Temperature Rise Characteristics of Vertical Grounding Electrodes of Ultra-High Voltage DC ± 800 kV Pu'er Converter Station

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Abstract. The vertical grounding electrode (VGE) is a new type of grounding design of ultra-high voltage direct current (UHVDC) power transmission project, which can greatly reduce the grounding area. The main structure of VGE is several or dozens of vertical electrode wells connected with each other by cables to form a conductor system. However, the ends of the VGE temperature may rise severely due to the non-uniform grounding current of each electrode. In serious cases, cable failures or other accidents may occur. In order to investigate the VGE temperature rise characteristics of the UHV ±800kV Pu'er Converter Station in China, firstly a single VGE was simulated in the laboratory. Measurements of the single VGE temperature rise were compared with the calculations by finite element method (FEM) to verify the validity of the algorithm. Then the calculation model was utilized to compute the current distribution of each VGE of Pu'er Converter Station, and a current balance design was proposed in this paper. Calculations demonstrated that the maximal temperature rise of the VGE was 31 °C, which was lower than the design limit. This paper may provide some useful reference for the design and operation of the UHVDC vertical ground electrodes.

1. Introduction

The vertical grounding electrode (VGE) is a new type of grounding design of ultra-high voltage direct current (UHVDC) power transmission project [1]. This kind of design can greatly reduce the grounding area and is especially suitable for the DC power grounding project with limit area. The main structure of VGE is several or dozens of vertical electrode wells connected with each other by cables to form a conductor system.

However, there are some disadvantages in the design of VGE. Grounding current may be uneven due to serious end effect in the linear electrode, contributing to extreme temperature rise at the end of the VGE. Moreover, it is lacking in the design and operation of HVDC vertical grounding electrode. Design optimization of the VGE and some problems, for instance, electrochemical gas production and electrode corrosion still need to be solved.

The VGE system of ±800 kV Pu'er Converter Station in the Pu-Qiao power transmission of China Southern Power Grid is the first UHVDC power transmission VGE design in the world. Little operation experience can be refereed and the geological environment at Pu'er station is also complex. In order to find out potential problems and to optimize the VGE system design further, it is necessary

to investigate the temperature rise characteristics of Pu'er Converter Station's VGE, and it is beneficial to the grounding site selection in the future.

In this paper the temperature rise of a signal VGE in the laboratory was calculated and measured to verify the validity of the algorithm. Then the calculation model was utilized to compute the current distribution of each VGE of Pu'er Converter Station. A current balance design was proposed to reduce the uneven grounding current distribution. Calculations demonstrated that the maximal temperature rise of the VGE was lower than the design limit.

2. Calculation principle and method

2.1. Governing equation
According to the thermodynamics theory, the temperature at any point of isotropic material remains stable if the heat exchange condition does not vary with time. This kind of heat exchange problem is known as the stable problem. Poisson equation of temperature distribution of the VGE can be derived from the steady heat conduction equation, written as [2]

$$\nabla^2 T = -\frac{E^2}{\lambda \rho} \tag{1}$$

where T is temperature °C; ρ is soil resistivity, $\Omega \cdot m$; E is electric field strength, V/m; λ is heat conduction constant, W/(m·°C).

2.2. Boundary conditions
The soil temperature increases due to the heat generated from the VGE in operation. Part of the heat generated diffuses to infinite and the other transfers heat with the air through the ground.

For the interfaces between soil layers and the ones between the VGE and soil, it is the second boundary condition when the heat input and output are given at the boundaries. And it is the third boundary condition when the convection heat transfer is given at the interface between the soil and air. These conditions are written, as

$$\lambda \cdot \nabla T = \frac{E^2}{\rho} \tag{2}$$

$$\lambda \cdot \nabla T = h(T_f - T_s) \tag{3}$$

where λ is heat conduction constant vector, $\lambda = \lambda_x \boldsymbol{n}_x + \lambda_y \boldsymbol{n}_y + \lambda_z \boldsymbol{n}_z$; h is heat transfer constant, W/(m·°C); T_s and T_f are the temperatures of the soil and air respectively, °C.

2.3. Calculation method
Stable temperature field and heat conduction problems of direct current VGE can be solved by the finite element method (FEM), which is one of the standard solution methods to the differential equation.

The impact of initial temperature distributions of soil and air to the final stable distributions needn't to be considered. Thus, only heat transfer conditions are utilized. After the calculation domain is being discrete into finite elements, there is only one variable which is the temperature at each node of the element. Temperature of the space between the nodes can be calculated by the element interpolation function.

3. Experiments and results

3.1. Experiment platform
The temperature rise of a signal VGE in the laboratory was measured to verify the validity of the algorithm. A steel canister with diameter 0.5 m and height 0.5 m was applied in the measurement and a steel bar of 0.5 m in height and 1 cm in diameter was used as the VGE, as shown in figure 1(a). The current distribution of the steel bar was similar with the one of actual VGE of UHVDC power

transmission project. The space between the canister and the bar was filled by soil and sand. For the actual grounding electrode, coke powder was utilized to reduce the grounding resistance. A cylindrical coke powder layer with diameter 8 cm was used in the experiment, as can be seen in figure 1(b).

