Research on Transformer Direct Magnetic Bias Current Calculation Method Based on Field Circuit Iterative Algorithm

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Received: 31 July 2014 /Accepted: 29 August 2014 /Published: 31 August 2014

Abstract: In order to analyze the DC magnetic bias effect of neutral grounding AC transformer around convertor station grounding electrode, it proposes a new calculation method —field circuit iterative algorithm in this article. The method includes partial iterative algorithm and concentrated iterative algorithm. On the research base of direct injection current calculation methods, field circuit coupling method and resistor network method. Not only the effect of direct convertor station grounding electrode current on substation grounding grid potential, but also the effect of the current of each substation grounding grid on the grounding grid potential of other substation is considered in the field circuit iterative algorithm. Through the analyzing comparison of calculation model, it is proved that field circuit iterative algorithm is more accuracy and adaptative than field-circuit coupling method and resistor network method in the AC power system set by using the equivalent resistance circuit DC path to calculate DC current component of the transformer.

Keywords: Transformer, Neutral current, Direct magnetic bias current, Field circuit iterative algorithm, Design improvement.

1. Introductions

Except the earth induction current caused by solar magnetic storm, the main reason causing direct magnetic bias current in transformer is the potential difference between different grounding points in AC grid, when AC grid and DC grid running together. The principle is shown in Fig. 1 [1, 2].

DC transmission system is connected in single pole-ground loop mode. The working current flows into the ground through grounding pole. The potential distribution on ground is uneven, so that the potential difference is caused between different grounding points. A part of DC current flows into the neutral point of the transformer in one end, and flows out of the neutral point of the other transformer in the other end. The direct current flows into the transformer winding. The direct magnetic bias current can cause transformer magnetizing current distortion and iron core saturation, accompanying with the problems of noise and loss increase, and overheat of iron core etc. When serious, the transformer could be damaged and the protection misoperation could be caused [3].

The calculation methods of direct current flowing through transformer neutral point mainly include
field-circuit coupling method and resistor grid method [4].

Fig. 1. The schematic diagram of direct current in neutral point grounding transformer.

1.1. Field-circuit Coupling Method

Field-circuit coupling method is the buried conductor current field as a current source, the current is the conductor to the earth leakage (absorption) current, and put communication system in the ground as a resistance network, then obtained each branch current size by using circuit theory in the network [5]. The method is shown in Fig. 2.

For the complex structure of grounding body, earthing conductor was divided into several small section of the unit, the equivalent circuit diagram as shown in Fig. 3.

Circuit theory was applied to the network to solve the equivalent active resistance of grounding system. Infinity as potential reference point, it can get the current source potential section (the conductor of neutral voltage) and current source current relationship (the leakage current) according to the theory of grounding resistance (the true value of resistance) and the concept of mutual resistance [6, 7].

![Local grounding conductor](image)

Fig. 2. Local grounding conductor.

\[ \varphi_n = R_{mn} I_n, \quad (1) \]

where \( \varphi_n \) is the potential of current source, \( I_n \) is the current of current source, the diagonal elements is the conductor resistance and others are the mutual resistance in \( R_{mn} \).

Resistance network node voltage equation is written by circuit theory.

\[ G_{mn} V_m - G'_{mn} \varphi_n = I_m, \quad (2) \]

where \( V_m \) is the each node potential, \( I_m \) is the node additional injection current (such as DC grounding current), \( G_{mn} \) and \( G'_{mn} \) can be obtained directly by the active resistance equivalent network.

It can be exported by the current of each current source as the unknown object.

\[ I_{n(i)} = \sum_{k=1}^{m} (A_{(k,i)} V_{m(k)} - \varphi_{n(i)}) / r_{(k,i)}, \quad (3) \]

where \( A_{(k,i)} \) is the relationship between the factor and the value is 1 when k node at the end of the conductor section, otherwise 0, \( r_{(k,i)} \) is the resistance of the current source where connected to branch for k node.

Each node voltage can be obtained by Eq. (1), (2) and (3), then current of each branch in the network can be obtained.

