Modeling and Analysis of DC Magnetic Bias Effect for 1000kV Ultra-High Voltage Transformer

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Abstract: DC magnetic bias refers to a series of complicated electrical, magnetic, force, sound, heat and other abnormal phenomena caused by DC current intrusion into the transformer winding, which causes half-cycle saturation of core flux, which will seriously endanger the safe and stable operation of the transformer. Since the 1000kV UHV substation is very important in the power system, and the UHV transformer has lower DC current tolerance than the general transformer, it is necessary to accurately evaluate the DC bias risk of the UHV transformer during the design phase. This paper provides a reference for the DC bias magnetization prevention and control of UHV transformers by modelling and analysing the DC bias magnetization of 1000 kV UHV substation in Changsha.

1. Introduction

The DC current flowing in the transformer winding will produce a DC flux. As shown in Fig.1 (a), the broken line is the flux curve containing the DC component, and Fig.1(b) is the magnetization curve of the transformer core[1-4]. The magnetizing current curve with a DC component is indicated by a broken line in Fig.1(c). When the DC component increases the magnetization of the transformer above the inflection point of the magnetization curve, the transformer core is in a saturated state. Due to the presence of DC bias, the excitation current increases, the waveform is severely distorted, and a half-wave spike occurs. If the DC current in the winding exceeds the allowable value, the eddy current loss caused by the leakage flux may cause the transformer core and the connector to overheat, and the noise and harmonics increase. In severe cases, the insulation damage may occur, thereby affecting the normal operation of the transformer.

Generally speaking, DC bias will have the following hazards:

1) The noise is increased. When a DC current flows through the transformer coil, the harmonic content of the transformer increases, and the noise frequency of the transformer changes, which may increase the noise due to resonance of a certain frequency with the structural components of the transformer.

2) The voltage waveform is distorted. When the core is working in a severely saturated region, the leakage flux will increase, and the voltage peak will be flattened to a certain extent.

3) The copper consumption of the transformer increases. Under the influence of DC current, the excitation current of the transformer will increase greatly, resulting in a sharp increase in the basic copper consumption of the transformer.
(4) The transformer’s iron consumption increases. Since the excitation current enters the saturation region of the magnetization curve, the magnetic permeability of the core and the air are close to each other, so that the leakage flux of the transformer is greatly increased, and eddy current loss, that is, additional iron loss, is generated therein.

For the DC bias problem of the transformer, according to the provisions of China's High-voltage DC Grounding Technical Guidelines, the allowable DC current of each phase winding of the transformer is that single-phase transformer is 0.3% of rated current, three-phase five-column transformer is 0.5% of rated current, and three-phase three-column transformer 0.7% of the rated current. At present, in the actual domestic processing, the DC bias evaluation indicators are taken from the neutral point of the transformer, and the threshold is different according to the actual situation of the regional power grid. Details are shown in Table I.

The UHV transformer is currently a single-phase four-column core structure, which is an auto-coupling variable, and its main body is changed and the voltage-regulating compensation transformer is arranged separately [5]. The main body change and voltage regulation compensation transformer are connected by external leads. The electrical connection diagram of the UHV transformer is shown in Fig. 2. In Fig. 2, SV is series winding, CV is common winding, LV is low voltage winding, EV is excitation winding, TV is voltage regulating winding, LE is excitation winding, and LT is compensation winding. R₁, R₂, R₃, R₄, R₅, R₆, and R₇ are the resistances of the respective windings. u₁, u₂, and u₃ are respectively the high voltage side, the medium voltage side, and the low voltage side voltage of the UHV transformer. Due to its special structural form, the auto-coupling neutral point current does not reflect the DC bias level of the transformer. Therefore, the evaluation method using the neutral point current in Table I is not suitable for evaluating the degree of DC bias of the auto-transformation. On the contrary, the DC flux generated by the DC current flowing through the series winding and the common winding should be considered comprehensively. Consequently, this paper will use the new evaluation method of DC bias current as the evaluation index of the DC bias risk of the transformer.