A direct current power supply (HSPY-600, Hanshengpuyuan Ltd, Beijing) was applied between the bar electrode and the canister. The output current of the power supply in the experiments was DC 0.5 A. The voltage between the electrode and the canister was measured by a digital voltmeter.

The temperature at the end of electrode in the soil was measured by a K type patch thermocouple. The initial temperatures of the soil and air were 30 °C and 20 °C, respectively. The resistivity, heat conduction constant, heat capacity were used as 200 Ω·m, 0.952 W/m·°C, 1200 J/kg·°C. The resistivity values of coke powder and mental electrode are 0.3 Ω·m and 1.7×10^{-7} Ω·m

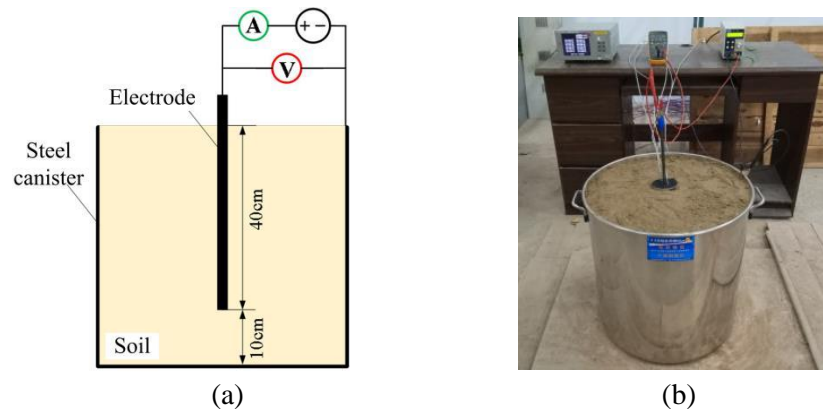(a)   (b)

Figure 1. Schematic diagram and photograph of the experimental apparatus

3.2. Calculations and measurements

Referring to electromagnetic theories, the temperature rise of the end of the grounding electrode in the soil is the largest. Calculations by the algorithm described in Part 2 and measurements are demonstrated in figure 2.
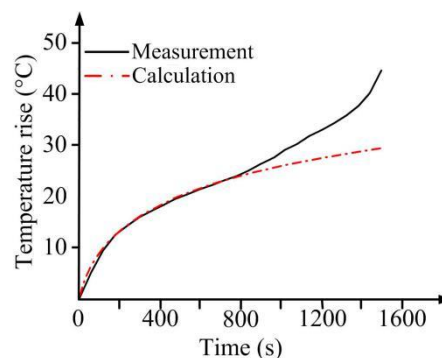

Figure 2. Temperature rise of the end of the single VGE

As can be seen from figure 2, in the first few minutes after applied to the power supply the temperature at the end of the VGE increased sharply. Then the temperature rise became stable in the subsequent 10 minutes and the calculations agreed with the measurements. However, temperature increased rapidly again in the last stage. The reason is that the moisture in the soil became little and the soil resistivity raised due to the evaporation effect when the soil temperature increased and there was no more water supplied into the soil in the canister.

4. Calculation and analysis of VGE temperature rise of Pu'er Converter Station

4.1. Boundary conditions

The grounding site of the Pu'er Converter Station is 5 km north to the Yongping town, Jinggu county, Pu'er city. The soil resistivity of each layer at this site is shown in table 1. The rated transmission power of the UHVDC Pu-Qiao project is 5 GW and the rated grounding current is 3125 A when single polar is in operation.

Double-circle construction is used in the Pu'er station's VGE. There are 40 and 23 VGEs consisted of the outer and inner circle, respectively. The diameter and depth of each grounding well are 1.2 m and 35 m. The diameter of each grounding electrode is 50 mm. Coke powder is filled in the grounding wells to reduce the grounding resistance.

The software CDEGS was applied to build the actual geometry model of Pu'er station's VGE system, as shown in figure 3. The grounding site is surrounded by a river named Mengga by three sides. The river is 20-meter-wide and 5-meter-deep. The resistivity is used as 50 Ω·m in the calculation.