1.2. Resistor Grid Method

For convenience of analysis, scholars A.P. Sakis, Zhi-Qiang Ma, et al, pure resistance equivalent circuit model [8, 9] is concepted by reference
electrode coupling resistance to simplify the analysis of the soil electrical conductivity, multiple grounding influence each other. The resistor grid method is to use grounding resistance and electrode coupling resistance to describe the running situation of grounding, the original field-circuit coupling problem turned into pure circuit calculation method. As shown in Fig. 4, \( R_{AA} \) is the grounding body resistance of said A pole, \( R_{BB} \) is B pole the grounding body resistance of B pole, \( M_{AB} \) is two electrode coupling grounding body resistance. So it can be used to describe the grounding electrode coupling operation condition, and the field-circuit coupling problem of current field calculation is evolved into pure circuit analysis. so it is greatly simplified.

Parameters of each component are calculated by the mutual resistance concept in Fig. 4.

By circuit theory

\[
\begin{bmatrix}
U_A \\
U_B
\end{bmatrix} = 
\begin{bmatrix}
R_A & R_{AB} \\
R_{AB} & R_B
\end{bmatrix}
\begin{bmatrix}
I_a \\
I_b
\end{bmatrix},
\]

(4)

where \( U_A / U_B \) is potential of two grounding body, \( R_A / R_B \) is grounding resistance of two grounding body, \( I_a / I_b \) is current of two grounding body, \( R_{AB} \) is impedance between the two grounding body.

Eq. (5) can be converted by Eq. (4).

\[
\begin{bmatrix}
I_a \\
I_b
\end{bmatrix} = 
\frac{1}{R_A R_B - R_{AB}^2}
\begin{bmatrix}
R_B & -R_{AB} \\
-R_{AB} & R_A
\end{bmatrix}
\begin{bmatrix}
U_A \\
U_B
\end{bmatrix},
\]

(5)

Node voltage equations can be obtained by the circuit of Fig. 4.

\[
\begin{bmatrix}
I_a \\
I_b
\end{bmatrix} = 
\begin{bmatrix}
1 & 1/M_{AB} & -1/M_{AB} \\
-1/M_{AB} & 1 & 1/M_{AB}
\end{bmatrix}
\begin{bmatrix}
U_A \\
U_B
\end{bmatrix},
\]

(6)

Eq.(7) can be obtained by Eq. (5), (6).

\[
\begin{aligned}
(R_B - R_{AB}) / (R_A R_B - R_{AB}^2) &= 1 / R_{AA} \\
(R_A - R_{AB}) / (R_A R_B - R_{AB}^2) &= 1 / R_{BB} \\
-R_{AB} / (R_A R_B - R_{AB}^2) &= -1 / M_{AB}
\end{aligned}
\]

Considering the distance between two grounding system in practical engineering d is very larger, then \( R_{AB} \ll R_A, R_{AB} \ll R_B \). So approximate solution is shown in Eq.(8).

\[
\begin{aligned}
R_{AA} &= R_A \\
R_{BB} &= R_B \\
M_{AB} &= R_A R_B / R_{AB}
\end{aligned}
\]

(8)

Impedance parameters obtained by model, can get the whole resistance network parameters. Resistance theory to solve pure resistance equivalent circuit, the size of each branch current.

The equation of electric field and electric circuit are commonly listed in field circuit coupling method. But the physical concepts of parameters, resistance and conductance, are defined differently in field circuit, which could bring some inconvenience for calculation. In order to turn the electric field relation into unified electric circuit form, some parameters should be simplified and equalized, which could bring inevitable calculation error \([10, 11]\).

Combining the faults of the above two methods, this article proposed a new calculation method—field circuit iterative algorithm. Combining classical grounding calculation theory and electric circuit theory, equations are listed respectively and solved mutually and iteratively. The magnitude of direct current flowing through transformer neutral point can be calculated exactly. It will provide data support to the transformer magnetic bias current limitation.

