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Review of the comprehensive utilization of regenerative braking energy in alternating-current electrified railways

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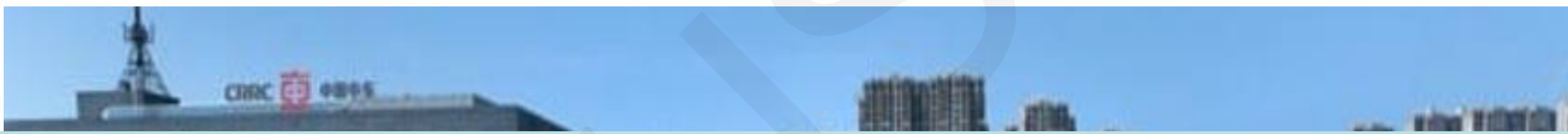
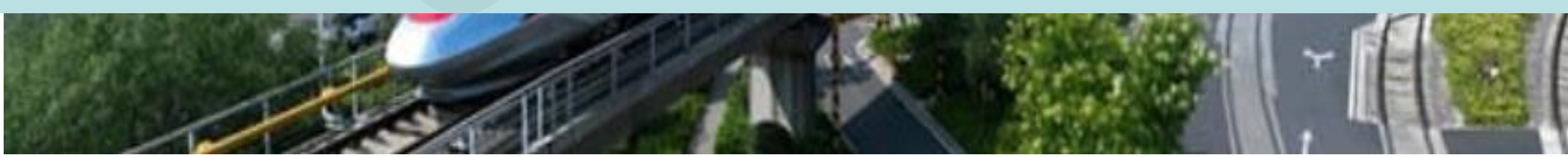
Introduction

- By the end of 2024, the operational mileage of China's railway had expanded to 162,000 kilometers, marking significant progress in railway infrastructure development.
- 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 approximately 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.



Critical Utilization Schemes of RBE

- **Utilization Schemes of RBE Based on Train Operational Scheduling Optimization**

