Postprint of Study on Scheme for Converter Station Grounding Grid Replacing DC Grounding Electrode Operation

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Abstract

The ground-electrode-free operation mode of DC transmission facilitates early achievement of bipolar power delivery, and utilizing the converter station grounding grid as a substitute for the DC ground electrode represents the most effective measure currently available. However, such replacement may give rise to safety issues concerning personnel and secondary equipment, DC bias hazards to transformers, as well as heating and corrosion problems in the grounding grid. This paper conducts a systematic analysis of these issues, and ultimately, by synthesizing various influencing factors, proposes requirements for DC transmission control strategies, namely bipolar trip on single-pole fault, unbalanced current control, and bipolar synchronous deblocking. The research work provides an effective reference for the novel ground-electrode-free operation mode of DC transmission, and the relevant control strategies have been successfully applied in the Puqiao UHVDC transmission project of China Southern Power Grid.

Full Text

Application Analysis on Converter Station Grounding Grid as DC Grounding Electrode

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Abstract: Operation of HVDC transmission without a grounding electrode facilitates early realization of bipolar power delivery, and using the converter station grounding grid as a substitute for the DC grounding electrode represents the most effective measure currently available. However, this approach may introduce safety hazards for personnel and secondary equipment, cause

DC bias in transformers, and lead to heating and corrosion problems in the grounding grid. This paper analyzes these issues systematically and proposes comprehensive requirements for DC transmission control strategies, including unipolar fault tripping of both poles, unbalanced current control, and bipolar synchronous unlocking/locking. The research provides an effective reference for the new grounding-electrode-free operation mode of HVDC transmission, and the related control strategies have been successfully applied in the Puqiao UHVDC transmission project of the China Southern Power Grid.

Keywords: Converter station; Grounding grid; DC grounding electrode; Heating and corrosion of grounding grid

1 Introduction

The DC grounding electrode serves as the working ground for HVDC transmission [1] and plays a crucial role in the safe and stable operation of HVDC systems. During the construction of DC grounding electrodes, external factors such as land acquisition and site selection often cause delays in commissioning, thereby affecting the scheduled operation of HVDC transmission projects. With the large-scale construction of high-capacity HVDC transmission projects in China, research on grounding-electrode-free operation modes for DC systems has become essential to achieve early power delivery [2].

The most effective scheme for grounding-electrode-free operation in current HVDC transmission projects is to use the converter station grounding grid as the DC grounding electrode to enable bipolar operation. This substitution introduces several challenges, including impacts on personnel and secondary equipment safety, DC bias in system transformers, heating and corrosion of the grounding grid, and adjustments to DC transmission operation modes. Extensive research is required to analyze and address these issues.

This paper presents the overall requirements for grounding-electrode-free operation in HVDC transmission projects, conducts detailed analyses of personnel and secondary equipment safety, transformer DC bias, and grounding grid heating and corrosion, and finally proposes control strategy requirements for DC transmission that integrate all influencing factors. The research provides an effective reference for this new operation mode, and the related control strategies have been successfully applied in the Puqiao UHVDC transmission project of the China Southern Power Grid, demonstrating excellent performance.

2 Overall Analysis of Converter Station Grounding Grid Replacing DC Grounding Electrode

The key issues in using a converter station grounding grid to replace the DC grounding electrode include the following aspects [3-5]:

1. Ensuring strict safety for station personnel and secondary equipment.
2. Protecting converter transformers and other transformers within the system from severe DC bias hazards.
3. Preventing excessive temperature rise in grounding down-leads and the grounding grid itself.
4. Addressing grounding grid corrosion and developing countermeasures.

These four factors constitute the primary considerations for converter station grounding grid replacement of DC electrodes, and the boundary conditions they establish will serve as control requirements for DC transmission. The following sections analyze each factor in detail.

3.1 Personnel Safety Analysis

Steady-State Criterion: The maximum touch potential difference U_t within the station must satisfy the requirements of DL/T 437-2012 *Technical Guide for HVDC Grounding Electrodes* and DL/T 5224-2014 *Technical Code for Design of HVDC Earth Return Systems*, which specify $U_t \leq 50\,\mathrm{V}$. For personnel outside the station, the maximum touch potential difference must satisfy $U_t \leq 7.42 + 0.008\rho_S$, where ρ_S is the surface soil resistivity.

