Construction Technology and Application of Graphite-based Flexible Grounding Bodies for Wind Farms and Photovoltaic Power Stations

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Abstract

To fundamentally solve the challenges of grounding grid corrosion, difficult construction, and high environmental risk in highly corrosive and high-resistivity complex terrain areas for wind farms and photovoltaic (PV) stations, a complete set of construction techniques for graphite-based flexible grounding bodies is proposed and systematically summarized. This technology uses high-carbon flake graphite as the main body material, utilizes the principles of electric field dispersion and composite anti-corrosion, ensures long-term resistance reduction, and completely avoids open-flame operations in the field. This paper elaborates on the construction process flow, key operation points, materials and equipment, and quality control measures for graphite-based flexible grounding bodies. Through life-cycle cost analysis and typical engineering case verification, its technical and economic superiority is demonstrated. The results show that this method can stably maintain grounding resistance below the design value, reduce the life-cycle cost by approximately 60% compared with the traditional copper-clad steel scheme, and avoid heavy metal pollution, offering significant economic, social, and environmental benefits.

Keywords

Graphite-based Flexible Grounding Body; Wind Farm; Photovoltaic Power Station; Grounding Grid Construction; Anti-corrosion and Resistance Reduction.

1. Introduction

With the continuous advancement of wind power and photovoltaic projects into complex geological regions such as mountains, coastal beaches, and Gobi sandy areas, the limitations of traditional metal grounding devices have become increasingly prominent. In saline-alkali land, saline soil, and high-humidity coastal areas, the corrosion rate of galvanized steel and copper-clad steel grounding bodies can reach 0.1 mm/a, with a service life of only 7–15 years[1-3]. The resulting excessive grounding resistance often leads to lightning trip accidents and equipment damage[4]. Moreover, material transportation in mountainous areas is difficult, conventional exothermic welding brings fire safety risks in forests and grasslands, and heavy metal ions from corrosion products pollute soil and groundwater; these problems remain unsolved [5-6].

In recent years, non-metallic grounding materials mainly composed of graphite have drawn attention due to their excellent electrical conductivity, chemical stability, and flexible processability[7-8]. Graphite-based flexible grounding bodies can be coiled for transport and connected without hot work, and theoretically require no maintenance over their entire life cycle, making them an ideal solution to the aforementioned issues. China has issued relevant technical standards for flexible graphite grounding materials[9], providing a basic basis for engineering applications. However, standardized construction techniques for different topographical conditions of wind farms and PV stations, joint anti-corrosion sealing methods, and enhanced layout processes in high-resistance areas still need systematic development. Therefore, based on a number of practical engineering studies[10-12], this paper refines and forms a complete set of construction methods for graphite-based flexible grounding bodies. The process principles, workflow, key control points, and application results are comprehensively presented to provide a transferable technical reference for similar projects.

2. Process Principles and Characteristics

2.1 Resistance Reduction and Anti-Corrosion Mechanism

The method is based on two core principles that achieve long-lasting resistance reduction and corrosion protection.

(1) Electric field dispersion principle. The graphite grounding body is ribbon or cable shaped, allowing it to be laid in a serpentine or radial pattern following the terrain, with a much larger effective contact area with the soil compared to an equivalent length of metal round steel [8]. Concurrently, the relative magnetic permeability of graphite is approximately 1 ($\mu r \approx 0.999979$), eliminating the high-frequency skin effect typical of ferromagnetic materials; the effective utilization rate of the current-dissipating cross-sectional area can exceed 80%, significantly reducing the impulse grounding resistance [13,15].

(2) Composite anti-corrosion principle. High-carbon flake graphite exhibits strong chemical inertness, with an average corrosion rate of less than 0.008 mm/a in acidic, alkaline, saline, and high-humidity soil, giving it a theoretical service life exceeding 50 years [7,9], fundamentally preventing the electrochemical corrosion pathways inherent to metallic materials. For connections to metal down conductors, a copper-graphite double-sided conductive transition sheet, graphite conductive paste, and multi-layer sealed isolation measures (heat-shrink insulating tube, butyl anti-corrosion tape, flexible PVC protective sheath) are employed, realizing a "sacrificial anode + physical isolation" mechanism that completely blocks the permeation of corrosive media and ensures long-term electrical stability [10-12].

