Research on Design and Construction Technologies for Green Low-Carbon Flexible DC Conversion Stations in South China

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Abstract. Driven by the strategic goals of the Dual-carbon initiative, the green and low-carbon transformation of flexible converter stations in the construction of new power systems has become an inevitable trend. Incorporating environmentally friendly, energy-efficient, high-performance, and harmonious design and construction concepts into the development of green converter stations is a crucial foundation for advancing eco-friendly green grids. This paper focuses on converter stations in South China, systematically integrating two core elements: the green and low-carbon technology system and construction techniques for HVDC converter stations. It constructs an energy-saving technology framework covering the entire life cycle of converter stations, addressing dimensions such as overall architectural planning, energy efficiency of building envelopes, optimization of ventilation, lighting, and water conservation, and utilization of renewable energy. At the construction technology level, it focuses on synergistic innovation between mechanized construction and green construction practices. A green construction management system is established to control dust, noise, and solid waste recycling, providing theoretical support and practical paradigms for the green and low-carbon construction of HVDC converter stations. This contributes to achieving synergistic development of efficiency enhancement and ecological benefits in the power infrastructure sector.

Keywords: Flexible DC converter station, Green Low-Carbon System, Mechanized Construction, Resource Recycling, Carbon Emission Monitoring

1 Introduction

Under global low-carbon sustainable development, Guangdong, a major economic hub, has growing electricity demand and increased converter station construction[1]. Flexible DC converter stations are pivotal for integrating high-proportion renewable energy into

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grids due to efficient flexible conversion and no commutation failures. Current green building design research focuses on residential structures; for high-voltage projects like HVDC converter stations, systematic low-carbon technology frameworks remain underdeveloped[2]. Coordination between mechanized construction and green management is insufficient, with low digital integration for lifecycle energy consumption and carbon emissions monitoring[3, 4]. South China's hot summers and mild winters impose unique demands on architectural design[5]. As shown in Fig. 1, the green and low-carbon construction plan of Guangzhou 500kV Kebei Substation, the first "Near Zero Energy" dual carbon substation in China, provides us with a preliminary technical demonstration and important inspiration for this article. Thus, this paper takes a Guangzhou flexible DC converter station as the subject, establishing a comprehensive technical framework based on South China's climate and converter stations' "high energy consumption and strong interference" nature, encompassing building energy efficiency, renewable energy utilization, mechanized-intelligent construction, green management technologies, and a BIM-driven digital twin monitoring platform for energy consumption and carbon emissions. This study integrates green and low-carbon design and construction technologies applicable to flexible DC converter stations, providing theoretical support and technical references for establishing a green and low-carbon construction system for high-voltage power infrastructure. It contributes to the green transformation of the new power system.

Fig. 1. The first "Near Zero Energy" dual carbon demonstration substation in China - Guangzhou 500kV Kebei Substation.

2 Methodology

This study employed a multi-method approach integrating systematic literature review, in-depth case studies of Guangdong-based projects, and numerical simulations. Systematic literature review established theoretical foundations, while case studies of in-province converter stations identified regional best practices. Key ventilation and water-saving systems were validated via computational fluid dynamics (CFD) and building performance simulations on a Guangzhou converter station, ensuring technical feasibility and environmental suitability. This triangulated methodology ensured robust theoretical support and technical reference.

3 Green and Low-Carbon Design Technology System for Soft-Direct Converter Stations.

3.1 Master Planning and Conceptual Design

Converter station site selection prioritizes land conservation, minimizing soil erosion/pollution, using safe wasteland/marginal land, and strictly controlling farmland/high-value land use[6]. Coordinate with urban/industrial/nature reserve plans and leverage proximity to public facilities. Climate-optimized layout: ensure winter sunlight, avoid prevailing winds, enhance summer ventilation, mitigate heat islands via landscaping[7]. Use north-south orientation with south-facing rooms for long-occupancy areas; keep form factor ≤0.4, optimize window-to-wall ratios for daylight/ventilation, cutting energy/HVAC use[8].

3.2 Energy-Efficient Technologies for Building Envelopes

Building envelopes, critical for energy efficiency, rely on thermal performance to control energy consumption, requiring material optimization and technological integration[9]. Transparent components address energy loss from conduction and solar radiation through low-SHGC glass, double-pane vacuum/inert gas units, warm-edge spacers and Low-E coatings, balancing thermal transmittance (K-value) and SHGC to meet South China converter stations' year-round efficiency needs. In hot-summer/warm-winter regions, industrial buildings balance temperature differentials and spatial efficiency by moderating insulation thickness. Converter stations demand Class A fire resistance: exterior walls use rock wool (insulation, fire/sound resistance), roofs low-water-absorption, high-compressive-strength XPS boards. Steel structures integrate modular construction with insulated panels; factory prefabrication and lightweight design reduce wet work and structural loads, forming a green construction paradigm for high-voltage specialty engineering.