The steady-state criterion addresses two scenarios: safety for personnel inside the station and safety for those outside. For station personnel, the standard is based on the $U_t \leq 50\,\mathrm{V}$ limit. By defining k_t as the ratio of maximum touch potential difference to ground potential rise and letting I_f be the DC current injected into the ground, the boundary condition for the touch potential difference expression becomes $U_t = k_t R I_f \leq 50\,\mathrm{V}$. This yields the allowable ground current limit:

$$I_f \leq \frac{50}{k_t R}$$

Using this equation, the allowable ground current limits can be calculated, with results shown in Table 1 . The results indicate that to ensure personnel safety, the allowable DC current through the converter station grounding grid may be as low as 500 A. This steady-state criterion provides a reference for developing ground current suppression strategies and can guide both operation and design.

Since the converter station connects to multiple transmission lines whose shield wires are bonded to the station grounding grid, the shield wire-tower system can cause high-potential extension issues during DC faults for overhead towers accessible to the public and power system personnel. If DC faults persist for extended durations and given the large number of towers and lines, the risk of electric shock to personnel outside the station cannot be ignored. As tower grounding designs do not typically consider electric shock hazards, this paper recommends upgrading tower grounding with potential equalization modifications. Where such modifications are not feasible, it is recommended that the converter station avoid prolonged unipolar operation and instead adopt unipolar fault tripping of both poles to ensure safety for personnel outside the station.

Transient Criterion: When implementing unipolar fault tripping of both poles, the maximum touch potential difference U_t within the station must satisfy the requirements of GB/T 50065-2011 *Code for Design of AC Electrical Installations Earthing*:

$$U_t = 174 + \frac{0.17 C_S \rho_S}{\sqrt{t_S}}$$

where C_S and ρ_S are the surface attenuation coefficient and surface soil resistivity, respectively, and t_S is the fault duration.

Considering two scenarios—without a high-resistance surface layer ($C_S \rho_S \approx 100$) and with a high-resistance layer ($C_S \rho_S \approx 3000$)—the approximate expressions are:

$$U_t = k_t R I_f \leq 174 + \frac{17}{\sqrt{t_S}} \quad \text{(without high-resistance layer)}$$

$$U_t = k_t R I_f \leq 174 + \frac{510}{\sqrt{t_S}} \quad \text{(with high-resistance layer)}$$

Comparing these equations demonstrates the critical role of high-resistance layers in increasing the allowable touch potential difference. From these equations, the allowable current duration can be derived as:

$$t_S \leq \left(\frac{17}{k_t R I_f - 174} \right)^2 \quad \text{(without high-resistance layer)}$$

$$t_S \leq \left(\frac{510}{k_t R I_f - 174} \right)^2 \quad \text{(with high-resistance layer)}$$

Using these equations, the allowable ground current limits can be calculated. The results show that high-resistance layers can significantly increase the allowable duration of transient currents. For the Puqiao UHVDC project, the transient current during unipolar fault tripping of both poles can reach up to 16 kA for 0.1 s. With a high-resistance layer, the duration of 16 kA current can be limited to within 0.18 s, thus meeting requirements. Without a high-resistance layer, 6 kA current must be limited to within 14 ms, which exceeds the control capability of current HVDC projects. In conclusion, this paper recommends installing a high-resistance layer within the station to ensure personnel safety.

3.2 Secondary Equipment Safety

Secondary equipment safety must be considered in conjunction with the transient process of unipolar fault tripping of both poles. This transient process is similar to AC faults, and since AC faults in typical converter stations have greater current amplitudes and durations than DC unipolar fault tripping scenarios, secondary equipment that meets safety requirements during AC faults will also satisfy safety requirements during DC faults. Additionally, the probability of simultaneous AC and DC faults is extremely low, making verification of secondary equipment safety under hybrid fault conditions unnecessary.

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4 Grounding Grid Heating Analysis

Grounding grid heating analysis requires consideration of both the thermal stability of down-leads and the temperature rise of the grounding grid itself.

