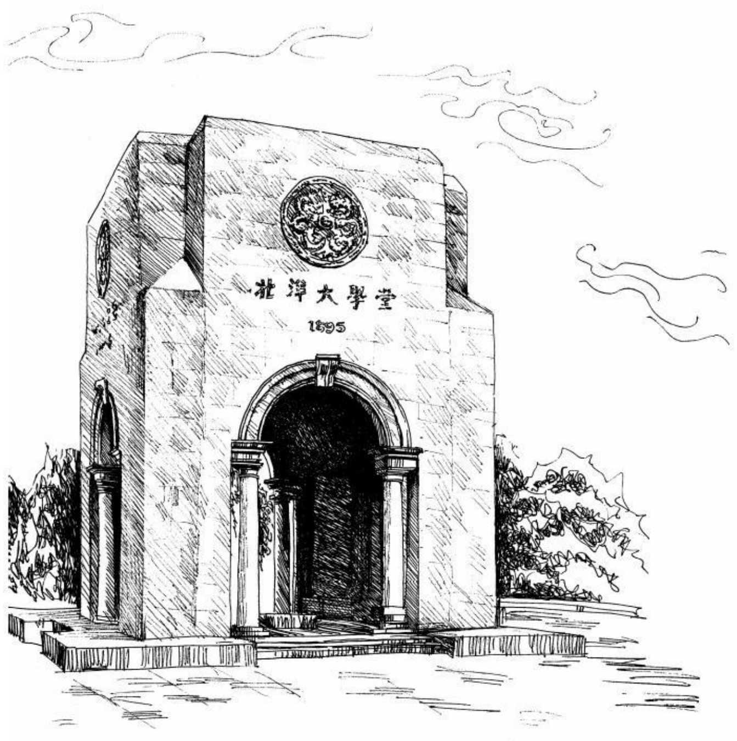

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Modelling of the dc Inductive Superconducting Fault Current Limiter

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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 superconductive 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 superconductive coil is powered by a dc source, producing magnetic flux in the opposite direction to that provided by the copper coil.

