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Research Article

Research on Frozen Soil Structure Influence over Transformer DC Magnetic Biasing in UHVDC Transmission

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Abstract: This study studies the exciting current of transformer affected by DC bias in the Tibet frozen soil structure when the UHVDC system is working in monopole state. Firstly, the model of calculating the ground potential for a typical frozen soil of the Tuotuo River substation was described and then the ground potential around the UHVDC grounding electrode for five-layer soil in summer and winter was calculated. According to the soil parameters, the magnetic bias current of the transformer were calculated. Results indicate that the distance is less than about 4 km and the earth potential is variable in different season. The substation electrode design parameters are complex, so building substation is very inconvenient. And when the distance is adjusted from 4 km to 8km, the earth potential is changed from 400 to 200 V, the exciting current decreased from 45 to 5 mA, the waveform unbalance will also decrease.

Keywords: Ground electrode, hvdc, soil structure, transformer dc bias

INTRODUCTION

When the ground is used as a return path for a HVDC transmission line, the earth potential can increase in substation in relation to other substations on the same power system. The low resistance of the lines, the transformer windings and their grounding are such that a DC current can flow through the transmission lines and their transformers and force the latter into saturation. Several studies have already investigated this topic, mostly aiming to define the impact of this current flow on the transformers and on the system itself by Hongzhi *et al*. (2009) and Wang *et al*. (2008), similar work by Li *et al*. (2007) and Li and Wen (2010).

In the study described in this study, the objective is to analyze DC excitation of transformer core near the HVDC convertor station in Tibet. As is known to all, the soil structure could affect the potential distribution in the earth. However, the soil of Tibet is very special simply because the soil structure is frozen soil by and large. It is in frozen condition in winter and in thawy condition in summer. So calculating and analyzing the earth potential is rather important.

The study mainly deals with the DC magnetic biasing for neutral grounding transformer when the soil parameter around the UHVDC grounding electrode in Tibet is different in winter and summer. Firstly the model of calculating the ground potential for multi-layer soil was described then the ground potential around the UHVDC grounding electrode for frozen soil was calculated. Based on the soil parameters, the magnetic bias current for the transformer was calculated.

The saturation increases with the increase of DC voltage and the exciting current. And the exciting current changes quite unevenly with decreasing distance between transformer grounding electrode and UHVDC grounding electrode. Saturation and exciting current by DC current can cause problems for the system in extreme cases as a result of the harmonics generated and transformer vibration, variations in the reactive power and resonances in the system. So, when we site the ac substation in the frozen soil especially in Tibet, we must consider the soil change in different season and compute the actual earth potential to ensure the ac system operates normally.

MATERIALS AND METHODS

When a bipolar HVDC system operates in monopole state, one pole is fault or under examination. The DC current producing exciting current for neutral grounding transformer is determined by earth potential. And the earth potential depends on soil structure. So it is a must to study the soil structure model.

The earth structure could use landscape layered-soil structure, especially the place near sea because the seawater resistivity is totally different from that of earth soil. We mainly consider power system DC bias phenomenon in Tibet here. Tibet is located inland and the earth is frozen, in soil geological structure. It is very complex and it needs about five layers and more soil structure to imitate. Then the soil model has been built below, as is shown in Fig. 1.

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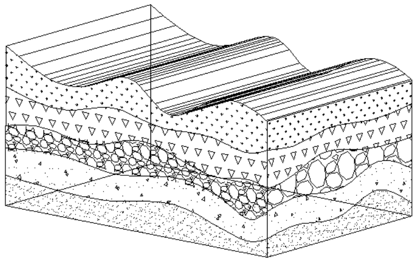