2.2 Main Features of the Method

(1) Stable anti-corrosion and resistance reduction. The inherent resistivity of the grounding body can be stably controlled at the $3.25\times10^{-5}\ \Omega\cdot m$ level[8,9]. Combined with graphite-modified conductive backfilling material (bentonite + fine graphite powder + loess), the contact resistance with the earth is effectively reduced.

(2) Convenient and efficient construction. No electric or gas welding is required, eliminating the persistent risk of wildfire at remote sites [5]. The material is cable-like and can be transported on reels; a single roll weighs only one-fifth that of galvanized steel of the same length[10], enabling manual handling on steep slopes and ridges.

(3) High adaptability to complex terrain. The flexible body can be naturally bent (bending radius ≥ 30 cm) and laid in shallow grooves (width ≥ 10 cm, depth ≥ 15 cm) on exposed rock[10-11]. In high-resistance sandy areas, the "umbrella branch" layout scheme significantly expands the current dispersion area and effectively reduces grounding resistance[12].

(4) Safety, environmental protection, and economic benefit. Graphite materials are non-toxic and contain no heavy metals; the carbon emissions during their production are far lower than those of hot-dip galvanizing and electrolytic copper coating processes[6]. The system is maintenance-free over a 40–50-year life cycle, and the overall cost is more than 40% lower than that of copper-clad steel solutions[10,12].

3. Scope of Application

This method is applicable to new, expanded, and renovated grounding grids of onshore wind farms (mountains, hills, coastal beaches, sandy Gobi, saline soils, etc.) and photovoltaic power stations (ground-mount utility-scale, mountain PV, fishery-solar complementary systems, saline-alkali PV, etc.)[9], specifically covering grounding grids for wind turbine foundations and box-type transformers, PV mounting structures and inverters, substation grounds, and collector line tower grounds. It is particularly suitable for the following conditions:

①Areas with soil resistivity > 300 Ω·m or mixed soil/rock where excavation is restricted[11];

②Highly corrosive soil areas with strong acid, alkali, or high salinity[2,3];

③Sites in forests, grasslands, or PV zones with strict open-flame operation restrictions[5];

④Mountainous areas where large transport and lifting equipment cannot access the sites[10].

4. Construction Process Flow and Key Operational Points

4.1 Process Flow

The standard construction process is: Preparation and setting out → Trench excavation and cleaning → Bottom treatment → Grounding body laying and fixing → Enhancement in special terrain sections → Down conductor connection and anti-corrosion sealing → Conductive backfill compaction → Grounding resistance measurement → Concealed work acceptance → Documentation and archiving [9,10].

4.2 Key Operation Points

4.2.1 Trench Excavation

In accordance with GB 50169[14] and design drawings, RTK or total station is used for precise marking. For conventional soil, the main trench depth is ≥ 60 cm, width 25–30 cm; in permafrost regions, burial depth should exceed the local maximum frost depth by 20 cm. In exposed rock areas, blasting is strictly prohibited; a pneumatic pick is used to cut a trench ≥ 10 cm wide and ≥ 15 cm deep, which is sufficient for the laying requirements[10-11]. The bottom must be levelled and cleared of stones and roots.

4.2.2 Laying and Fixing

Two workers uncoil and slowly drag the grounding body along the trench, avoiding brute force. Bending radius at turns must be ≥ 30 cm to prevent internal conductive structure damage. The body is fixed to the trench bottom center with U-shaped plastic steel anchors every 3 m to prevent displacement during backfilling. A 50 cm length is reserved at each end and sealed with a dedicated heat-shrink cap to prevent unwinding[10].

4.2.3 Down Conductor Connection and Anti-Corrosion Sealing (Core Technology)

This step must be performed in a dry environment; if necessary, a rainproof shelter is erected and insulating mats are laid [10].

(1) Joint preparation: Strip approximately 15 cm of the outer protective layer from the grounding body end to expose the conductive composite layer; polish the copper stranded wire or galvanized flat steel down conductor to bare metal.

(2) Transition connection: Insert a copper-graphite double-sided conductive transition sheet between the contact surfaces, and evenly apply graphite conductive paste.

(3) Crimping: Place the assembly into a 60 kN hydraulic crimper for two-stage asymmetric crimping to achieve stable mechanical interlocking and electrical connection[10]. After crimping, the joint dimensions must be verified with calipers, and the contact resistance tested using the two-pole method, which must be < 0.1 Ω[14].