Train trajectory optimization

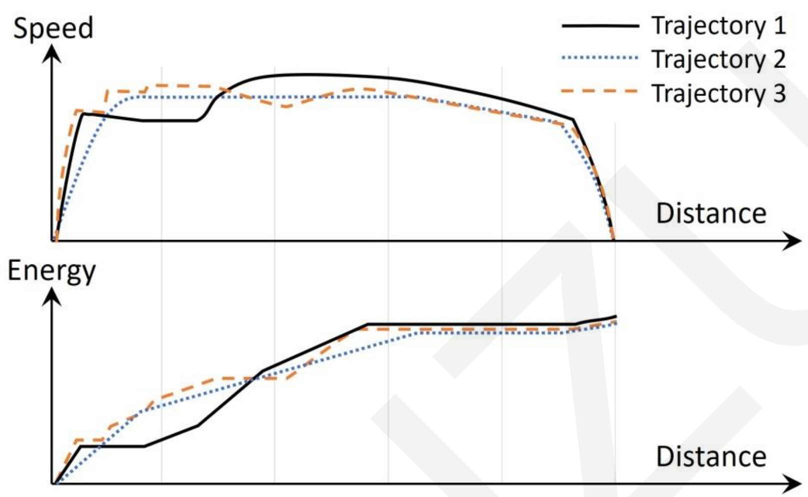


Fig. 1. Schematic diagrams of train trajectories

Train schedule optimization

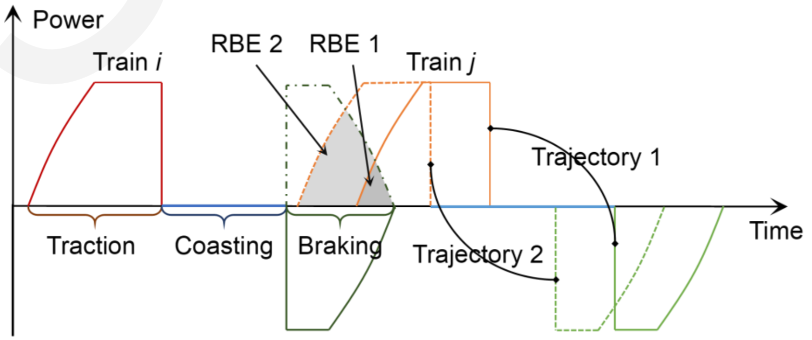


Fig. 2. Enhancement of RBE utilization based on train schedule optimization

Critical Utilization Schemes of RBE

■ Utilization Schemes of RBE Based on ESS

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

Critical Utilization Schemes of RBE

- **Utilization Schemes of RBE Based on Energy Feedback Technology**

Energy Sharing of RBE

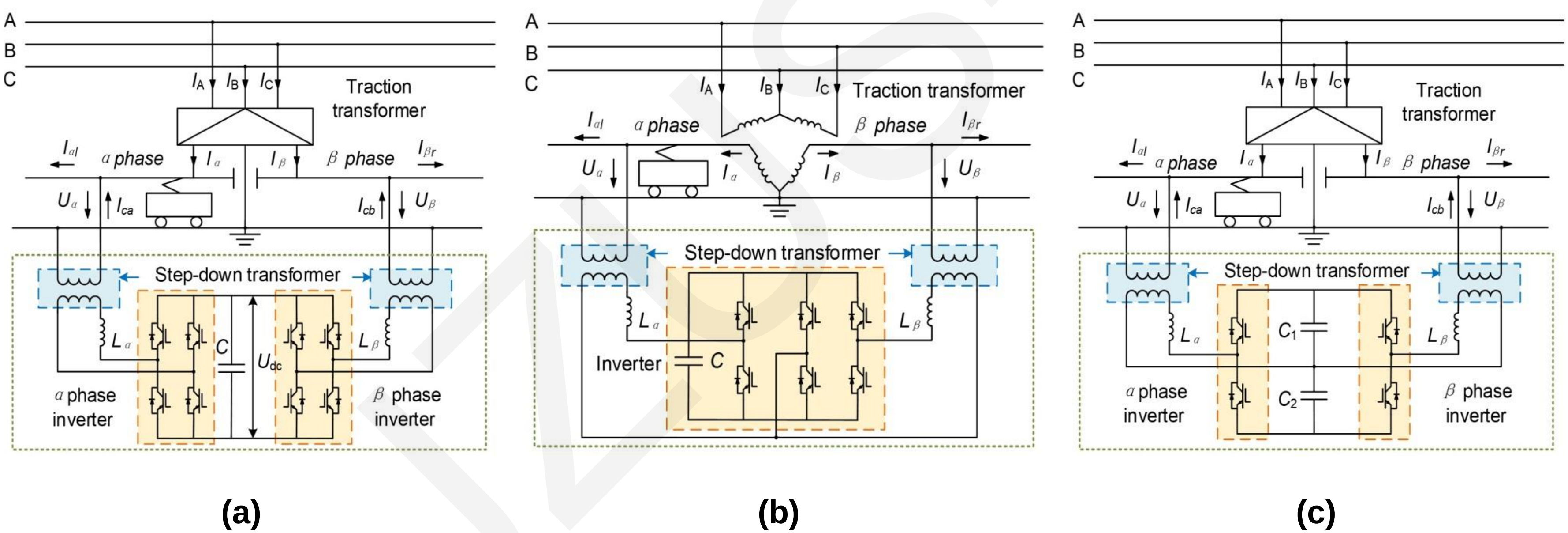


Fig 3. RPC and its derived topological configurations. (a) FT-RPC; (b) HT-RPC; (c) TW-RPC