### 2. Model Building Method

#### 2.1. DC Magnetic Bias Current
The derivation calculation method of DC bias is as follows. It is well known that for a transformer, the higher the half-saturation of the excitation curve of the core, the more severe the DC bias is, which is reflected in the DC flux of the core. The magnetic flux is determined by the magneto-motive force and is related to the magnitude of the DC current and the number of turns in all windings on the transformer core. As shown in Fig.3, if the turns of the high-voltage and medium-voltage windings of an autotransformer are respectively \( n_1 \) and \( n_2 \), and the DC currents of the high-voltage and medium-voltage windings are \( i_{dc}^H \) and \( i_{dc}^M \), then there is a direct electrical connection between the high voltage side and the low voltage side. The severity of the core bias is expressed by the magneto-motive force as:

\[
MMF_{dc} = n_ji_{dc}^H + n_ci_{dc}^M
\]

(1)

In equation (1): \( n_s \) and \( n_c \) are respectively the number of turns of the series winding and the common winding of the autotransformer. As can be seen from Fig.3, the neutral current does not reflect the full DC current in the winding. Even after a DC-blocking device is installed at the neutral point, if a large current flows through the series winding, the degree of DC magnetic bias of the auto-coupling is also very high.

Since the number of transformers in the power grid is large and the parameters are not the same, if the DC magneto-motive force is all reduced to the DC current on the high voltage side, a quantitative index for evaluating the severity of the DC bias can be obtained. It is defined as the equivalent DC power \( I_{dc} \) of the transformer winding as follows.

The equation of the single-winding transformer DC magnetic bias current is: \( I_{dc} = i_{dc} \)  

(2)

The equation of double-winding transformer DC bias current is: \( I_{dc} = i_{dc}^H + ki_{dc}^M \) 

(3)

The equation of autotransformer DC bias current is: \( I_{dc} = i_{dc}^H + \frac{1}{k-1}(i_{dc}^H - i_{dc}^M) \) 

(4)

In equations (3) and (4): \( k \) is the ratio of the high voltage to the medium voltage side of the transformer. From the above analysis, it can be seen that the DC bias current is used as an index to evaluate the severity of DC bias of the transformer, which is more scientific than the neutral current of the transformer.

2.2. Substation and Line Model

The above-ground part of the substation refers to the part of the ground above that does not contain lines as shown in Fig. 5(a), while the underground part refers to the part below the ground as shown in Fig.5(a). The equivalent DC model of the substation shown in Fig. 5 (a) can be referred to Fig. 5(b).

In Fig.5(a), the series winding of the autotransformer is connected to the high voltage bus and the medium voltage bus, and the medium voltage bus is connected to the neutral or neutral point series device via the common winding (such as small reactance and neutral point suppression DC current devices)[6]. In Fig.5(b), other forms of transformers (such as three-winding transformers) are series...
devices in which the high-voltage bus and the medium-voltage bus are connected to the neutral or neutral point via their respective windings.

![Fig.5. The DC model of AC power grid](image)

The above-ground part of the substation is a pure circuit problem. The model mainly includes substation nodes, transformer models, and neutral point series equipment models. The substation node model is shown in Fig. 5(b). The transformer model includes transformer winding type, winding DC resistance, and transformer bus. In the calculation of DC bias current distribution, it is only necessary to distinguish whether the transformer is an autotransformer. A schematic diagram of the transformer winding type can be found in Fig.4.

The step-down autotransformer which is widely used in the current 500kV substation is mostly grounded directly at the neutral point. As shown in Fig. 5(b), the two autotransformers behave as a 500kV node connected to two 220kV bus bar nodes via series windings, which are connected to their respective neutral or neutral point series devices via their respective common windings.

The grounding resistance of the underground part of the substation is only related to the soil near the site. The corresponding processing method is to take the measured value of the power frequency grounding resistance of the substation to replace the DC resistance. The line model is actually the three resistance branches connecting the three-phase bus bars of the substation. The key parameters are DC resistance and how to connect lines. The equation for estimating the DC resistance of the line is:

\[ R_L = \frac{\rho D}{S} \tag{5} \]

In equation (5), \( R_L \) is the line-one resistance (\( \Omega \)), \( \rho \) is the line material resistivity coefficient (\( \Omega \cdot m \)), \( S \) is the cross-sectional area (\( m^2 \)) of the one-phase line, and \( D \) is the length of the one-phase line (\( m \)). In power system components, the wiring of the line often changes, and the line is divided into multiple voltage levels. Consequently, only the line of 110kV and above voltage level can be considered in the calculation of the DC current distribution. In addition, the three-phase DC resistance and wiring of the line are the same and can be considered in parallel.