Fig. 1: A five-layer soil structure mode

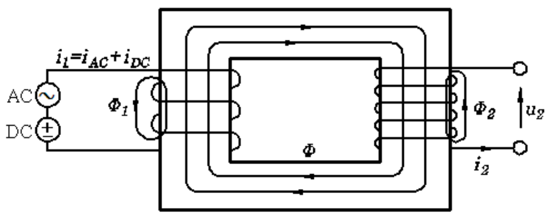

Fig. 2: Transformer winding diagram with DC from earth

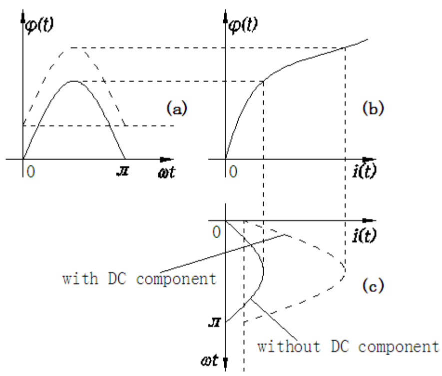

Fig. 3: Skeleton drawing of DC magnetic biasing

On the basis of Laplace's equation, the earth surface potential expression of point current density source in the first layer of level layered soil structure could be deduced by mirror image method of Green's function:

$$\phi = \frac{\rho_1 I}{2\pi}\int_0^{\infty} \alpha_1(\lambda) J_0(\lambda r) e^{-\lambda z} d\lambda \tag{1}$$

In the formula:

$$\alpha_1(\lambda) = 1 + \frac{2K_1 e^{-2\lambda h_1}}{1 - K_1 e^{-2\lambda h_1}}, \quad K_1(\lambda) = \frac{\rho_2\alpha_2 - \rho_1}{\rho_2\alpha_2 + \rho_1};$$

$$\alpha_2(\lambda) = 1 + \frac{2K_2 e^{-2\lambda h_2}}{1 - K_2 e^{-2\lambda h_2}}, \quad K_2(\lambda) = \frac{\rho_3\alpha_3 - \rho_2}{\rho_3\alpha_3 + \rho_2};$$

$$\ldots\ldots, \quad \ldots\ldots;$$

$$\alpha_{n-1}(\lambda) = 1 + \frac{2K_{n-1} e^{-2\lambda h_{n-1}}}{1 - K_{n-1} e^{-2\lambda h_{n-1}}}, \quad K_{n-1}(\lambda) = \frac{\rho_n - \rho_{n-1}}{\rho_n - \rho_{n-1}}.$$

where,

f = Earth surface potential
r_n = The soil resistivity of the number n layer
I = The DC current of UHVDC grounding electrode
J_0 = The first kind of zero order Bessel function
Z = The depth of UHVDC grounding electrode
n = The number of soil layer from up to down
h_n = The thickness of the number n soil layer

The phenomenon of DC magnetic biasing is caused by DC magnetic flow in transformer iron core, which would cause asymmetric saturation of positive or negative half cycle and a series of magnetic effects. Geomagnetic storm and the larger current of DC transmission system earth electrode are the main reason for this phenomenon.

When HVDC earth electrode pour DC current in single pole operation, it would form potential distribution in nearby ground, through the earth the current would flow to contra variant substation DC electrode. If there is transformer near DC electrode neutral grounded, part of the current would flow into transformer through grounding neutral point, a loop formed with AC electric network. This makes exciting current join DC current with AC field current, shown in Fig. 2, which cause magnetization curve into saturation region.

Figure 3 shows the magnetizing current resulting from the saturation of a transformer by a DC bias. It contains the magnetization curve, the flux and magnetizing current curves for cases with and without DC current. The magnetizing current is plotted from the flux and the magnetization curve:

- Is the flux curve
- Is exciting curve of transformer
- Is the curve of exciting current

The distortion of exciting current with DC current component is caused by the nonlinearity of the transformer magnetization curve. In this condition, the transformer core is in saturated state. The magnitude of exciting current is concerned with DC current size besides transformer design by Cao *et al*. (2008) and Zhanyuan *et al*. (2009), similar work by Dang *et al*. (2009).

By the action of excitation magnetic potential, the main flux is built in transformer core. The Synthesis magnetic potential which is generated by current in the core winding is excitation magnetic potential. Just like the single-phase transformer in Fig. 4.