4.1 Thermal Stability Verification of Grounding Down-Leads

Under the operation mode of unipolar fault tripping of both poles, GB/T 50065-2011 *Code for Design of AC Electrical Installations Earthing* requires that the cross-sectional area of grounding down-leads must satisfy:

$$S_g \geq \frac{I_g}{C}\sqrt{t_e}$$

where S_g is the minimum cross-sectional area of the down-lead (mm^2), I_g is the DC current flowing through the down-lead (A), C is the thermal stability coefficient, and t_e is the current duration (s).

Based on the actual operating conditions of the Puqiao UHVDC project, the minimum cross-sectional areas of down-leads under various fault currents and durations were calculated, with results shown in Table 2 . The results demonstrate that these cross-sectional areas are smaller than the minimum areas required for thermal stability under typical AC fault currents, indicating that down-leads can fully meet the thermal stability requirements for DC fault currents.

4.2 Transient Temperature Rise Verification

The steady-state temperature rise calculation formula for grounding electrodes is:

$$\tau_\omega = I^2 R^2$$

Since the control strategy of unipolar fault tripping of both poles is adopted, the grounding grid does not experience prolonged DC currents, making transient temperature rise the primary concern. The transient temperature rise expression is:

$$\tau(t) = \tau_\omega \left(1 - e^{-t/T_r}\right)$$

where τ_ω is the steady-state temperature rise of the soil and T_r is the time constant of soil heating. T_r is related to the local current density on grounding conductors:

$$T_r = \frac{I^2 R^2}{2J^2 \rho^2}$$

The surface current distribution on grounding conductors is non-uniform when earth return current is injected into the grounding grid. Defining an average linear current density for the grounding grid as:

$$J_0 = \frac{I}{L}$$

where I is the return current and L is the total length of grounding grid conductors. The maximum linear current density is $J_{\max} = kJ_0 = k\frac{I}{L}$, where k is the current non-uniformity coefficient of the grounding grid conductors. The maximum surface current density is then:

$$J_{\max} = \frac{kI}{\pi d L}$$

After calculating the heating time constant T_r using the above relationships, the allowable operation time for the converter station grounding grid when substituting for the DC electrode can be derived from the transient temperature rise equation as:

$$t_m = T_r \log\left(\frac{1}{1 - \tau_m/\tau_\omega}\right)$$

Since $\tau_\omega \ll \tau_m$, this can be approximated as:

$$t_m \approx T_r \log\left(\frac{\tau_\omega}{\tau_\omega - \tau_m}\right)$$

Using a 3 kA-rated DC transmission project as an example and incorporating the current non-uniformity coefficient k from the previous heating analysis, the local maximum corrosion amount G is:

$$G = \frac{1\% \times 3000 \times 27.93 \times 365 \times 24 \times 3600 \times 50\% \times k\mu}{96490L}$$

where y is the design service life, k is taken as 5-10, and μ is the ground current coefficient with a typical value of 0.1. Considering current division through station transformer neutral point DC blocking capacitors and line shield wire connections to the converter station grounding grid, the current entering the converter station ground is only a portion of the DC transmission single-pole current. The coefficient μ is related to the number of outgoing lines, shield wire DC resistance, tower grounding resistance, and location of the opposite system, with typical values of $\mu < 0.3$.

With a total grounding grid conductor length of 20–40 km and conductor cross-section dimensions of 50 mm (L) × 7 mm (L), the above data can be substituted into the corrosion formula to calculate the uniform corrosion thickness δ. Calculations were performed for design lifetimes y of 30 years and 50 years, with the relationship between corrosion thickness and current non-uniformity coefficient for different total conductor lengths shown in Figure 2 [Figure 2: see original paper] and Figure 3 [Figure 3: see original paper].

Generally, the corrosion thickness due to unbalanced operation current is related to the grounding grid design life: 0.4 mm for 30 years and 0.7 mm for 50 years. This corrosion allowance should be fully considered during the grounding grid design phase by appropriately increasing conductor cross-sectional areas.

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5 Grounding Grid Corrosion Analysis

By appropriately adjusting the currents between the two poles (making the positive pole current greater than the negative pole) and operating the station grounding grid as the negative electrode (with current direction from the grid into the neutral bus at the sending end), corrosion of station grounding conductors caused by unbalanced current can be avoided. Additionally, if the cross-sectional area of grounding conductors for 10–20 towers near the converter station is increased, corrosion of tower grounding bodies caused by current division from the converter station can be prevented.

