equipment. Its core control objectives include two main aspects: (1) maintaining the stability of the DC bus voltage; (2) through current or power control, executing the scheduling instructions of the energy management layer for the utilization of RBE (Chen et al., 2024). Therefore, an interconnected converter usually adopts the strategy of outer DC bus voltage control and inner current control. Also, the scheduling instructions are usually converted into feedforward current reference values to enhance the dynamic response performance of the system when the operating conditions change rapidly (He et al., 2019). However, RPC control based on the MMC usually includes multiple control objectives, such as the output terminal voltage, the voltage balance of the SM capacitor (Ma et al., 2016), and the circulating

current (Wu and Cheng, 2018). When using a PI controller, the dynamic response is slow and the stable range is narrow, which is not entirely suitable for a cascaded structure with multiple control objectives (Wang and Wang, 2018).

To address the issue of capacitor voltage imbalance caused by the series-connected capacitors on the intermediate DC side in the MMC-RPC structure, three main solutions have been proposed: (1) an SM capacitor voltage equalization strategy based on a hardware auxiliary circuit. An auxiliary voltage equalization loop is added between the SM capacitors, enabling the MMC to spontaneously achieve capacitor voltage equalization during the SM switching process. However, its cost and volume generally increase with the number of SMs, which not only increases the system complexity but also raises the failure rate. (2) an SM capacitor voltage equalization strategy based on sorting. This strategy requires sorting the SM capacitor voltages and, within each control cycle, controlling the charging and discharging of a predetermined number of SMs based on the direction of the arm current (Sun et al., 2019). The effectiveness of this balancing strategy is positively correlated with the execution frequency, which in turn is positively correlated with SM switching losses. To achieve a balance between the SM capacitor voltage equalization effect and the system switching loss, there are currently two main research directions: extending the execution cycle of the SM capacitor voltage equalization or improving the sorting algorithm. But how to effectively balance the voltage equalization effect and the switching loss remains a critical challenge for this strategy. (3) an SM capacitor voltage equalization strategy based on closed-loop control. This voltage equalization strategy uses a PI controller to independently adjust the voltage equalization of each SM and then superimposes each voltage equalization adjustment value with the arm reference voltage. The charging and discharging time of the SM capacitor is adjusted by adjusting parameters such as the duty cycle of each SM. This voltage equalization strategy is generally applicable only to phase-shifted carrier modulation. The complexity of the system control will increase with the number of equalization controllers. In addition, when the carrier frequency is low, the slower switching speed of the SMs can lead to distortion in the arm reference voltage, resulting in distortion of the AC output voltage.

The suppression of circulating currents in the MMC-RPC structure can be categorized into two main approaches: (1) a passive circulating current suppression strategy. The circulating current is suppressed by increasing the arm inductor value or adding a hardware filter on the arm. This kind of circulating current suppression strategy will increase the system cost and volume, making it less commonly used. (2) an active circulating current suppression strategy. Based on the principle of negative-sequence second-harmonic circulating current generation, this strategy introduces a circulating current suppression voltage component into the closed-loop controlled arm reference voltage. By applying a negative-sequence double-frequency rotating coordinate transformation, the three-phase circulating currents inside the converter are decomposed into two DC components. A circulating current suppression controller is then used to eliminate the circulating current components in the arm currents, effectively reducing harmonics. Additionally, a circulating current control strategy based on a dual-frequency rotating reference frame can determine the controller coefficients by minimizing the error between the system's open-loop transfer function and the desired transfer function (Bahrani et al., 2016). Although both control strategies can effectively suppress the negative-sequence double-frequency components of circulating currents, they are applicable only to three-phase MMCs. To address this limitation, some scholars have proposed methods to indirectly suppress circulating currents by controlling the SMs to achieve self-balancing of voltage or energy without relying on any external circuits or closed-loop control. This approach can effectively achieve single-phase control (He, 2013; Talooki et al, 2021). Leveraging the characteristic of resonant control having infinite gain at a specific frequency (Li et al., 2015), the inner-loop current control based on a steady-state αβ-frame non-ideal PR controller is implemented. By superimposing multiple quasi-resonant components, harmonic components such as the second, fourth, and sixth harmonics are suppressed. Furthermore, MPC has been widely applied in hybrid control strategies for circulating current suppression (Sun et al., 2019; Brenna et al., 2010). By combining the advantages of MPC and linear control, these strategies improve circulating current suppression performance while reducing computational burden. Building upon the preceding

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analysis of lower-layer converter control systems, Table 7 synthesizes a comparative evaluation of three distinct control methodologies: conventional control, voltage balancing control and circulating current suppression control.