Suppose N_1 is primary winding circle number and i_1 is primary current. N_2 is second winding circle number and i_2 is second current. So excitation magnetic potential is:

$$F_m = i_1 N_1 + i_2 N_2 \tag{2}$$

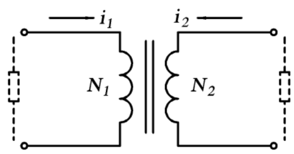

Fig. 4: Single duplex winding transformer

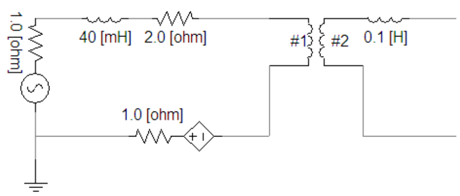

Fig. 5: EMTDC/PSCAD Transformer model

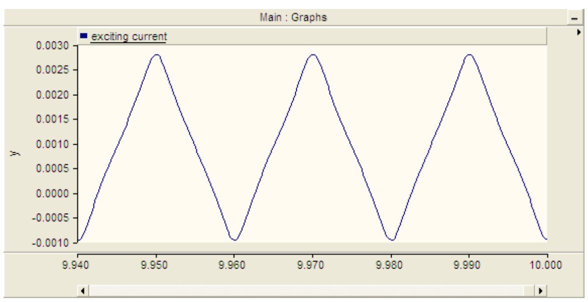

Fig. 6: Exciting current waveform for single-phase transformer without bias

To correct the second current to the primary winding and suppose:

$$i_2' = i_2 N_2 / N_1 \tag{3}$$

$$F_m = i_1 N_1 + i_2' N_1 = (i_1 + i_2') N_1 = i_m N_1 \tag{4}$$

where, $i_m = i_1 + i'_2$, is exciting current

The earth potential were calculated by Matlab software. Then, the exciting current was imitated by using EMTDC /PSCAD software.

The transformer parameter: rated active power 100 MVA, $R1=0.1$ *pu*; $L2 = 0.1$ *pu*; $R2 = 0.1$ *pu*; $L2 = 0.1$ *pu*, is shown in Fig. 5.

Referring to formula 4, it could work out the exciting current waveform for single-phase transformer without DC magnetic biasing, shown in Fig. 6.

In that simulation experiment, different DC current flow into transformer, than, compute and imitate the waveform of transformer winding exciting current and analyze the distinction.

The influence on Electrical equipment caused by DC current is affected by soil resistivity by Ma *et al.* (2006), similar work by Zhao *et al.* (2010). Some simulations about the soil resistivity are carried out.

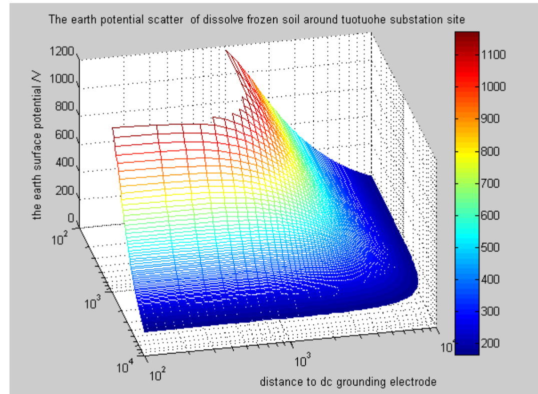

Fig. 7: The earth potential scatter gram of dissolve frozen soil around Tuotuo River substation

Table 1: The multi-layer soil models of tuotuo river substation sites in Tibet

Soil structure		Dissolve frozen	Frozen
Top-layer	Resistivity/(Ω·m)	398	2878
	Thickness/(m)	1.88	3.20
Mid-layer 1	Resistivity/(Ω·m)	172	1098
	Thickness/(m)	2.46	7.72
Mid-layer 2	Resistivity/(Ω·m)	1098	254
	Thickness/(m)	7.72	16.68
Mid-layer 3	Resistivity/(Ω·m)	254	—
	Thickness/(m)	16.68	—
Bottom-layer	Resistivity/(Ω·m)	3503	3505

We find the Tuotuo River substation is a typical place in Tibet to construct the soil model, which is shown in Table 1.