Furthermore, since the control strategy of unipolar fault tripping of both poles is employed, the corrosion caused by these brief current pulses is extremely minor.

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6 DC Transmission Control Strategy

The DC transmission control strategy requires three key elements: unipolar fault tripping of both poles, unbalanced current control, and bipolar synchronous unlocking/locking.

1) Unipolar Fault Tripping of Both Poles: To prevent sustained unipolar operation current from entering the ground and causing personnel safety and grounding grid heating issues, the duration of ground current should be minimized and measures should be taken to ensure bipolar synchronous unlocking. Based on experience from the Puqiao UHVDC project, it is recommended to use bipolar power control mode during unlocking and power ramping processes. This requires minimal software modification, as bipolar power reference values and ramp rates are sent directly to the DC station control, which then transmits them to both pole control systems via high-speed control buses with short communication delays, ensuring synchronous bipolar power changes. The actual requirement is that the entire tripping process be completed within 100 ms.

It should be noted that after adopting the unipolar fault tripping both poles control strategy, the Puqiao UHVDC project requires 3,500 MW of generator shedding in the sending-end Yunnan power grid to ensure system stability. Thorough analysis of unipolar fault tripping both poles is necessary to ensure stable system operation.

2) Unbalanced Current Control: During DC operation, one pole may experience current limitations and reduction due to equipment or environmental temperature factors, triggering pole-to-pole power transfer that increases the current in the other pole and creates bipolar unbalanced current. Therefore, the control program must include bipolar current synchronous tracking functionality to ensure balanced bipolar operation. If controlling ground current direction to reduce grounding grid corrosion is desired, after unlocking and ramping to the set power value, the control mode can be switched to current control with independent bipolar current settings to manage the unbalance degree. Even with this corrosion control thickness, proper measures can achieve effective control. This paper concludes that corrosion from unbalanced operation current can be avoided, but requires increasing the cross-sectional area of grounding conductors for 10–20 towers near the converter station to prevent tower grounding body corrosion from converter station current division.

3) Bipolar Synchronous Unlocking/Blocking: Based on experience from the Puqiao UHVDC project, four improvements should be implemented for bipolar synchronous unlocking/blocking:

1. Disable the function allowing operators to block single valve groups or single poles in bipolar operation mode, retaining only the bipolar blocking function. The blocking command should be sent to both pole control

systems via the DC station control through control buses to maximize command synchronization.

2. Implement response functions in each pole to the other pole' s control protection blocking and emergency shutdown signals, enabling rapid sharing of blocking and emergency shutdown information between poles through the DC station control. Upon receiving such information from the other pole, each pole should execute emergency shutdown sequences.
3. Treat shutdown commands from the other pole uniformly as emergency shutdowns, regardless of whether they are blocking or emergency shutdown commands, to reduce shutdown time and maximize bipolar shutdown synchronization.
4. Within the same pole, no longer distinguish between single or multiple valve group blocking or emergency shutdown information. If any valve group requires blocking or emergency shutdown, in addition to executing the normal sequence, the pole control should execute the emergency shutdown sequence for that pole and transmit the information to the other pole through the DC station control.

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7 Conclusion

1. This paper proposes a new concept of using converter station grounding grids to replace grounding electrodes and presents overall requirements for grounding-electrode-free operation of HVDC transmission projects.
2. Through analysis of personnel and secondary equipment safety, transformer DC bias, and grounding grid heating and corrosion issues, this paper proposes a comprehensive DC transmission control strategy that integrates all influencing factors.
3. To ensure personnel safety both inside and outside the station, DC transmission must employ control methods of unipolar fault tripping both poles and bipolar synchronous unlocking/locking.
4. To avoid DC current corrosion of grounding grid conductors, DC transmission must utilize unbalanced current control.
5. After implementing the control strategies of unipolar fault tripping both poles, unbalanced current control, and bipolar synchronous unlocking/locking, the grounding grid will not experience overheating problems.
6. This work provides an effective reference for the new grounding-electrode-free operation mode of HVDC transmission. The related control strategies have been successfully applied in the Puqiao UHVDC transmission project of the China Southern Power Grid, demonstrating excellent performance

with all indicators fully meeting operational requirements after nearly one year of operation.

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Note: Figure translations are in progress. See original paper for figures.