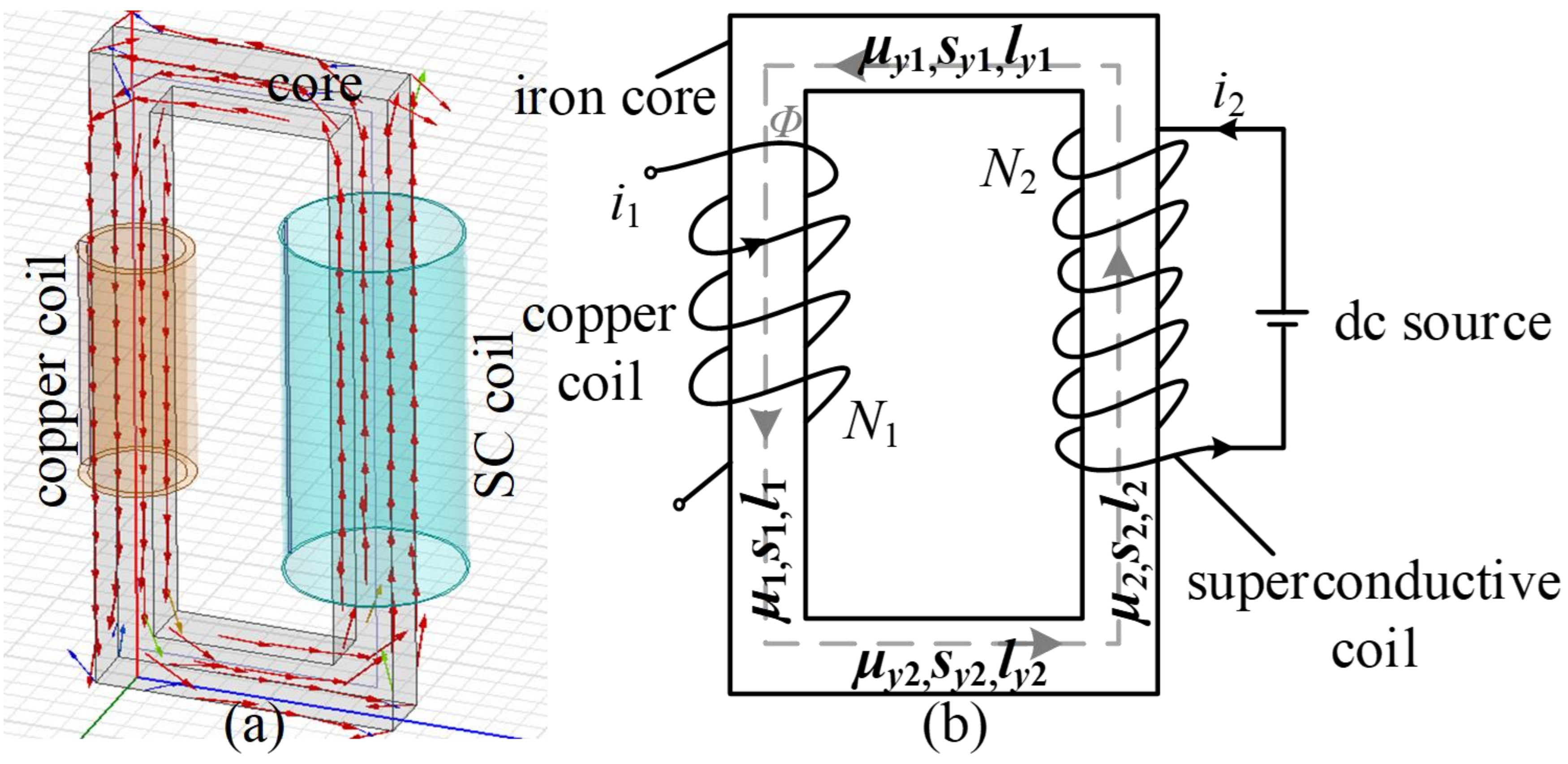


Fig. 1 structure of dc I-SFCL

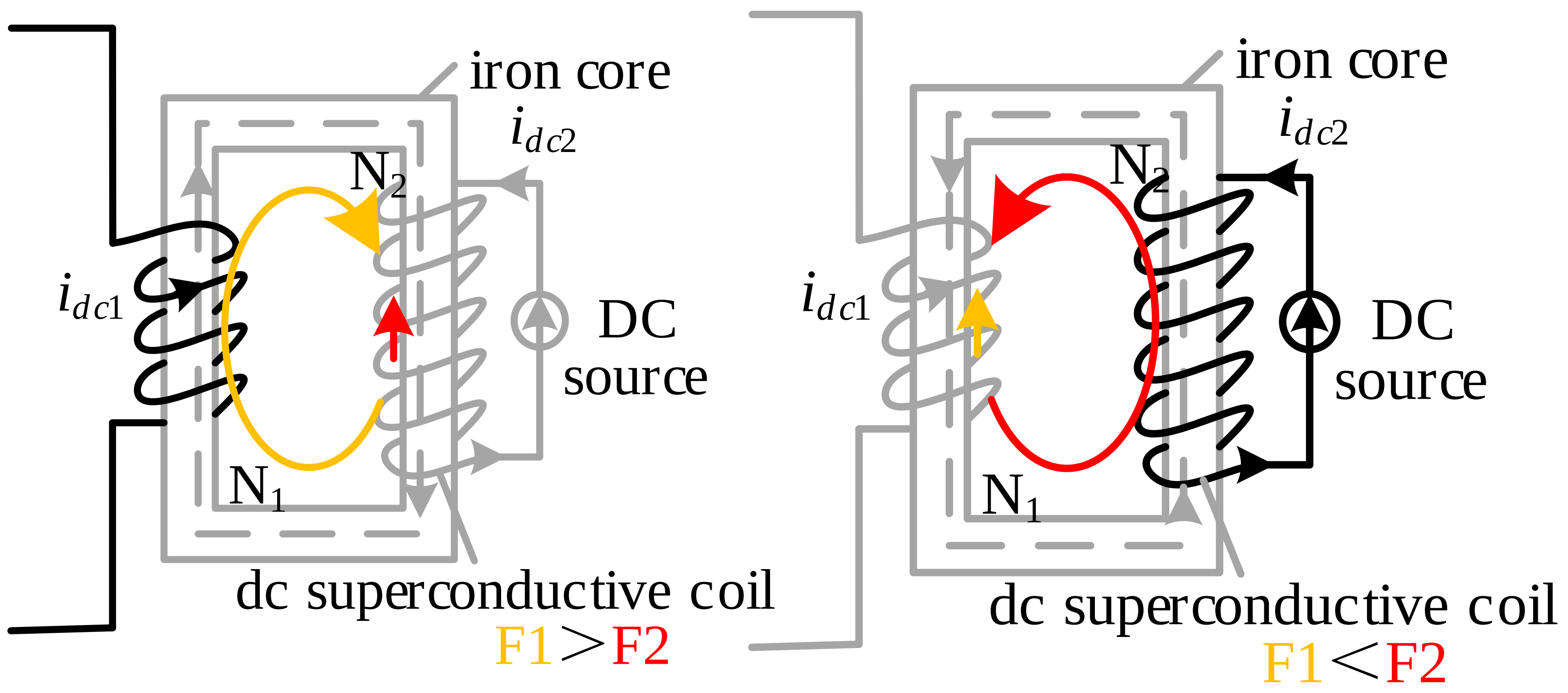


Fig. 2 the working principle of dc I-SFCL[*1]

$$F = F_2 - F_1 = N_2 i_2 - N_1 i_1 = \Phi \sum R_m$$

$$\Phi \sum R_m = \Phi R_1 + \Phi R_2 + \Phi R_{y1} + \Phi R_{y2}$$

F_1, F_2: the MMF of the copper and the superconductive coils.

N_1: the copper coil turns.

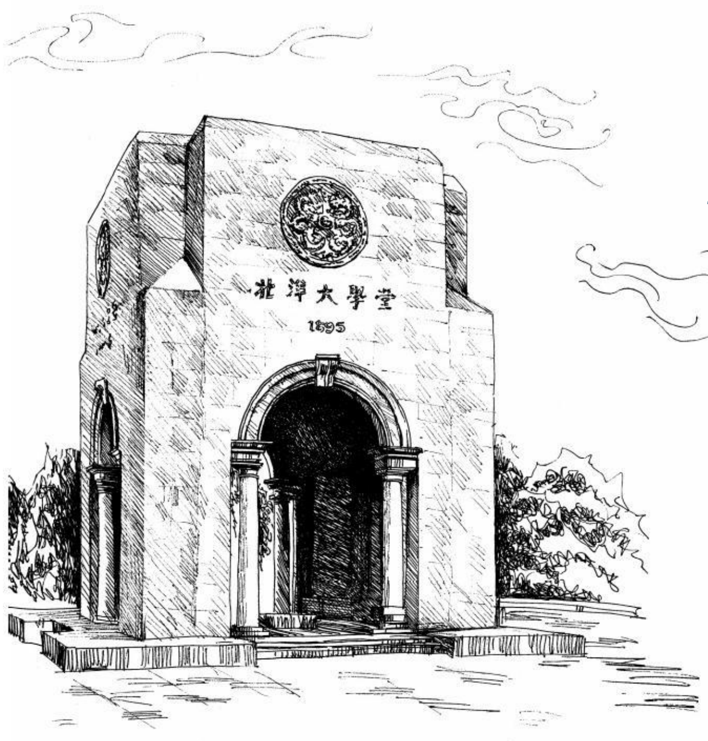
N_2: the superconductive coil turns.

I_1: the dc load current in copper coil.

I_2: the dc bias current in superconducting coil

	copper-side limb	superconducting-side limb	upper yoke	lower yoke
cross-sectional areas	s_1	s_2	s_{y1}	s_{y2}
length	l_1	l_2	l_{y1}	l_{y2}
permeability	μ_1	μ_2	μ_{y1}	μ_{y2}
excitation current	i_{m1}	i_{m2}	i_{my1}	i_{my2}
reluctance	R_1	R_2	R_{y1}	R_{y2}

[*1] Changqi Wang, Bin Li, Ying Xin, “Design and Application of the SFCL in MMC Based DC System”, IEEE Trans. Appl. Supercond., 27(4), 3800504, June 2017.