Frozen soil often has two conditions: frozen and unfrozen. In Table 1, soil structure usually has 5 layers in frozen condition, with 4 layers in unfrozen condition. The soil resistivity under dissolve frozen condition is seriously smaller than that in frozen condition in the first and second layer. However, the soil resistivity of dissolve frozen condition is much bigger than that in frozen condition in the third layer. Now, it can be concluded that the soil layers and soil resistivity are quite different in these two conditions, based on which, soil model can be constructed.

Referring to formula.1, when the DC current of grounding electrode is 3000A, the earth potential scatter gram of dissolve frozen soil around Tuotuo River substation is imitated by MATLAB software as Fig. 7.

The earth potential scatter gram of frozen soil around the Tuotuo River substation is imitated by MATLAB software as Fig. 8.

As is shown in Fig. 9 the grams of two conditions are combined into a 2-dimensional gram e. From the figure, the difference of the earth potential between unfrozen and frozen soil structures is obvious.

As is shown in Fig. 9, when the distance between HVDC grounding electrode and objective is less than 3 km around the Tuotuo River substation, the earth potential changes a lot from frozen condition to

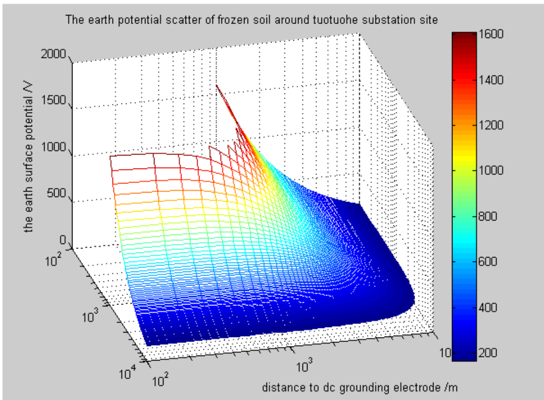

Fig. 8: The earth potential scatter gram of frozen soil around Tuotuo River substation site

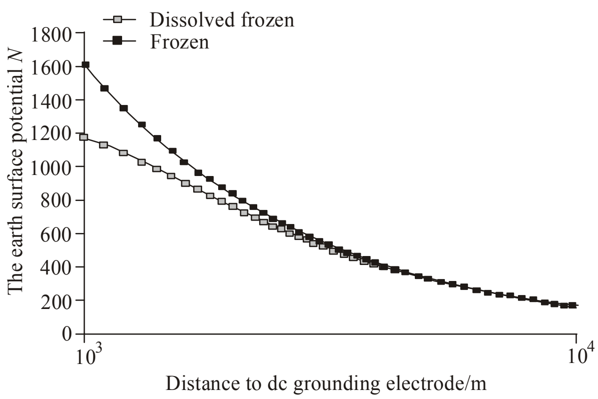

Fig. 9: The earth potential contrast chart of dissolve frozen soil and frozen soil around Tuotuo River substation

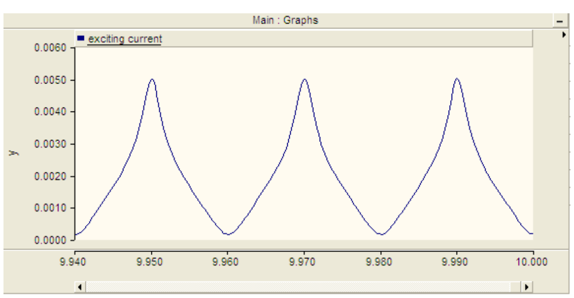

Fig. 10: Exciting current waveform for transformer when the distance is 8 km

unfrozen one, while the earth potential profiles of two conditions are almost the same when the range is over 3 km. The reason is that the frozen earth structure and soil resistivity are variable in different season. Therefore, power equipment should be built within 3 km away from HVDC grounding electrode that is improper and they could be built out of a certain distance yet.

The following paragraphs present an example of a PSCAD program simulation of transformer DC magnetic biasing wave by a DC potential. The potential is defined with previous section.