Table 1. Soil resistivity of each layer at Pu'er Converter Station

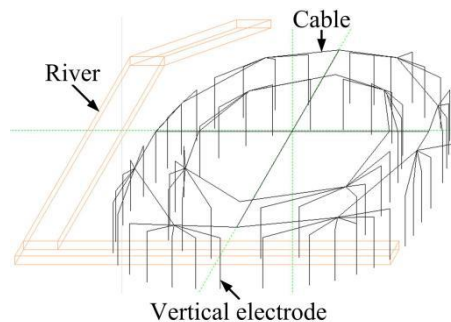| No.	Thickness (m)	Resistivity (Ω·m)
1	6	600
2	7	120
3	140	75
4	150	105
5	7000	98
6	30000	18
7	∞	83

Figure 3. Schematic diagram of the calculation model

4.2. Grounding current distribution and its optimization

Calculated values of the grounding current of each VGE are shown in figure 4(a). The average grounding current of No. 1 to 40 VGE (outer circle) is 55.3 A and the maximum is 68.1 A of No. 4 VGE. The average grounding current of the inner circle (No. 41 to 63) is 39.7 A and the maximum is 46.4 A of No. 51. The average value of the outer circle is 40% larger than the one of the inner circle. Thus, the uneven distribution is obvious.

In order to reduce the uneven grounding current distribution of the VGE the length of the inner VGE increased from 30 m to 40 m. The calculation results are shown in figure 4(b). The average values of grounding current of the outer and inner VGE were 49.8 A and 49.3 A, respectively. Thus, increasing the inner VGE length can be utilized to optimize the grounding current distribution.
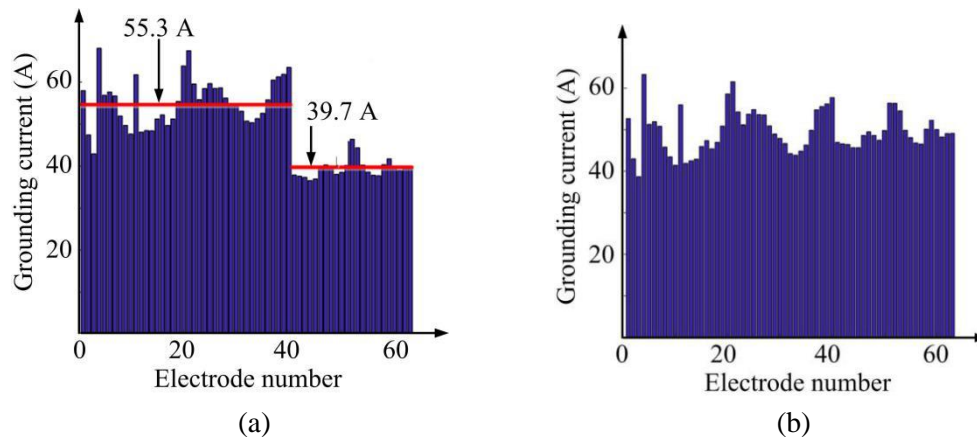
Figure 4. Calculation results of current distribution of each VGE

4.3. Calculation and analysis of VGE temperature rise
It is difficult to calculate the dynamic process of the VGE temperature rise, namely temperature increasing from air temperature to stable high temperature. Because the number of elements is quite large and the time consumption of the computation is about days. Thus a simplified numerical model is utilized in this part. For a specific VGE only the VEGs within 50 m were considered. Theoretically, the VGE at the long axis of the grounding system (No. 20) has the maximum temperature rise and the VGEs of No. 18 to 22 were calculated.

The grounding current of No. 20 VGE was taken as 120 A and the one of other VGEs was 100 A. According the operation procedure of China Southern Power Grid, the time period of earth return system must be within 2 h [3] and the temperature rise period was taken as 120 hours (5 days).The calculation time was about 2 days and the results were shown in figure 5. The maximal temperature of the VGE increased from 20 °C to 51 °C (No. 20) and the temperature rise values of other VGEs was about 20 °C, which were less than the design limit (100 °C) [3].
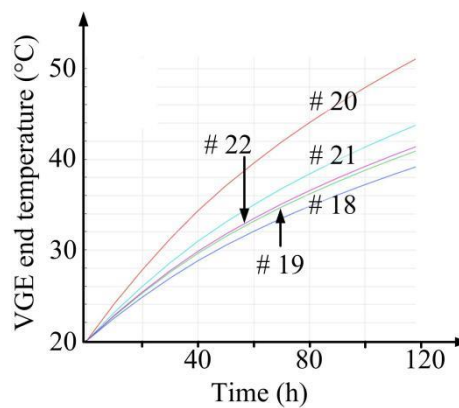

Figure 5. Temperature rise of the No. 18 to 22 VGEs of Pu'er Converter Station in 5 days

5. Conclusion
Grounding current distribution and temperature rise of the VGE system of UHVDC ±800 kV Pu'er Converter Station were calculated and analyzed in this paper. The conclusions may be obtained as follows:
● The end of a single VGE increased sharply after being in operation. Then the temperature rise became stable. Temperature could increase rapidly again in the last stage if there was not enough water added.

- For the double-circle design of the VGE the average value of the outer circle could be 40% larger than the one of the inner circle if the geometric parameters of the outer and inner VGEs were the same. It could be utilized to reduce the obvious uneven grounding current distribution that increasing the inner VGE length.
- The maximal temperature rise of the VGE of Pu'er Converter Station was 31 °C which was less than the design limit.

References
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