Modelling method

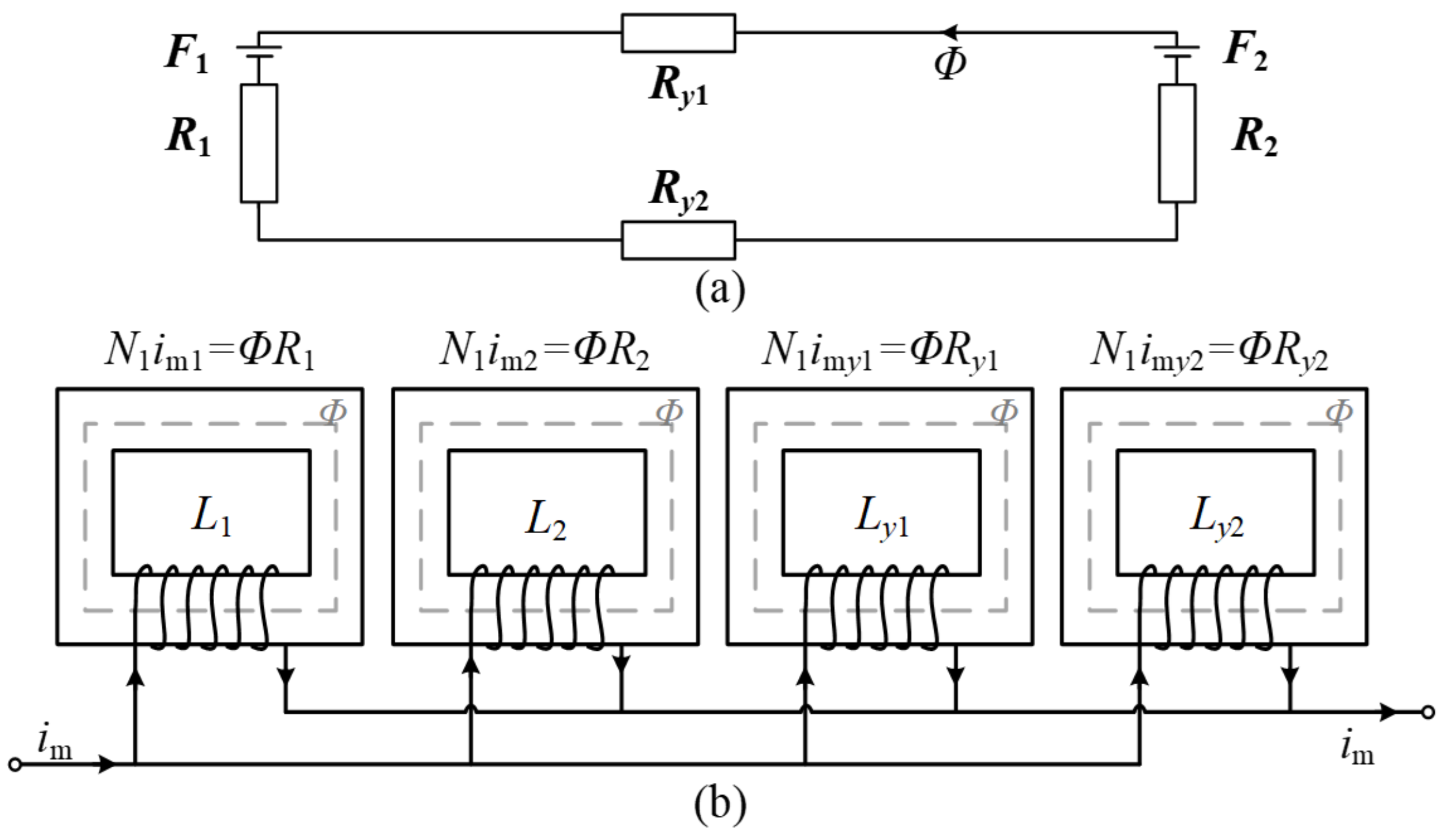