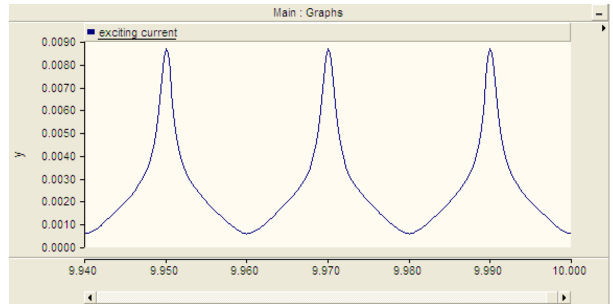

Fig. 11: Exciting current waveform for transformer when the distance is 6 km

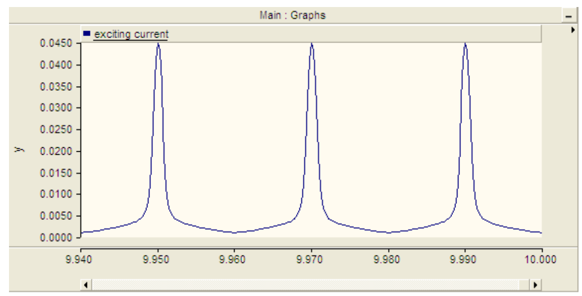

Fig. 12: Exciting current waveform for transformer when the distance is 4 km

Firstly, the DC voltage (200 V) distance about 8km from HVDC grounding electrode. Figure 10 shows the circuit where a DC voltage of 200 V is applied in series with the ac voltage on a transformer, the exciting current waveform is shown in Fig. 10.

Important note is that it must get the waveform when the waves keep good stability, because the transformer does not saturate immediately. At the very beginning of the DC voltage application, the plot for the transformer magnetizing current is great important because the unit reaches saturation not that easily. So, the wave form is adopted with the later in time axis.

When the distance between transformer and HVDC grounding electrode is about 6 km, the earth potential is about 290 V. The PSCAD simulation was performed for this DC voltage of 290 V, the exciting current waveform is shown in Fig. 11.

And if distance is about 4 km from transformer to HVDC grounding electrode and 400 V DC voltage is applied, the waveform of the exciting current in the transformer is shown in Fig. 12.

As these figures shown, compared with the results presented above like Fig. 10, 11, 12 and 6, the wave crests of exciting current skewing to positive direction gradually. Referring to Fig. 10, 11 and 12, the waveforms distortions change increasingly with rise of earth potential from 8 to 4 km. The exciting balance current changed from 5 to 45 mA (Table 2).

It illustrates the DC grounding electrode close to transformer electrode more, the earth surface potential is higher. And the DC current that invades into the ac

Table 2: The exciting current in different distances

Distance/km	DC voltage/V	Exciting current/mA
	0	2.8
8	200	5
6	290	8.8
4	400	45

transformer is larger, so the DC excitation of transformer core is more serious.

CONCLUSION

The approximation formula of n layers soil structure developed in for transformer core saturation under the effect of a DC current which is produced by UHVDC grounding electrode in the frozen earth soil in different season. The Tuotuo River substation as a typical frozen soil adopted with EMTDC/PSCAD simulation results testifies to the two different conditions of frozen soil when a DC voltage is applied. The following points are concluded:

- Tibet earth is almost frozen soil. It must be divided into two kinds of cases to discuss. One is the frozen condition in winter; the other is unfrozen condition. The soil structure, such as soil layer number and soil resistivity of every layer are different in the two conditions. Then, it is necessary to calculate earth potential from two cases.
- Within a certain range of the transformer and UHVDC grounding electrode, 4 km in this study, the earth potential is different at the same point because the frozen soil structure and the unfrozen soil structure in the different season. The earth potential is indeterminable. The transformer grounding electrode design parameters can't be defined. So, it must consider out of this distance to site the substation.
- Out of a certain range, 4 km in this study, the earth potential is unacted in the two soil conditions. The potentials tendencies are same in two seasons. So, we could design the substation in this range. Within this range, the saturation increases with the inccrease of the DC voltage and the exciting current. And the exciting current changed very unevenly with decreasing distance between transformer grounding electrode and UHVDC grounding electrode.

Saturation and exciting current by DC current can cause problems for the system in extreme cases as a result of the harmonics generated and transformer vibration, variations in the reactive power and resonances in the system. So, when we site the ac substation in the frozen soil especially in Tibet, we must consider the soil change in different season and compute the actual earth potential to ensure the ac system operates normally.

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