3.3 Ventilation Energy-Saving Technology

The fully indoor compact layout of urban power grid projects requires controlling temperature, humidity, pollution, and noise, while traditional ventilation systems are costly and noisy. The flexible DC converter station adopts auxiliary ventilation combining mechanical (high-heat areas), air conditioning (battery rooms), and natural ventilation, forming a synergistic model to optimize costs and energy efficiency[10]. Building layout maximizes wind exposure by aligning the long axis perpendicular to prevailing winds;

open floor plans reduce airflow resistance, with airflow guides enhancing natural ventilation. Zoning by depth uses pressure ventilation in shallow bays, thermal pressure in deep core bays, and transitional zones synergizing both for efficiency.

3.4 Lighting Energy-Saving Technology

Energy-efficient lighting design integrates natural and artificial lighting technologies. Natural lighting employs light pipes[11], smart dimming glass[12], fiber-optic concrete walls[13], and hybrid solar lighting[14] to capture daylight, minimize light loss, balance illumination, and reduce energy use. Artificial lighting uses high-efficiency, long-life, high-CRI LEDs with smart control systems (sensors, communication, dimming) that auto-adjust via motion detection and scheduling. Coordinated with building management systems for monitoring logic and zone control, this dual strategy reduces consumption through natural light and enhances efficiency via artificial lighting.

3.5 Water-Saving Technology

Against global water scarcity, converter stations' water-saving design establishes a comprehensive control system centered on conservation prioritization, new-source supplementation, and recycling promotion[15]. Conservation employs Class 1 water-efficient fixtures, with pipeline tiered metering, pressure optimization, and zero-leakage valves mitigating leakage. New sources integrate Guangzhou-climate-tailored rooftop rainwater harvesting, treating water for road cleaning and cooling tower replenishment. Recycling uses "physical-chemical + biological" industrial wastewater treatment[16]; cooling water is reused via reverse osmosis, condensate recovered for converter valve cooling, saving 5,000 tons/year and supporting landscaping. Closed-loop cooling towers replace open systems, using sealed circulation to prevent contamination, reduce losses/discharges, and enhance stability[17].

3.6 Renewable Energy Utilization Design

The converter station's renewable energy utilization focuses on photovoltaic power via South China’s 3D BIPV layout. Rooftop PV modules, optimized for Guangzhou’s latitude with 28° tilt and 15° west azimuth to match peak demand, generate 276,000 kWh/year; vertical amorphous silicon thin-film facade modules with ventilation gaps. Both integrate building function with power generation, cutting structural load by 30% and saving 15 tons of steel. The PV-storage-direct-flexible system forms a closed loop (PV-storage-DC distribution-flexible control); direct busbar connection eliminates AC/DC conversion, boosting energy efficiency by 15%-20% (see Figure. 2)[18]. Intelligent control balances supply-demand and reserves charging interfaces. Economically, it achieves 200 tons/year CO_2 reduction, 8% renewable substitution rate, PV cost of 0.3-0.5 yuan/kWh, 5-year payback and 6.9 million yuan cumulative electricity savings over 25-year lifecycle. Wind power is excluded due to insufficient speeds, limited space, and blade vibration interference, but suburban mountain potential remains.

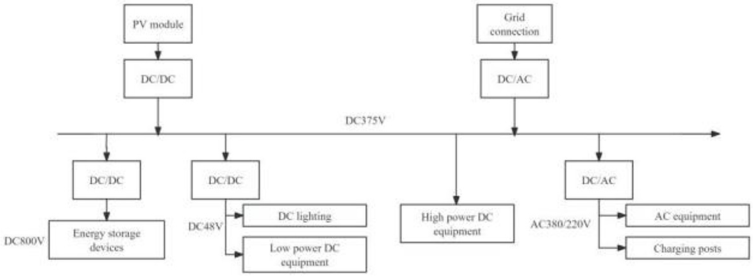

Fig. 2. Diagram of light storage and straight flexible system.

4 Green and Low-Carbon Construction Technologies for Soft-Direct Converter Stations

Converter station construction employs mechanization-intelligence-green synergy to reduce labor, shorten timelines, optimize workflows[19,20]. Green practices use clean-energy machinery; collaborative innovation enhances resource recycling[21], with digital platforms monitoring energy and pollution.