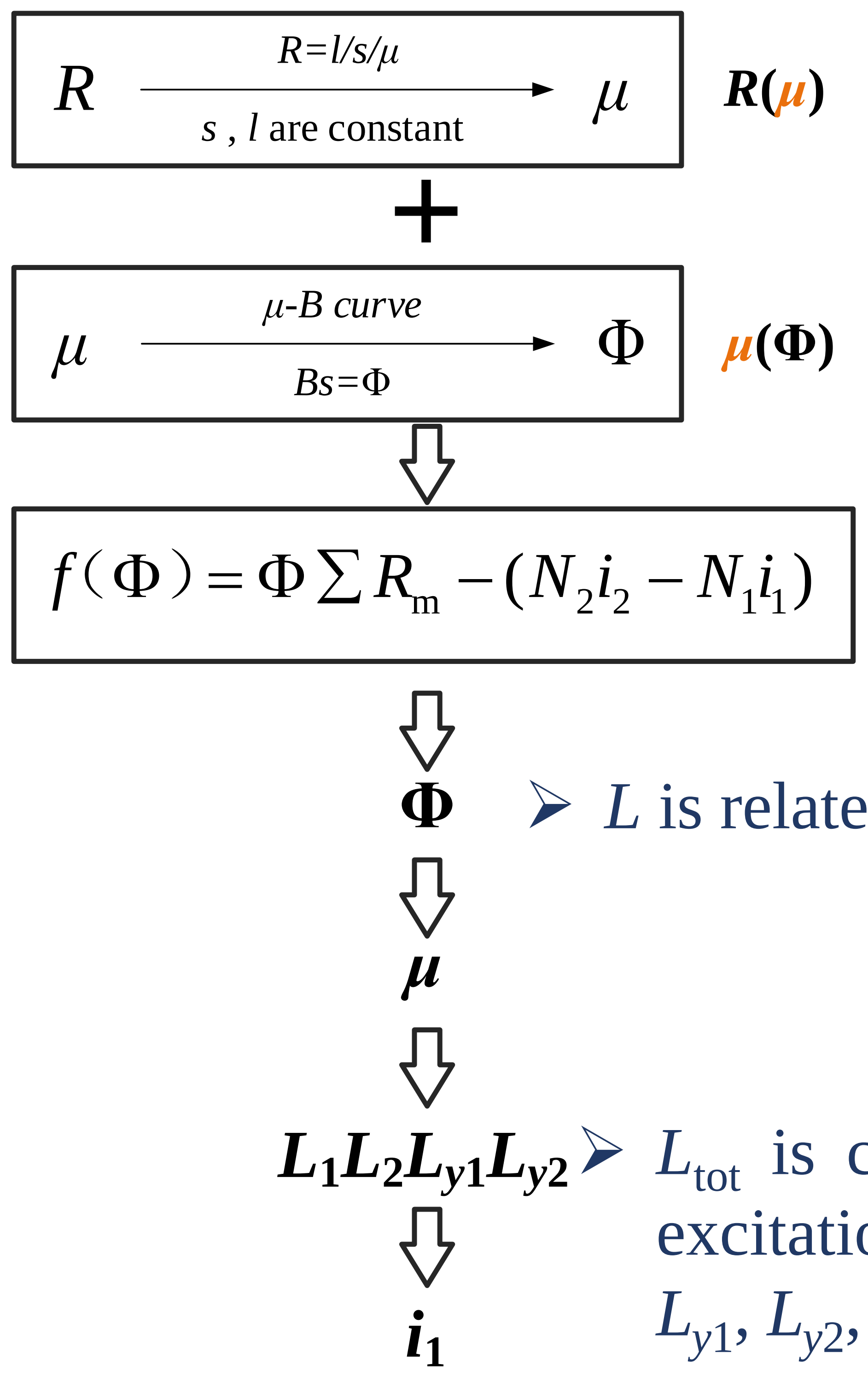


