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Study on Regenerative Braking Energy Recovery of Low-Voltage Energy Feeding System Based on Supercapacitor

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ABSTRACT

Addressing the issue of energy waste from regenerative braking in subways, this paper reviews the research progress made over the past decade in integrating supercapacitors with low-voltage energy feedback systems. The review indicates that supercapacitors are well-suited for braking energy recovery due to their high power density and long cycle life, but there is insufficient research on the coordinated control between supercapacitors and low-voltage energy feedback systems. Existing technologies face challenges such as energy supply-demand imbalance, harmonic pollution, and difficulty in parameter matching, and the integrated topology and control strategies have not yet been standardised. Research indicates that supercapacitors offer a feasible path to improve efficiency. Future efforts should focus on topology optimisation, intelligent control, experimental validation, and economic optimisation to drive the practical application of this technology.

KEYWORDS

Supercapacitor; Low-voltage energy supply system; Regenerative braking energy recovery; Inverter feedback technology; Energy efficiency

1 Introduction

1.1 Background and significance of the study

Under the background of China's rapid economic development and accelerated urbanisation, the problems of urban traffic congestion and air pollution have become more and more significant, which seriously restrict the further development of cities. With the advantages of green safety, convenient and punctual, and large transport capacity, metro has become the core force to relieve urban traffic pressure and improve transport efficiency. However, due to the short distance between stations and the frequent starting and stopping of the metro, a large amount of regenerative braking energy is generated during the braking process, which, if not effectively recycled, will result in a serious waste of energy. Driven by the goal of "double carbon", it has become an important research direction to improve the utilisation rate of regenerative braking energy in metro, among which the energy utilisation efficiency of low-voltage feeder system has attracted a lot of attention.

1.2 Research status and problems

At present, the metro mainly adopts three regenerative braking energy recovery technologies: resistance energy consumption type, inverter feedback type and energy storage type. Low-voltage inverter-feedback technology reduces energy loss to a certain extent by converting braking energy into low-voltage electrical energy for load use, but when the low-voltage system loads cannot fully absorb regenerative energy, the excess energy still needs to be consumed through the resistance, and there exists a low utilisation rate of the feed-back energy. In existing research, supercapacitors have been widely explored in the field of energy recovery by virtue of their excellent energy storage characteristics, but the systematic research on combining them with low-voltage energy feeding systems to optimise the energy recovery efficiency still needs to be deepened.

1.3 Purpose and scope of the review

The purpose of this paper is to comprehensively review the research progress of supercapacitors in regenerative braking energy recovery in low-voltage energy-feeding systems, and to clarify the current state of the art, core issues, and future directions in this field. The scope of the review covers domestic and international research in the past 10 years (2015-2025), focusing on the three core contents of supercapacitor characteristics, low-voltage energy-feeding system working mechanism, and optimisation of energy recovery strategies.

1.4 Structure of the paper

This paper will be developed according to the structure of "current state of technology - core issues - future outlook". In

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the first part, the research status of supercapacitor technology, regenerative braking energy recovery technology and their integration is described by topic; in the second part, the key challenges in the application of the existing technologies are analysed; and in the third part, the limitations of the research are summarised and the future direction is proposed.