4.1 Mechanized and Intelligent Equipment Construction

Conventional construction machinery dominates converter stations, with advanced equipment underutilized due to high initial costs, skilled labor shortages, and traditional inertia[22]. New stations adopt full-process mechanized-intelligent construction via five synergistic upgrades: site leveling (all-electric machinery + total stations: zero emissions, 30% shorter construction period); foundation treatment (hydraulic/static pile presses: 200% efficiency, 80% dust reduction); foundation construction (laser leveling robots: ≤3mm error, 2% steel wastage); steel structure installation (electric cranes/theodolites: ±2mm precision; welding robots: 42% higher wire utilization); electrical installation (intelligent transporters/automated welders: 40% faster, improved pass rate (see Figure. 3(a)-(c)). This reduces labor by 60%, carbon emissions by 48%, and project cycles by 50%, establishing an electrified-unmanned-digital model.

(a) (b) (c)

Fig. 3. (a). Hydraulic pile breaking machine, **(b).** Four wheel laser ground leveling robot, **(c).** Fully automatic intelligent welding robot.

4.2 Green Construction Management Technologies

Construction Dust Control Technology. Converter station construction dust from material transport, stockpiling, loading/unloading, earthwork excavation, and exposed ground requires tech-driven digital-intelligent control. As shown in the intelligent monitoring system in Fig. 4, IoT integrates PM2.5/meteorological sensors to trigger sprinklers/fog cannons; AI identifies uncovered soil, LiDAR locates sources, drones generate heat maps for remediation[23,24]. Integrated with government platforms, blockchain ensures tamper-proof storage for precise oversight, efficient remediation, and enforcement evidence.

Fig. 4. Control platform coordinates with front-end monitoring to assess pollution levels.

Construction Noise Control Technology. Converter station noise from construction/operational activities, such as transportation, excavation, installation, equipment vibration/EMI, which are controlled via multi-dimensional coordination: active intervention (LMS algorithms for counter-sound), source suppression (rotary drilling rig soil discharge, pneumatic mufflers[25, 26], intelligent monitoring (noise database for dynamic adjustments), passive isolation (lightweight steel/solid acoustic barriers, deployable enclosures[27]). This ensures compliance, community harmony, cost optimization and supporting green power systems.

Material Management and Resource Recycling Technology. Converter station construction waste treatment and resource recycling rely on intelligent material management and resource recovery systems. Intelligent material management uses BIM-driven closed-loop management, integrating multi-source information to cover material transportation, entry, acceptance, storage, issuance, with computer vision and deep learning enabling dynamic balance and traceability. Resource recovery centers on high-efficiency sorting-precise regeneration-environmental sustainability[28]; on-site operations use multispectral CCD, multi-sensor fusion, PLC systems for sorting purity and efficiency. Regeneration employs categorized recycling, material processing, biological/chemical treatment, energy recovery to advance resource circulation and stewardship.

Energy Consumption **and Carbon Emissions Monitoring Technology.** Converter station construction energy consumption monitoring system uses hub layout planning, targeting earthwork and lifting/transportation machinery energy use. It builds a three-tier digital twin platform supporting real-time monitoring, progress tracking, process optimization via flexible genetic algorithms. RFID tags on tower crane booms enable component highlighting and full-cycle traceability. Carbon emissions monitoring follows international/domestic standards, defining building material phase boundaries across five stages. Quantified via life cycle theory, it uses the Construction Engineering Carbon Measurement and Management Platform with BIM carbon calculation, carbon budgeting, construction carbon sensor, and material information modules interfacing digital supply chains for precise measurement.

5 Summary and Outlook

This study developed a full-cycle green and low-carbon technology framework for flexible DC converter stations in South China, encompassing building energy efficiency, renewable energy utilization, mechanized intelligent construction, and BIM digital twin carbon monitoring. Unlike residential-focused rating systems such as LEED, its innovation lies in addressing the "high energy consumption and strong interference" characteristics of high-voltage industrial facilities. By integrating climate-responsive design with comprehensive green management throughout the construction process, it provides theoretical support and reference for the systematic low-carbon transformation of large-scale power projects. Applicable to high-voltage transmission facilities, its effectiveness in enhancing energy efficiency and reducing carbon emissions has been validated through the Guangzhou case study. Future implementation across national renewable energy base interconnection projects will contribute to establishing a green standard system for power infrastructure.

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