Fig. 3 equivalent magnetic circuit

According to Fig. 3(a)

$$
\begin{aligned}
N_1 i_m &= N_1(i_{m1}+i_{m2}+i_{my1}+i_{my2}) \\
&= \Phi \sum R_m = \Phi\left(\frac{l_1}{s_1\cdot\mu_1}+\frac{l_2}{s_2\cdot\mu_2}+\frac{l_{y1}}{s_{y1}\cdot\mu_{y1}}+\frac{l_{y2}}{s_{y2}\cdot\mu_{y2}}\right) \\
&= \Phi N_1^2\left(\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_{y1}}+\frac{1}{L_{y2}}\right) = \Phi N_1^2 \frac{1}{L_{tot}} \qquad (1)
\end{aligned}
$$



- the excitation current is $i_m=(F_2-F_1)/N_1$
- L is related to the magnetic flux Φ
- L_{tot} is composed of the four excitation inductances L_1, L_2, L_{y1}, L_{y2}, connected in parallel.
- an interaction between L and i_1 during dc fault condition

Simulation analyses

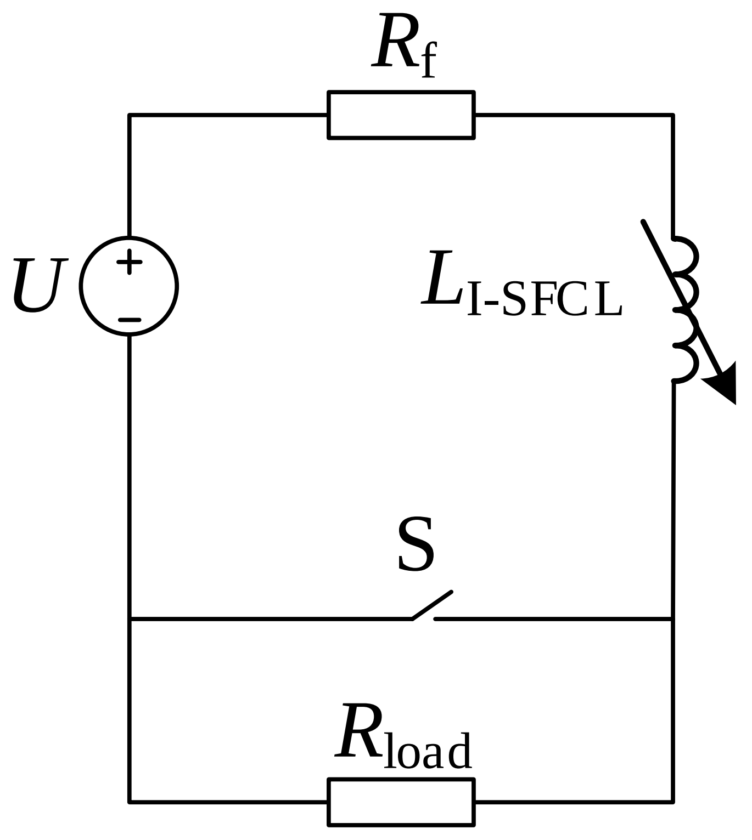


Fig. 4 dc test crcuit

S: the switch
U: the dc voltage source
R_f: the short-circuit resistance
R_{load}: the load resistance

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.

Symbol	Value	Symbol	Value
U	60V	i_2	25A
R_f	0.28Ω	l_1、l_2	0.47m
R_{load}	0.84Ω	l_3、l_4	0.18m
N_1	12	s_1、s_2	0.0016m ²
N_2	60	s_3、s_4	0.0025m ²

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 cur-rents 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.**