Critical Utilization Schemes of RBE

- **Comprehensive utilization type**

MMC Based on Energy Storage Structure

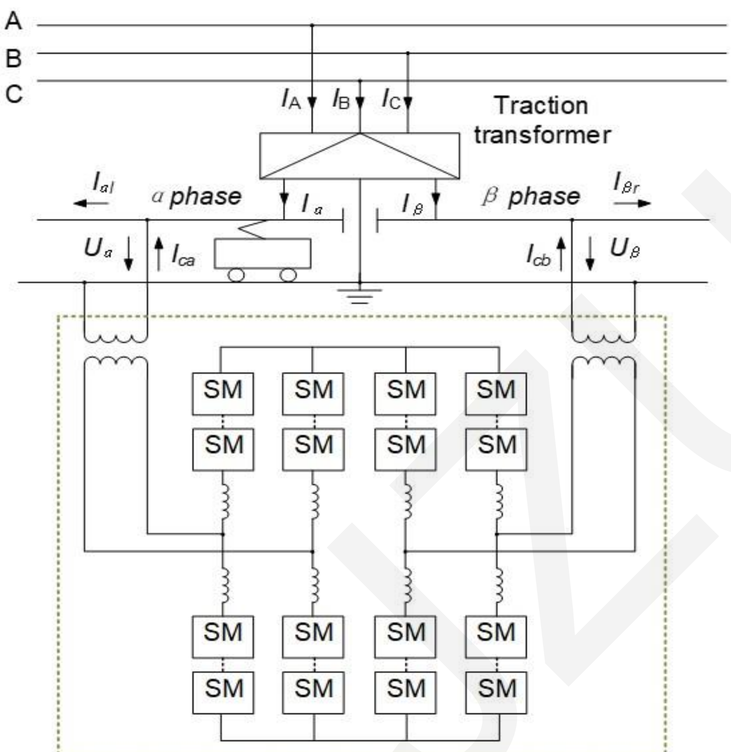


Fig. 7 Traction power supply structure of a typical four-branch MMC

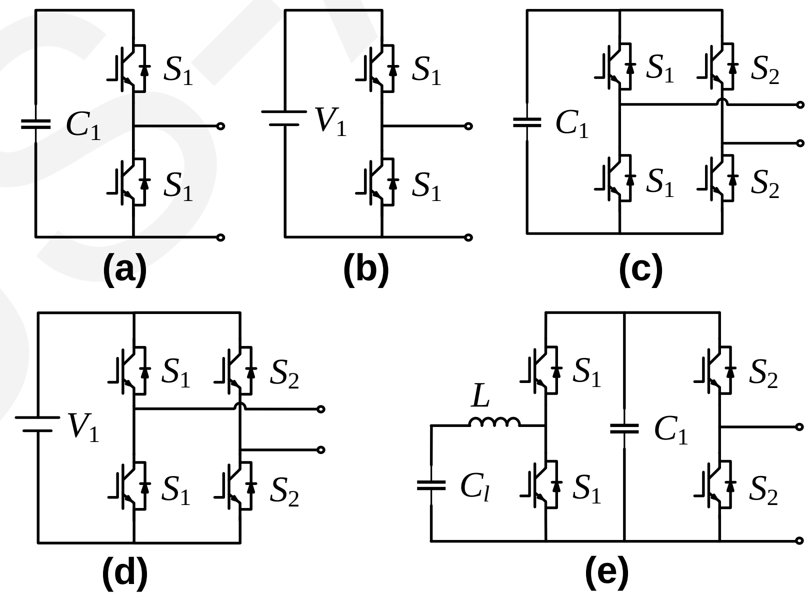


Fig. 8 SM topology structures.
(a) Half-bridge structure; (b) Half-bridge structure with battery unit; (c) Full-bridge structure; (d) Full-bridge structure with battery unit; (e) SM with energy storage device