2 Research status of core technologies

2.1 Research progress of supercapacitor technology

2.1.1 Research on technical characteristics

Although China started late in this area, it has been developing rapidly in recent years. As a new type of electric energy storage device, supercapacitor has both the energy storage function of traditional battery (two-way reversible energy storage) and the fast charging and discharging characteristics of capacitor, and the research on its core parameters (charging and discharging principle, capacity, internal resistance, power density, and life span) has been relatively mature [1]. Experimental data show that although the energy density of supercapacitor is only 5-30 Wh/kg [5], it shows unique technical advantages in power characteristics, cycle life and environmental adaptability. The core advantages of supercapacitors are reflected in the ultra-high power density and fast response characteristics, and the cycle life can exceed one million times [6]. This high power pulse output capability makes it irreplaceable in short-time high-power demand scenarios. At the same time, the supercapacitor operating temperature range can be extended to -40°C to 80°C, effectively solving the capacity degradation of lithium-ion batteries at low temperatures, and based on the ion adsorption/de-adsorption mechanism, but also to avoid the risk of dendrite growth of electrochemical batteries, fundamentally eliminating the internal short-circuit and thermal runaway and other safety hazards [7-8]. Supercapacitors can be classified according to electrodes [9], principle [10], electrolyte [11], and power density [12], as shown in Fig. 1. In supercapacitor research and development, supercapacitors are generally classified into double layer supercapacitors and hybrid supercapacitors by principle. The cycle life of supercapacitor in high-frequency charging and discharging scenarios can reach tens of thousands of times, and the power density is significantly higher than that of traditional batteries, which is suitable for dealing with the transient energy impact of regenerative braking.

2.1.2 Application Scenario Exploration

Existing research focuses on the energy management of on-board supercapacitor energy storage system, and achieves the efficient use of energy through the optimisation of the state of charge (SOC) control, but there are fewer studies on the synergistic control with ground-based low-voltage energy feeder systems, and a standardised integration scheme has not yet been formed [1].

2.2 Regenerative braking energy recovery technology development

2.2.1 Technology Path Classification

Three types of mature technologies have been formed in the field of global rail transport: resistive energy consumption type (direct waste of energy), inverter feedback type (energy conversion and reuse), and energy storage type (buffer for energy storage devices). Among them, the inverter-feedback type has become the mainstream due to the high energy utilisation rate, which is especially suitable for the centralised power supply urban rail transit system [2].

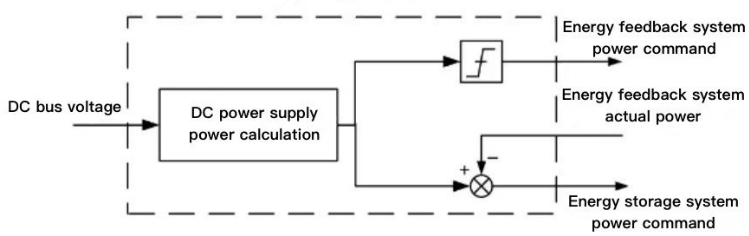
2.2.2 Current status of low-voltage inverter-feedback technology

regenerative braking energy is fed back to the AC power grid of urban rail transit through the addition of energy-feeding devices (including inverters and isolation transformers) [13]. The energy-feeding technology can be divided into two categories according to the different voltage levels of the feedback target: low-voltage energy-feeding technology and medium-voltage energy-feeding technology [14], as shown in Fig. 1-4(a) and (b), respectively. Among them, the LV feeder technology targets the 400V LV distribution system to provide power for auxiliary equipment in the station. Due to the low voltage level, the performance requirements and investment cost of the feeder are low. However, due to the capacity of the low-voltage distribution system, it is difficult to fully absorb the regenerative braking energy by using a single low-voltage energy-feeding technology, and it is generally necessary to set up a separate resistor to work with the technology, which leads to a waste of regenerative braking energy and needs to be further optimised to improve the utilisation of regenerative braking energy [15]. This technology converts braking energy into 0.4kV AC through inverter, which is sent to the low-voltage system through isolation transformer to supply loads, and can stabilise the voltage of traction network [4]. However, there are two major problems in actual operation: first, the intermittent nature of braking energy leads to a mismatch with the low-voltage load demand, and the excess energy needs to be consumed by the resistor; second, the power electronic devices introduce harmonic pollution and voltage fluctuations, which require additional equipment to manage and increase the cost [3]. At present, this technology has been applied in Beijing, Chongqing and other metro lines, but there is still room for improvement in energy utilisation [2].