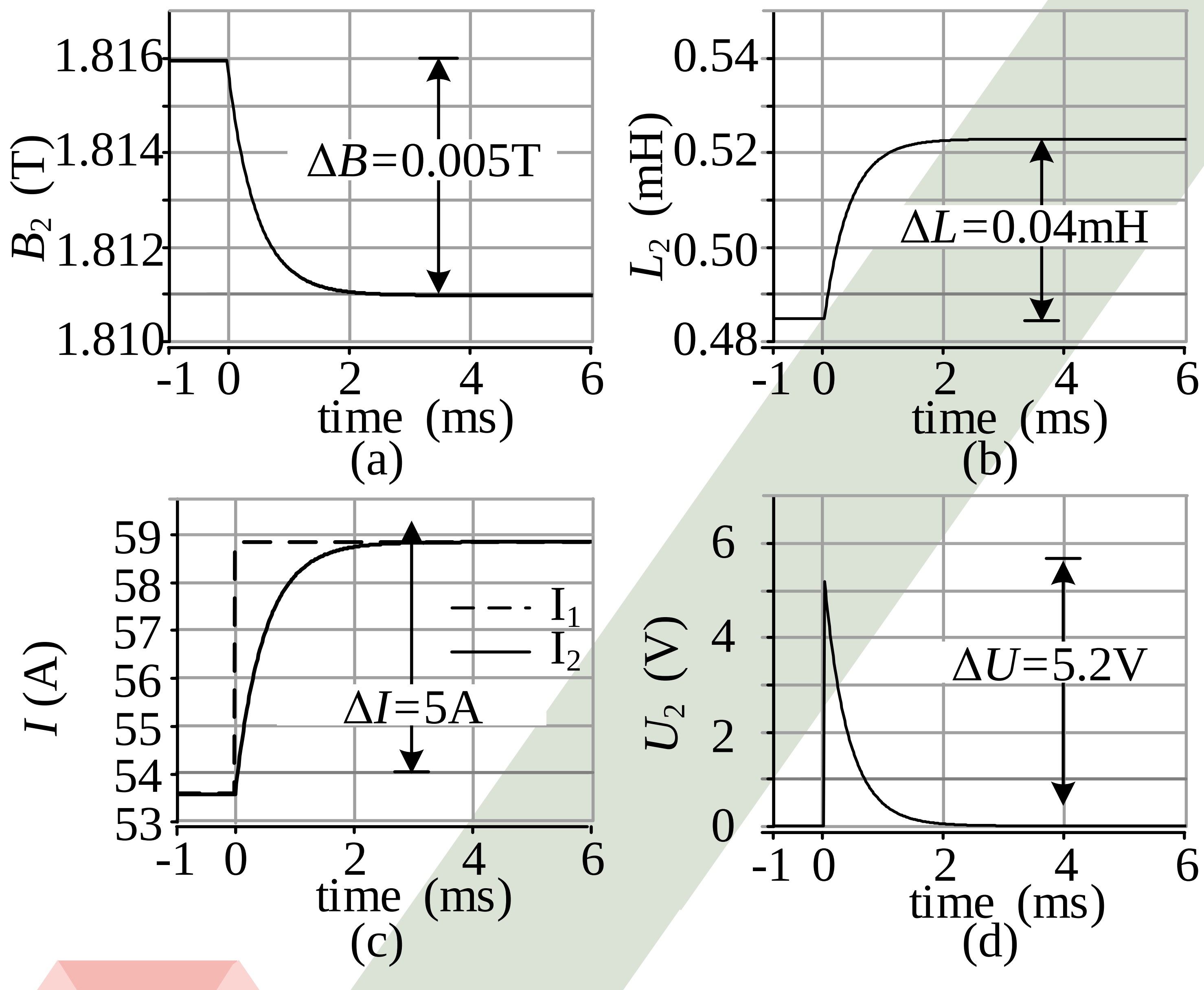


Fig. 5 small disturbance in dc test circuit

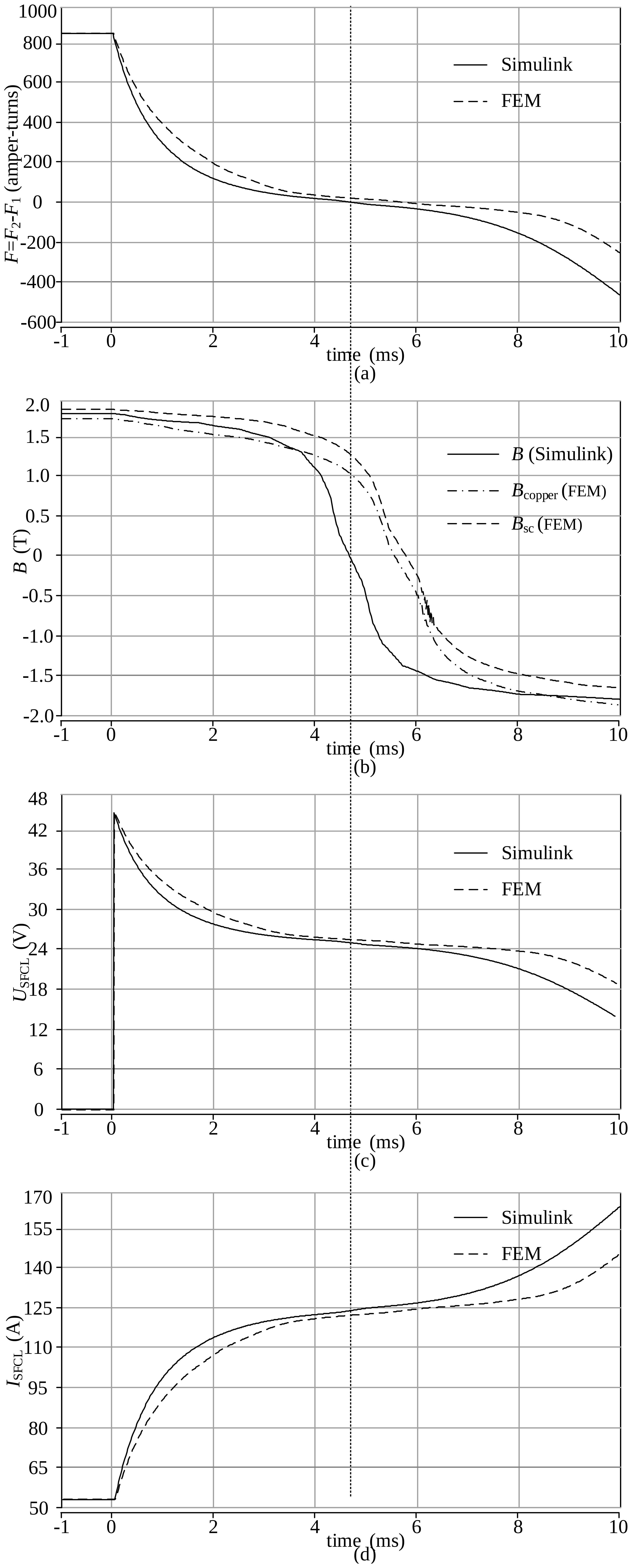


Fig. 6 the feature curves of dc I-SFCL in FEM and Matlab. (a)MMF produced by the excitation current. (b)magnetic flux density of the dc I-SFCL. (c)voltage of the dc I-SFCL. (d)current of the dc I-SFCL.