(4) Three-layer sealing: Immediately after crimping, wrap a heat-shrink insulating tube and heat evenly until fully shrunk; then tightly wrap butyl anti-corrosion tape, covering all exposed metal and extending 5 cm beyond; finally, wrap a flexible PVC protective sleeve and lock both ends with stainless steel worm drive clamps. The joint is then coded, labelled, and photographed for documentation[10].

4.2.4 Enhancement in Special Sections

High-resistance sandy areas (> 300 Ω·m): Cover the top and bottom of the conductor with 10 cm of graphite-modified conductive soil, and install 1.5 m long transverse branches at 2 m intervals along the main ray; the interfaces are crimped and sealed with flexible connection sheets, forming an umbrella-shaped dispersion network[12].

Mountain slopes: Use a stepped horizontal segmentation layout with flexible transition arcs between segments; construct small reverse drainage ditches along the slope and backfill with gravel to prevent rain erosion[11].

PV array areas: In densely packed mounting structure zones, adopt a "grid + short radial" configuration, routing the flexible conductor through gaps between pile foundations to minimize extra land use. Module frames are connected to flexible grounding body branches using dedicated stainless steel clamps, following the same crimping and sealing procedures[12].

4.2.5 Backfilling and Compaction

Layer by layer: first backfill with a mixture of graphite conductive powder and original soil (ratio 3:1) to 20 cm below ground level, manually tamping lightly; then backfill the remaining 20 cm with original topsoil, compacting every 10 cm until the design density is achieved. Heavy mechanical compaction is strictly prohibited to avoid damaging the grounding body or displacing connections[10,14].

4.3 Labor Organization

For a standard work surface (one wind turbine foundation grid / 500 m grounding line / 2 MW PV sub-array grounding grid), a single shift requires: 1 site supervisor, 1 technician/tester, 2 certified electricians, and 4–6 general workers, totaling 8–10 people [10].

5. Materials and Equipment

Main construction materials include: graphite-based flexible grounding body (flat strip, resistivity ≤ 3.25×10^{-5} Ω·m), copper-graphite double-sided conductive transition sheet, graphite conductive paste, heat-shrink insulating tubing, butyl anti-corrosion tape, flexible PVC protective sheath, and graphite-modified conductive soil[9,10].

Main construction equipment includes: soil resistivity tester (e.g., CA6472), double-clamp/three-pole grounding resistance tester (e.g., ETCR4100), 60 kN hydraulic crimping tool with dedicated dies, 2000 W temperature-controlled hot air gun, light-duty gasoline/electric impact compactor, and G10 pneumatic pick[10].

6. Quality Control

Construction strictly follows GB/T 50065[13] and GB 50169[14].

(1) Material inspection: Each batch of graphite grounding bodies must be inspected for appearance (no severe wear or strand breakage), and factory test reports must be verified; key batches shall be sampled and sent to third-party testing for resistivity and thermal stability. Non-conforming materials are strictly prohibited[9].

(2) Process control: Trenches must pass concealed-work inspection before laying. Each crimped joint, after visual inspection for virtual pressure or cracks, must pass a two-pole contact resistance test (< 0.1 Ω) with conductive paste fully filled before three-layer sealing is applied[10,14].

(3) Grounding resistance: After completion, the deviation of resistance values measured in all directions must be ≤ 10%, and all values must meet the design requirement (typically ≤ 4 Ω for wind turbine foundations and PV booster stations/large arrays; PV mounting structure grounding resistance as per design) [13-14].

(4) Visual traceability: All joints, trench sections, and test readings are numbered, photographed, and entered into the project management system for lifelong quality traceability[10].

7. Safety and Environmental Protection Measures

7.1 Safety Measures

Field operations must prevent landslides and rockfalls; outdoor electrical work shall be halted immediately in thunderstorms, high winds, or heavy snow, and personnel evacuated to safe areas[5]. Although this method uses no open flame, a fire extinguisher must be present near hot air gun operation, with all combustibles cleared within a 1 m radius. Pneumatic pick operators must wear dust masks, goggles, and earplugs. Keep hands away from the hydraulic crimper jaw. For trenches deeper than 0.6 m, safe access channels must be provided; exposed ends of completed sections must be temporarily wrapped with insulating tape[10].