2.3 Supercapacitor and low-voltage energy feed system integration research status quo

Currently, the integration of the two research is in the preliminary exploration stage. A small number of studies have proposed the topology concept of "low-voltage energy feed + supercapacitor", i. e., the excess braking energy not absorbed by the load is stored by the supercapacitor, and then released when the load is in demand [1,4]. However, there are obvious shortcomings in the existing studies: the system topology design does not specify the interface between the supercapacitor and the inverter and transformer; the energy distribution strategy does not consider the dynamic factors such as braking intensity and SOC state; and there is a lack of simulation and experimental validation, especially the scarcity of hardware-in-the-loop test data.

The DC side of the low-voltage energy feeder system and the energy storage device are connected in parallel on the DC bus, and it is very important to issue the braking power absorption command to start the braking energy absorption of the metro train and stabilise the bus voltage of the traction network. Only one master-slave control scheme is introduced in detail here, as shown in the figure, the main control block diagram of the low-voltage energy feeder priority allocation strategy is adopted. When the subway train is in the starting state, the calculated traction power is positive, and the energy-feeding system is not involved in the work; when the subway train is in the braking stage, the calculated traction power is negative, and the supercapacitor and low-voltage energy-feeding system start to work. In the energy-feeding priority strategy, the braking power of the metro is preferentially absorbed by the energy-feeding system, and the energy storage device decides according to the difference between the actual power value returned by the metro train and the power absorbed by the energy-feeding system[16].



3 Analysis of key issues and challenges

3.1 Inherent bottlenecks in low voltage energy feeding systems

Imbalance between energy supply and demand: There is a time difference between the pulsed output of metro braking energy and the smooth load demand of the LV system, which results in about 20%-30% of the regenerative energy being consumed by the resistor, and becomes a major obstacle to efficiency improvement [4]. Power quality and cost contradiction: the harmonic distortion rate generated in the process of inverter feedback can be up to 5%-15%, which requires the configuration of filters and other equipment, resulting in an increase in system cost of 10%-15% [3].

3.2 Supercapacitor application technology difficulties

Parameter matching problem: supercapacitor capacity selection needs to balance the energy storage needs and costs, capacity is too large leading to a decline in the economy, too small can not absorb the peak energy, the existing research lack of quantitative matching model. Charge/discharge control conflict: improve the charging current can improve the energy recovery efficiency, but easy to lead to the traction network voltage fluctuations over the ±10% safety threshold, how to coordinate the efficiency and stability is the core challenge [1].

3.3 Research limitations of integrated systems

Disconnect between theory and practice: most of the research stays at the simulation level, using a simplified system model, without considering the complex working conditions of the actual line (e.g., concurrent braking of multiple trains, sudden load changes). Lack of standard system: The interface specification and energy interaction protocol between supercapacitor and low-voltage energy feeder system have not yet formed the industry standard, which restricts the application of the technology on the ground.

4 Future research direction

4.1 Topology optimisation

develop a modular supercapacitor-inverter integration unit to simplify the system interface and reduce harmonic pollution to less than 5%.

4.2 Intelligent control strategy

Introduce model predictive control (MPC) algorithm to achieve dynamic energy distribution based on real-time operating conditions, with the goal of increasing the energy utilisation rate to more than 90%.

4.3 Experimental verification system

build hardware platforms for various situations, such as simulating the operation of metro trains at different time intervals, carry out long-cycle tests under actual line conditions, collect the energy recovery rate of metro trains and the utilisation rate of the fed-back energy in different situations, and improve the verification of the feasibility of the technology.

4.4 Economic optimisation

Optimise the supercapacitor capacity configuration through life cycle cost analysis to reduce the whole life cycle cost by 10%-20%.

5 Research conclusion and future prospect

5.1 Core research conclusion

The fast charging and discharging characteristics of supercapacitors provide a feasible path for solving the energy waste problem of low-voltage energy-feeding systems, but the existing research has obvious deficiencies in the integration topology, dynamic control, and experimental verification. Although the low-voltage inverter feedback technology is mature, it is still necessary to break the bottleneck of energy supply-demand imbalance through supercapacitor integration.

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