2. The Principle of Field Circuit Iterative Algorithm

In field circuit iterative algorithm, the current, flowing in or out of the substation grounding grid, is not concerned at beginning, and only the potential influence of the current, flowing in or out of DC grounding pole, to ground grid conductor through the earth’s surface, is concerned. The magnitude of current, flowing in or out of AC grounding grid, can be obtained through the resolution of AC circuit. The influence of the current, among each substation grounding grid, to electric potential is added to update the potential value of the grounding conductor. The resolution steps are repeated over and over again. The value of the grounding conductor potential and AC circuit current can be solved, until the stable values are obtained. Then the sub-circuit current is the transformer neutral point current required.
According to the different processing modes of grounding pole field parameters, the field circuit iterative algorithm can be divided into two parts: partial iterative algorithm and concentrated iterative algorithm. In this article, the first method is selected.

The flow diagram of partial iterative algorithm is shown in Fig. 5.

![Flow diagram of partial iterative algorithm](image)

**Fig. 5. The flow diagram of partial iterative algorithm.**

1) Suppose that there are totally $a$ DC converter station grounding poles and substation grounding grids. They are divided into $a$ sections: $m_1, m_2, m_3, ..., m_a$, and $a$ nodes: $n_1, n_2, n_3, ..., n_a$.

$$\begin{cases}
M = m_1 + m_2 + m_3 + ... + m_a \\
N = n_1 + n_2 + n_3 + ... + n_a
\end{cases}$$

(9)

The relationship equation of the conductor section electric potential and the stray current is described as Eq.(10).

$$V_M = R_c \cdot I_M,$$

(10)

where $V_M$ is the electric potential of every conductor section’s middle part, $R_c$ is the diagonal elements are the self resistances of conductors and the off-diagonal elements are mutual resistances and $I_M$ is the stray current of each conductor section.

The electric potential equation of conductor section node and middle node is Eq.(11).

$$G_i \phi_N = G_i^0 V_M = I_d,$$

(11)

where $\phi_N$ is the potential of each conductor section, $I_d$ is the direct current flowing into each node.

$G_{i(i,j)}$ is the conductance sum of the conductor between node $i$ and its neighbor middle node $j$, $G_{i(i,j)}^0$ is the conductance sum of the conductor between node $i$ and middle node $j$.

Note that at initial state, the influence of AC grid to grounding body is not considered. The resistance of AC grid is not included in the specific conductance.

The relationship equation of conductor section electric potential and the stray current is Eq.(12).

$$G_i \phi_N - G_i^0 V_M = I_d,$$

(12)

where $G_{h(i,j)}$ is the conductance sum of the conductor between the node $i$ and the middle node $j$. $G_{h(i,j)}^0$ is the conductance sum of the conductor between the node $i$ and its neighbor node $j$.

2) At the initial state, suppose that only the current $I_s$ flows in or out of the DC pole in single pole earth running system. The node 1 is the injection point. So that the initial value of $I_d$ is Eq.(13).

$$I_s^0 = \begin{bmatrix}
0 \\
\vdots \\
0
\end{bmatrix},$$

(13)

Substitute it into Eq.(10), (11) and (12), the middle point electric potential $V_M^0$ of conductor section, the node electric potential $\phi_M^0$ and the stray current is $I_d^0$.

3) Eq.(14) is the equation of the node voltage.

$$I_k = G_k U_k,$$

(14)

where $I_k$ is the injection (outflow) current of the DC injection point of the grounding grid, and the direction of injection in grounding grid is the positive direction. $U_k$ is the electric potential of the current injection point in grounding grid.

Then

$$\begin{bmatrix}
U_{k(1)} \\
U_{k(2)} \\
U_{k(3)} \\
\vdots \\
U_{k(a)}
\end{bmatrix} = \begin{bmatrix}
\phi_{N(1)} \\
\phi_{N(n_1+n_2)} \\
\phi_{N(n_1+n_2+n_3)} \\
\vdots \\
\phi_{N(1+n_1+n_2+...+n_a)}
\end{bmatrix},$$

(15)
where \( G_k \) is the DC channel conductance matrix of the AC circuit among the substation.