Critical Utilization Schemes of RBE

- **Comprehensive utilization type**

Overall Structure of the Traction Power Supply System

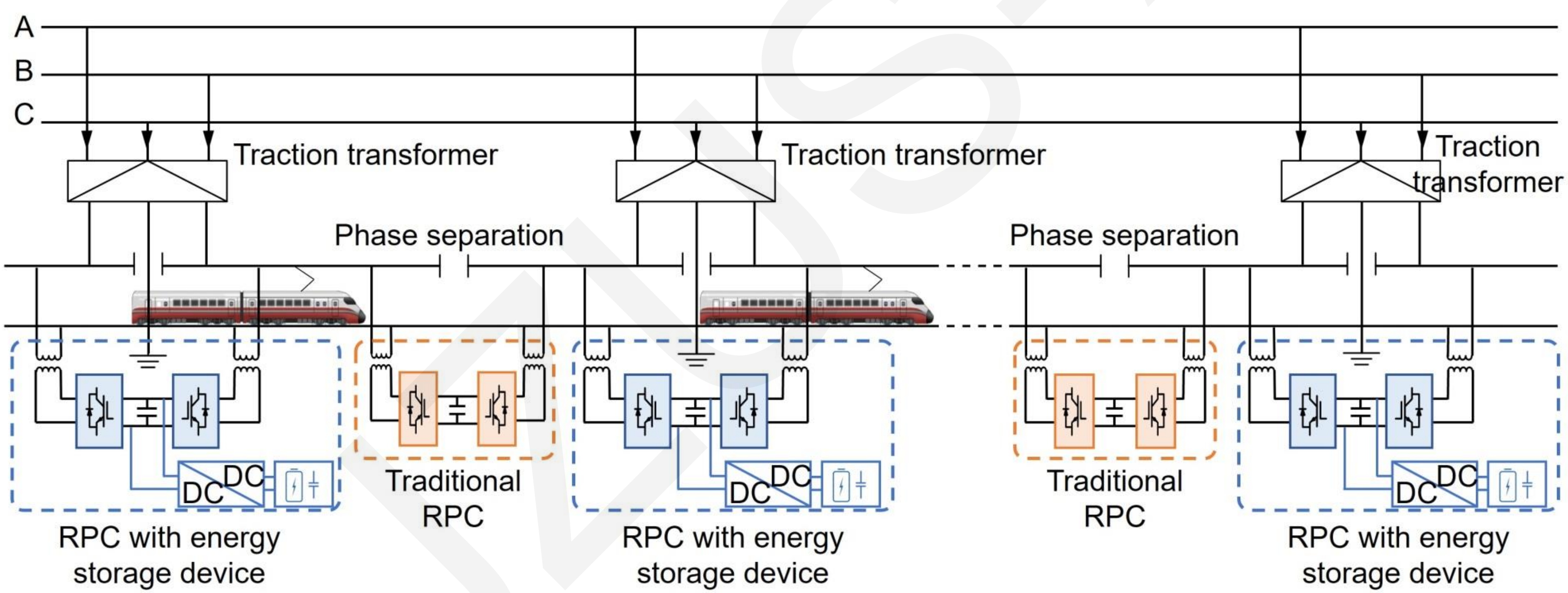


Fig. 9 Traction power supply structure for the comprehensive utilization of RBE

Critical Utilization Schemes of RBE

■ Comprehensive utilization type

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

The Control System of RBE

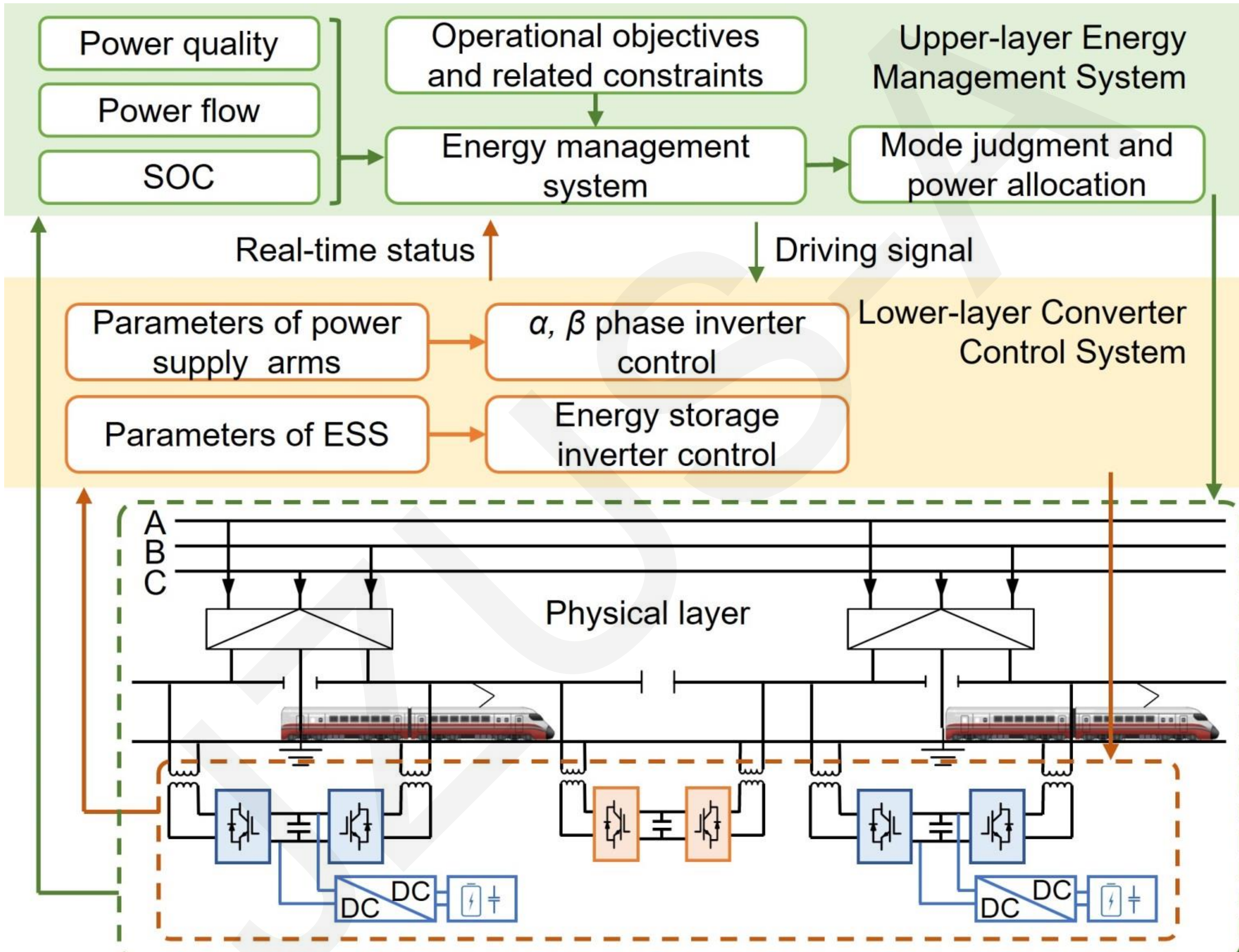


Fig. 10 Structure of the dual -layer control system of ACER

Conclusions

- This paper takes the current RBE utilization schemes as a starting point and comprehensively analyses train operational scheduling optimization, the characteristics of RBE storage media, energy sharing methods, and energy feedback architectures.
- Furthermore, the structural hierarchy of current RBE control systems is explored, 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, the paper analyzes and summarizes the characteristics of RBE utilization in current ACER systems, while proposing for-ward-looking and feasible recommendations.