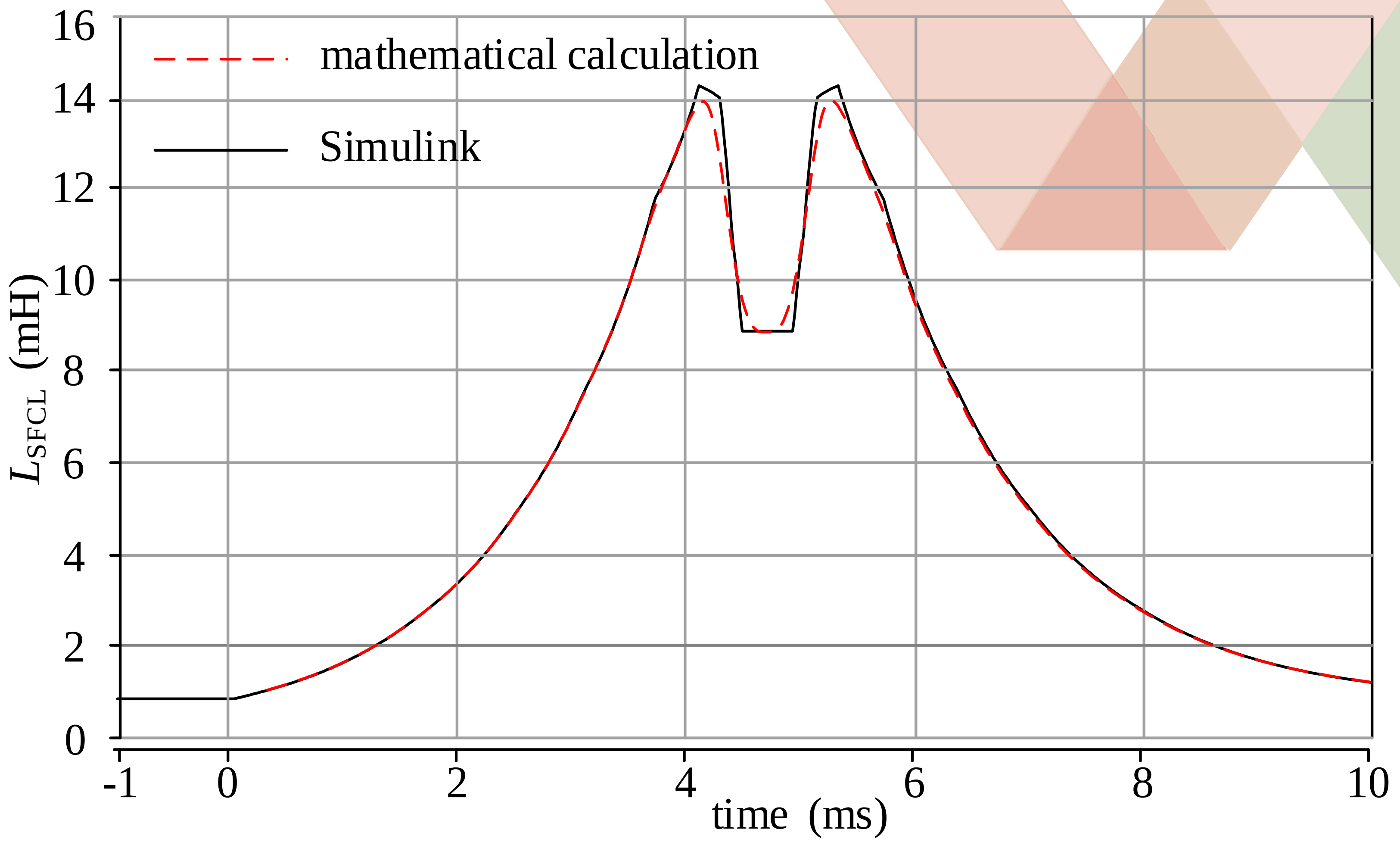


Fig. 7 The **current-limiting** inductance of dc I-SFCL**.**

The current-limiting inductance L_{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 $L_{SFCL}=U_{SFCL}/(dI_{SFCL}/dt)$ and the calculation in Similink 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_{SFCL}, U_{SFCL} and I_{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**.