The elements in \( G_k \) are defined as Eq. (16).

\[
G_{kl} = \left( \frac{1}{R_{g1} + R_{g2} + R_{g3} / 3 + R_{g4} / 3} \right) \frac{1}{\sqrt{3}},
\]

(16)

where \( R_{g1}, R_{g2} \) are the grounding resistances of the substation grounding grid, \( R_{t1}, R_{t2} \) is the resistance of the transformer winding, \( R_{s1}, R_{s2} \) are the resistances of the line and transformer are connected in parallel equivalently.

Substitute the \( U_0^0 \) obtained from \( \phi_n^0 \) into the Eq.(13), \( I_0^0 \) is solved.

4) Using the value of injection (outflow) current in \( I_0^0 \) to update the value of \( I_d^0 \) in Eq.(13), recorded as \( I_d^1 \). The updating mode is Eq.(17).

\[
\begin{bmatrix}
I_d^{1(1)} \\
I_d^{1(1+n_1)} \\
I_d^{1(1+n_1+n_2)} \\
\vdots \\
I_d^{1(1+n_1+n_2+\ldots+n_r)}
\end{bmatrix} =
\begin{bmatrix}
I_0^{k(1)} \\
I_0^{k(2)} \\
I_0^{k(3)} \\
\vdots \\
I_0^{k(a)}
\end{bmatrix},
\]

(17)

Note that except the elements updated in \( I_d \), other elements are all 0.

5) Repeat steps 2) to 4) for \( p \) times, \( I_d^p \) can be solved.

6) When \( |I_d^p - I_d^{p-1}| < \varepsilon \) (where \( \varepsilon \) is a tiny positive number), the iterative is finished. The solved branch current \( I_d^{p-1} \) is the relative current of the transformer neutral point.

When the magnetic bias current is calculated with field circuit iterative algorithm, the grounding grid can be simplified, if the distance between each DC grounding pole and AC grounding grid is far. The self resistance is substituted by grounding body resistance. The mutual resistance is calculated form point charge focusing on the middle position of grounding body. So the simplified lumped parameter iterative algorithm is obtained. This algorithm can reduce the electric field equation scale, and the calculation speed is much faster.

3. The Calculation Example Model and Result

The calculation model is shown in Fig. 3. Point O is the DC grounding pole position. A, B, C and D is the positions of AC substation grounding grids near O [12, 13]. The coordinates are (18000, 0), (19500, 4750), (1620, 21500) and (32085, 5340). The four transformers in substations A, B, C and D are all 500 kV neutral grounding.

The earth resistivity is \( \rho = 20 \Omega \cdot m \). The depth of the grounding body is 1m under the earth surface.

In Fig. 6, the straight line represents the transforming line between substations. The line is four-divided wire. The unit resistance of each phase’s single wire is \( 0.20 \Omega / km \). The unit resistance of each phase’s wire is \( 0.05 \Omega / km \). The transformers’ winding resistance of the four substation are respectively \( 0.3 \Omega \), \( 0.3 \Omega \), \( 0.45 \Omega \) and \( 0.45 \Omega \). The current of DC grounding pole flowing into the earth is 2000 A.

![Fig. 6. The schematic diagram of the DC convertor stations and substations.](image)

The DC grounding pole is a circular ring with the radius of 290 m. The AC grounding grids A, B, C and D are respectively four circular rings with the radii of 375 m, 510 m, 290 m and 515 m.

The empirical calculation formula of the resistance of the annular grounding body is Eq.(18).

\[
R = \frac{\rho}{2\pi D} \ln \frac{16D^2}{hd},
\]

(18)

Suppose that the earth resistivity is \( \rho = 20 \Omega \cdot m \). According to Eq.(18), the calculated DC and AC grounding ring resistance are respectively \( 0.05 \Omega \), \( 0.04 \Omega \), \( 0.03 \Omega \), \( 0.05 \Omega \) and \( 0.03 \Omega \).

