Modelling of the dc Inductive Superconducting Fault Current Limiter

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Abstract

DC fault current limiter is an important device for the dc system, because the action speed of the existing selective protection cannot match the dc fault developing speed. Due to its excellent capacity on limiting dc fault rising speed, the analyses of dc inductive type superconducting fault current limiter (I-SFCL) are attracting more attention. In this poster, a modelling method for dc I-SFCL is proposed to describe its nonlinear characteristic of inductance. Firstly, the structure and working principle of the dc I-SFCL is briefly introduced, and the equivalent magnetic circuit is established according to the magnetic field distribution. Then, the relationship between dc transient current and the current-limiting inductance of dc I-SFCL is discussed. By analyzing the equivalent magnetic circuit, a mathematical I-SFCL model is proposed in Matlab based on the actual geometric and electrical parameters. Finally, under the same dc test platform, the electromagnetic variables $B$, $U_{SFCL}$ and $I_{SFCL}$ in Matlab model are compared with that in finite element method (FEM) model. Simulation results verifies the validity and the correctness of the model.

Electromagnetic analysis

The structure of the dc I-SFCL is shown in Fig. 1. It mainly consists of three parts: the copper coil, the superconducting coil and the rectangle iron core.

The copper coil connected into the dc line is the main current-limiting part of this I-SFCL. The superconducting coil is powered by a dc source, producing magnetic flux in the opposite direction to that provided by the copper coil.

![Fig. 1 structure of dc I-SFCL](image1)

![Fig. 2 the working principle of dc I-SFCL](image2)

<table>
<thead>
<tr>
<th>$m$</th>
<th>copper-side limb</th>
<th>superconducting-side limb</th>
<th>upper yoke</th>
<th>lower yoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-sectional areas $s_1$</td>
<td>$s_2$</td>
<td>$S_1$</td>
<td>$S_2$</td>
<td></td>
</tr>
<tr>
<td>Length $l_1$</td>
<td>$l_2$</td>
<td>$l_1$</td>
<td>$l_2$</td>
<td></td>
</tr>
<tr>
<td>Permeability $\mu_1$</td>
<td>$\mu_2$</td>
<td>$\mu_1$</td>
<td>$\mu_2$</td>
<td></td>
</tr>
<tr>
<td>Excitation current $i_{m1}$</td>
<td>$i_{m2}$</td>
<td>$i_{m1}$</td>
<td>$i_{m2}$</td>
<td></td>
</tr>
<tr>
<td>Reluctance $R_1$</td>
<td>$R_2$</td>
<td>$R_1$</td>
<td>$R_2$</td>
<td></td>
</tr>
</tbody>
</table>

Modelling method

According to Fig. 3(a)

\[ N_1 i_{n1} = N_2 (i_{a1} + i_{a2} + i_{m1} + i_{m2}) = \Phi \sum R_m = \Phi (\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_{12}} + \frac{1}{L_{13}} + \frac{1}{L_{23} - \Phi_i^2}) \]

\[ = \Phi N_2^2 \left( \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_{12}} + \frac{1}{L_{13}} - \frac{1}{L_{23}} \right) = \Phi N_2^2 \left( \frac{1}{L_{tot}} \right) \]

(1)

Simulation analyses

At the beginning, the switch is open and the dc load current is stable at around 53.3A. Then, closing the switch to bypass \( R_{load} \) and simulate the dc impulse process, at this time, the dc load current will be limited by the I-SFCL.

The Matlab model and the FEM model are both carried out by the above proposed method with the parameters in Table under this dc test circuit.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U )</td>
<td>60V</td>
<td>( i_2 )</td>
<td>25A</td>
</tr>
<tr>
<td>( R_f )</td>
<td>0.28Ω</td>
<td>( L_1, L_2 )</td>
<td>0.47m</td>
</tr>
<tr>
<td>( R_{load} )</td>
<td>0.84Ω</td>
<td>( L_3, L_4 )</td>
<td>0.18m</td>
</tr>
<tr>
<td>( N_1 )</td>
<td>12</td>
<td>( s_1, s_2 )</td>
<td>0.0016m²</td>
</tr>
<tr>
<td>( N_2 )</td>
<td>60</td>
<td>( s_3, s_4 )</td>
<td>0.0025m²</td>
</tr>
</tbody>
</table>

Fig. 5 shows the changes in the I-SFCL electromagnetic parameters in the case of a small disturbance (represented by small step current).

\( I_2 \) and \( I_1 \) respectively represent the load currents in the dc test circuit with and without the I-SFCL.

It can be deduced that when a small disturbance appears in the dc system during normal operation, it will not cause the iron core in I-SFCL to exit the deep saturation working status. The current-limiting inductance is almost unchanged, hence the impacts of the dc I-SFCL on the dc system can be negligible during this time.

![Simulation analyses](image)

![Modelling method](image)

![Fig. 3 equivalent magnetic circuit](image)

\[ R = \frac{U}{i}, \; s, \; l \text{ are constant} \]

\[ R(\mu) \]

\[ \mu \]

\[ \Phi \]

\[ L \]

\[ \text{is related to the magnetic flux } \Phi \]

\[ f(\Phi) = \Phi \sum R_m - (N_2 i_{a2} - N_1 i_1) \]

\[ \text{an interaction between } L \text{ and } i_1 \text{ during dc fault condition} \]

\[ L_{tot} \text{ is composed of the four excitation inductances } L_1, L_2, \]

\[ L_3, L_4, \text{ connected in parallel} \]

\[ \Delta B = 0.005T \]

\[ \Delta L = 0.04mH \]

\[ \Delta U = 2.2V \]
The current-limiting inductance $L_{\text{SFCL}}$ of the dc I-SFCL is a variable that relates electricity and magnetism, it is calculated and compared in Fig. 7 by electric circuit and magnetic circuit methods, respectively. The mathematical calculation is satisfied with $L_{\text{SFCL}}=U_{\text{SFCL}}/(dI_{\text{SFCL}}/dt)$ and the calculation in Simulink model can be deduced as Eq. (1). Fig. 7 demonstrates that the mathematical calculation curve closely coincides with Simulink curve, and further proves the accuracy of the Matlab model.

**Conclusion**

Due to the quick responding speed and the excellent voltage support capacity, the dc inductive type superconducting fault current limiter (I-SFCL) is a significant device for dc system. In this poster, a Matlab model of I-SFCL is proposed by using the equivalent magnetic circuit method and the Newton iteration method. By the comparison with FEM model in terms of the electromagnetic variables $F$, $B$, $L_{\text{SFCL}}$, $U_{\text{SFCL}}$ and $I_{\text{SFCL}}$, their features are highly similar between the two models, it can be concluded that the Matlab model can well reflects the physical meaning of dc I-SFCL and is able to accurately reflect current-limiting performance. Utilizing this model, the dc I-SFCL is able to be designed based on actual structure parameters. Moreover, since the model is built in Matlab, it also helpful to the simulation time and the software compatibility.