Table 7 Comparison of lower-layer converter control systems

Type		Advantages	Disadvantages
Conventional control	PI	Simple structure	Significant secondary ripples
	PR	Single frequency communication with no static error tracking	Frequency sensitivity, bandwidth stability contradiction
	PI-Repetitive	Enhances robustness	Increased system complexity and response time
Voltage balancing control	Hardware-assisted	Automatic balancing during SM switching	Cost/volume increase with more SMs, higher failure risk
	Sorting-based	Balances via charging/discharging control	Trade-off between balancing effect and switching losses
	Closed-loop	Independently adjusts SM duty cycles	High complexity, output distortion at low carrier frequencies
Circulating current suppression control	Passive	Hardware suppression (inductors/filters), simple structure and high reliability, strong anti-interference ability	Limited inhibitory effect and poor adaptability
	Active	Strong dynamic suppression capability with high adaptability, strong functional scalability	Elevated control complexity complicates system commissioning

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4 Suggestions for the Comprehensive Utilization of RBE

4.1 Highly Interconnected Train Operational Scheduling Optimization

From the perspective of improving the utilization rate of RBE, train operational scheduling optimization remains essential despite its limited capacity for stochastic RBE recovery. Currently, China's railway and power systems operate under centralized dispatch protocols. Establishing an efficient coupling mechanism between the railway and power systems to achieve coordinated optimization of trains and the power grid holds significant research potential. This approach could unlock substantial opportunities for enhancing energy efficiency and sustainability in railway operations.

(1) Optimization of train operation scheduling with active response. With the development of technologies such as an active distribution grid, demand response, and through-type co-phase power supply, ACER trains are expected to provide grid auxiliary services as actively responsive distributed energy resources through optimized train operations. Leveraging advanced intelligent monitoring and analysis systems, dynamic and precise regulation of power distribution can be achieved, enabling refined management of power resources. Additionally, by integrating demand response technologies, such as price incentive mechanisms and direct load control, ACER power users can be guided to modify their electricity consumption behaviors. Furthermore, through-type co-phase power supply technology facilitates the efficient transmission and sharing of RBE across the entire line.

(2) Empowering train operation scheduling with digital and intelligent technologies. By leveraging digital technologies, a refined ACER operation monitoring network can be established. High-precision sensors deployed at key locations on the train can collect real-time operational data such as speed, position, acceleration, and braking status. These data are transmitted to a central data processing center via 5G communication networks, where data mining algorithms and machine learning models are used for in-depth analysis and insights. Simultaneously, based on real-time grid load conditions, electricity price fluctuations, and train operation schedules, intelligent algorithms can dynamically plan train operation modes and braking strategies, enabling intelligent dispatching. The deep integration and application of digital and intelligent technologies provide strong technical support and implementation pathways for breaking down barriers between railway and power systems, improving the utilization rate of RBE, and driving innovative development in ACER operation models.

4.2 Diversification of energy storage forms

Energy storage devices can serve as storage media for RBE. Different storage methods exhibit distinct characteristics suitable for various application scenarios prevalent in China's diverse railway networks, such as high-altitude lines and heavy-haul corridors. From an engineering perspective, efficiently and economically utilizing ESSs remains complex and challenging.

(1) Hybrid ESSs. Energy storage solutions with high power density, such as flywheels and supercapacitors, are commonly used for RBE recovery and line power compensation. Batteries, as a high-energy-density storage solution, can charge and discharge over extended periods and have long storage times. In ACER systems, they can serve not only as uninterruptible power supplies but also as backup power sources. However, a single ESS often cannot meet all the requirements of ACER energy storage. Hybrid ESSs offer greater reliability and robustness, enabling them to fulfill various demands of ACER energy storage in terms of energy density, power density, operational efficiency, investment costs, and environmental impact.