7.2 Environmental Measures

Topsoil is stripped and stored separately; during backfilling, the lower subsoil is placed first, and the topsoil is finally spread on the surface to facilitate vegetation recovery. All construction waste (graphite wire ends, discarded packaging tapes, adhesive tapes, etc.) is collected and handed over to local sanitation services; on-site burial or burning is strictly prohibited[10]. In mountainous stepped and slope sections, reverse drainage and temporary covers must be installed as designed to prevent soil erosion. Temporary construction sites within wind farm and PV array areas must be promptly restored by sowing grass seeds after completion. By replacing copper, zinc, and other metals with high-purity graphite, the entire technology poses no risk of heavy metal pollution to soil or groundwater during both construction and operation phases, complying with the requirements of the Soil Pollution Prevention and Control Action Plan[6].

8. Benefit Analysis and Application Cases

8.1 Economic Benefit

Taking a 500 MW mountain wind power project as a sample for comparison between the traditional copper-clad steel scheme (Scheme A) and the proposed graphite-based scheme (Scheme B)[10,12]: The initial total investment of Scheme A is approximately 1.5431 million CNY, while Scheme B is approximately 1.0367 million CNY, saving 506,400 CNY in initial construction cost, a reduction of 32.8%. Over a 40-year life cycle, the copper-clad steel scheme requires a major overhaul after about 25 years of operation, with an estimated rehabilitation cost of 1.1 million CNY (including materials, construction, and power outage losses). The proposed method is maintenance-free for life, incurring no such expense. The total life-cycle cost is approximately 2.6431 million CNY for Scheme A and 1.0367 million CNY for Scheme B, resulting in savings of 1.6064 million CNY, a reduction of 60.8%[12].

8.2 Social and Environmental Benefits

Application of this method can stably maintain grounding resistance at a very low level, significantly reducing lightning trip-out rates and equipment damage in wind and PV stations, thus enhancing the intrinsic safety level of the power grid[4]. In this case, approximately 28 tons of copper and 2 tons of zinc can be saved, effectively conserving non-renewable metal resources and reducing dependence on imported refined copper[6,12]. Environmentally, several tons of copper ion migration into water bodies and soil can be prevented over the life cycle, protecting water conservation areas and ecologically sensitive zones. Based on industry data estimates, producing 1 ton of copper emits approximately 3 tons of carbon, and 1 ton of zinc emits approximately 2.5 tons of carbon; the project's combined reduction in carbon emissions is about 102.5 tons[12].

8.3 Typical Application Cases

(1) A 110 kV substation in Guizhou[11]. The soil consists mainly of gravel and yellow loam, with resistivity of 600–850 Ω·m and weak acidity. A φ28 mm pure graphite-based flexible grounding body was laid in a grid-plus-radial pattern. The completed grounding resistance measured 0.87 Ω, far better

than the ≤4 Ω design requirement; after three thunderstorm seasons of operation, the re-measured value stabilized at about 0.91 Ω with no drift.

(2) Retrofitting of 20 sets of 1.5 MW wind turbine foundations in Yancheng, Jiangsu [10]. The original galvanized flat steel grid exhibited an 80% corrosion rate after 9 years, with grounding resistance exceeding 10 Ω for all units. After applying this method, the average grounding resistance dropped from 11.8 Ω to 1.2 Ω (a reduction rate of 89.8%). After two years of operation, no signs of rust or peeling were observed on the surface of the grounding bodies.

(3) A 100 MWp PV power station in Ordos, Inner Mongolia [12]. The sandy soil resistivity was 500–700 Ω·m. A 40 mm × 5 mm graphite-based flexible grounding body was laid in a grid pattern along the mounting structure arrays. Upon completion, spot tests in 12 sub-arrays showed grounding resistance values ranging from 1.8 to 2.6 Ω, all meeting the ≤4 Ω design requirement. No open flame was used during construction; materials were transported manually, improving work efficiency by about 30% compared with traditional methods. After one year of operation, the grounding resistance remained unchanged, and the connection point seals were intact.

9. Conclusion

This paper systematically presents a construction method for graphite-based flexible grounding bodies in wind farms and PV power stations. Through theoretical analysis and multi-regional engineering validation, it demonstrates that this method effectively solves the construction and operation challenges of traditional metal grounding grids in highly corrosive, high-resistance, and complex terrain areas. Its characteristics of lifetime corrosion resistance and zero maintenance not only bring remarkable economic advantages but also completely eliminate open-flame fire hazards and heavy metal pollution risks, aligning with the development trends of intrinsic power grid safety and green construction. The method is technically mature, advanced, and practical, possessing great value for large-scale application.

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