3. Distribution Model of DC Magnetic Bias Current in AC System

If the AC grid has a total of \( m \) substations, \( b \) bus bar nodes, \( n \) DC potential independent neutral points (if the two neutral points of the same substation are grounded and ungrounded, the two potentials are different, and they are regarded as two independent nodes in the model), the node voltage method has\(^7\):

\[ YV = J \tag{6} \]

\( V \) — the grid node voltage column vector, representing the substation node voltage (V), the independent neutral point voltage (V), and the bus voltage column vector (V). If the neutral point is shorted to the substation node, the neutral point of the station is deleted in the model, and only the substation node is reserved;

\( Y \) — the grid node conductance matrix, \( Y = HTG + Q \). \( H \) is the correlation matrix between the substation node and all nodes, and \( H^T \) is the transposition of \( H \). \( Em \) is an \( m \)-order unit array. \( G \) is the
substation grounding conductance array, \( G = R^{-1}, R = \text{diag} (R_{G1}, R_{G2}, \ldots, R_{Gm}) \), and \( R_{Gi} \) is the \( i \)-th substation DC grounding resistance (\( \Omega \)). \( Q \) is the ground node network node conductance matrix of the AC grid;

\[ J - \text{the grid node injection current column vector;} \quad J = [J_S; J_N; J_B] = [GP; 0; 0] = H^TGP \quad (7) \]

In the equation (7) of \( J_S, J_N, J_B \) — the substation node, independent neutral point, bus node injection current column vector (A); \( P \) — the induced potential column vector (V) of the substation.

The grounding theory is:

\[ DAP = MI + NI \quad (8) \]

\[ ID \] — the DC pole ground current (A).

\[ IA \] — the DC current (A) injected into the substation grounding grid. \( I_A = G(HV - P) \quad (9) \)

\( M \) — the mutual resistance matrix (\( \Omega \)) between the DC pole and the substation.

\( N \) — the mutual resistance matrix (\( \Omega \)) between substations (excluding their own functions).

\( P \) — the substation induced potential, which refers to the inlet potential (V) between the neutral point and the zero point.

After decoupling equation (8) and (9), it can be taken:

\[ (R - ZN)I = ZMI \quad (10) \]

Representing equation (10) in the form of a circuit, \( ZNI_A \) is actually the voltage source (ICVS) of other loop current control, the DC current distribution of the entire AC grid can be obtained. The essence of the DC current distribution of the AC grid is that under the mutual coupling coupling of many buried ground conductors [8], the equivalent low-resistance network of the AC grid provides a ground-distributing path for the DC current to the ground.

4. Model Analysis and Conclusion

According to the model construction method above, combined with the planning parameters of the 1000kV Changsha UHV substation in Table II, the Changsha UHV substation is connected to the Jingmen UHV substation in Hubei and the Nanchang UHV substation in Jiangxi through the double-circuit UHV line. In the 500kV line, the 500kV side of Changsha UHV is connected to 500kV Xingcheng, Dinggong and Liuyang through double-circuit line, and connected to 500kV Luocheng through a single-circuit line. The actual model is shown in Fig.6.

![Fig. 6 The simulation model of Changsha UHV](image)

**Table II. Modeling scale of 1000kV Changsha UHV substation**

| Feature                                      | Specification                           |
|----------------------------------------------|-----------------------------------------|
| The main transformer                         | 2 groups 3000 MVA each (No. 2 and No. 3) |
| 1000 kV line/500 kV line                     | 4 loops/7 loops                         |
| 1000kV High voltage shunt reactor            | 4 groups                                |
In the case of the grounding pole rated 5000A into the ground current, the No. 2 and No. 3 variable neutral points are directly grounded. The total ground current of the Changsha UHV substation is 5.50A, and the average DC current of each main transformer is only 2.75A. According to the previous guidelines, the transformer will only withstand a DC current of about 0.9A per phase, and there should be no significant DC bias damage. However, as described in Section 2.5.4 of the report, since the UHV transformer is a single-phase auto-transformer, the neutral DC current is only a reflection of the DC current on the common winding and does not fully represent the DC magneto-motive force that the transformer core is subjected to. A more reasonable DC bias risk assessment scheme should be the DC bias current of the transformer.

The DC current of the high-voltage winding of No. 2 and No. 3 is 8.39A/phase (the sum of three phases is equal to the current flowing from the UHV line), and the DC current of the common-voltage winding is 0.93A/phase (the sum of three phases is equal to neutral) Point current). The neutral point current of both main transformers is 2.79A, and the DC bias current of the two main transformers is 4.65A (check calculation equation). According to the current threshold value (2A/phase) of the DC bias risk assessment of UHV transformers, the DC bias current of the UHV main transformer is 4.65A, so the risk management of DC bias is needed.

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