(2) Mobile ESSs. With the rapid development of renewable energy technologies, how to use ESSs for renewable energy integration in ACER systems has become a global research hotspot. One approach is fixed ESSs, including trackside energy storage devices and energy storage devices within traction substations. The capacity configuration and location selection of ACER energy storage devices need to fully consider factors such as the location of renewable energy generation and its random variability. Another approach is mobile ESSs, including mobile traction substation ESSs and onboard megawatt-level battery storage systems. As a mobile energy storage carrier, ACER systems can effectively reduce investments in building new substations, laying additional transmission lines, and upgrading outdated equipment, while also addressing issues such as the extensive land resources required for redevelopment. Furthermore, they can enhance the coordinated operation of ACER mobile energy storage and grid dispatching, improving the stability and resilience of the grid in the face of sudden increases in power demand or extreme weather conditions.

4.3 Update of traction power supply systems

Regarding the RBE sharing and energy feedback of ACERs, power quality management methods such as PF, SVC, STATCOM, APF, and RPC have been widely adopted globally. Among these, Japan's Shinkansen prioritizes RPC technology for its dual capability of reactive power compensation and active power regulation between adjacent supply arms. In contrast, China focuses on balanced transformer-APC hybrid solutions to eliminate substation phase separation, exemplified by the Chengdu-Kunming Railway project. With the introduction of power electronic devices such as power electronic transformers (PETs) and MMC, co-phase power supply technology based on power flow converters will enable full-line co-phase power supply in the traction network, eliminating the impact of phase separation on train operation, and holds broad development prospects. Therefore, the overall structure of future ACER traction power supply systems will continue to evolve.

5 Conclusions

In this study we took the current RBE utilization schemes as a starting point and comprehensively analysed train operational scheduling optimization, the characteristics of RBE storage media, energy sharing methods, and energy feedback architectures. Furthermore, we explored the structural hierarchy of current RBE control systems, summarizing the development trends of both the upper-level energy management system and the lower-level converter control system. By combining specific engineering application examples, we analyzed and summarized the characteristics of RBE utilization in current ACER systems, while proposing forward-looking and feasible recommendations. The aim was to provide a solid theoretical reference and scientific decision-making basis for the continued development of ACERs.

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Author contributions

You-tong FANG designed the research. Yuan-lin GUO and Shi-feng LIU processed the corresponding data. Wen-jing

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TIAN wrote the first draft of the manuscript. Ji-en MA and Zhen-zhi LIN helped to organize the manuscript. You-tong FANG revised and edited the final version.

Conflict of interest

You-tong FANG, Wen-jing TIAN, Ji-en MA, Yuan-lin GUO, Shi-feng LIU and Zhen-zhi LIN declare that they have no conflict of interest.

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中文概要

题　目：交流电气化铁路再生制动能量综合利用研究综述

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概　要：在全球积极脱碳战略部署及交流电气化铁路迅速发展的时代背景下，再生制动能量的高效利用已成为我国力推的能源政策之一，不仅能够显著降低铁路系统能耗，而且高度具备为电力系统提供辅助服务的潜力，对提高铁路和电力系统的协调性、经济性和稳定性至关重要。本文从再生制动能量的利用方案着手，对行车组织优化、能量存储介质、能量共享方式及能量回馈架构进行了归纳。其次，从宏观视角探讨了再生制动能量控制系统的结构层次，发现再生制动上层能量管理系统主要呈现基于阈值、优化和学习的发展态势，下层变流器控制系统倾向改善MMC-RPC均压及环流结构性能、降低计算负担的控制方案策略选择。最后，结合现有的理论研究与实际工程应用给出提高再生制动能量利用率的合理化建议，为交流电气化铁路再生制动能量高效利用、技术创新和经济发展提供有力支持。

关键词：再生制动能量；行车组织优化；储能系统；能量共享及回馈；交流电气化铁路

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