Without counting the original DC component in AC system, the neutral point grounding current’s DC component of every transformer in AC grid, is the algebraic sum of the influence of all the DC convertor station’s grounding pole current in grid to it. So that only one terminal’s grounding pole of DC transforming line is presented in the calculation example. Applying the superposition principle,
through the same algorithm, the whole DC system’s influence to the transformer can be obtained.

Respectively, the model in Fig. 6 is calculated through the field circuit algorithm, the field circuit coupling method and resistor grid method. The calculation results are shown in Table 1. The error rate is referred to the calculation values of the field circuit coupling method.

<table>
<thead>
<tr>
<th>Method</th>
<th>$U_1$</th>
<th>$U_2$</th>
<th>$U_3$</th>
<th>$U_4$</th>
<th>$I_1$</th>
<th>$I_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial iterative algorithm</td>
<td>89.9812</td>
<td>0.3511</td>
<td>0.3224</td>
<td>0.2905</td>
<td>0.2003</td>
<td>0.09362</td>
</tr>
<tr>
<td>$e_1$ %</td>
<td>2.90</td>
<td>0.104</td>
<td>0.122</td>
<td>0.359</td>
<td>0.20</td>
<td>0.037</td>
</tr>
<tr>
<td>Concentrated iterative method</td>
<td>100.000</td>
<td>0.3487</td>
<td>0.3211</td>
<td>0.2899</td>
<td>0.1998</td>
<td>0.09339</td>
</tr>
<tr>
<td>$e_2$ %</td>
<td>7.931</td>
<td>0.115</td>
<td>0.097</td>
<td>0.369</td>
<td>0.215</td>
<td>0.264</td>
</tr>
<tr>
<td>Resistor grid method</td>
<td>98.4348</td>
<td>0.3420</td>
<td>0.3154</td>
<td>0.2850</td>
<td>0.1971</td>
<td>0.08812</td>
</tr>
<tr>
<td>$e_3$ %</td>
<td>6.28</td>
<td>2.275</td>
<td>1.948</td>
<td>2.168</td>
<td>1.667</td>
<td>5.945</td>
</tr>
<tr>
<td>Field circuit coupling method</td>
<td>92.6510</td>
<td>0.3504</td>
<td>0.3217</td>
<td>0.2911</td>
<td>0.2001</td>
<td>0.09359</td>
</tr>
</tbody>
</table>

According to the calculation results, it can be obtained that:

1) The calculation error is smaller in field circuit iterative algorithm than in resistor grid method, and similar in field circuit coupling method. The reason is that there are too much simplified model parameters in filed circuit iterative algorithm. When the AC transmission line is short in length, the resistance is small. The calculation error is big in resistor grid method. But accuracy result can be obtained in field circuit iterative algorithm.

2) In the field circuit iterative algorithm, not only the influence of the distance of the substation and DC convertor station to substation grounding grid potential is considered, the influence of the injection (outflow) current in each substation grounding grid to other substation’s grounding grid potential is also considered.

4. Conclusion

The field circuit algorithm, proposed in this article, can be used to calculate the magnetic bias current of the DC transmission system to transformer neutral point. Not only the influence of DC convertor station grounding pole current to substation grounding grid potential is considered, but also the influence of each substation grounding current to other substation grounding potential is considered. The calculation accuracy of partial iterative algorithm is very high, but the calculation quantity is large. Because of the difference of the parameter simplified degree, the field circuit iterative algorithm is more accuracy than resistor grid method.

This prediction method can analyze the whole system with simple principle and strong practicability. But in this algorithm, the DC current component in transformer is calculated through the DC channel in AC transmission system built by equivalent resistor circuit. So, this algorithm is mainly used to predict the DC current of the DC transmission earth loop flowing into the transformer neutral point. This can be considered as the reference of the high voltage DC transmission convertor station and substation location selection and substation design.

Acknowledgements

This work was supported by the Science Research Project of Henan Science and Technology Department (Grant No. 142102210292).

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