Analysis of key factors affecting the non-limiting state reactance of superconducting fault current limiter

Yuelong Jia\textsuperscript{1,3} and Jiansheng Yuan\textsuperscript{2}

\textsuperscript{1}State Grid Energy Research Institute Co., Ltd., Beijing, China
\textsuperscript{2}Tsinghua University, State Key Laboratory of Power System, Beijing, China
\textsuperscript{3}E-mail: jiayuelong@sgeri.sgcc.com.cn

Abstract. With the rapid development of the power grid, the voltage level is getting higher, and the degree of interconnection is becoming stronger. As a result, the level of the short-circuit fault current of the power grid keeps increasing, which seriously threatens the security of the power grid. The saturated-core superconducting fault current limiter (SCSFCL) is a new type of current limiting device, which can effectively limit the short-circuit current without influencing the flexibility of the power grid. The non-limiting state reactance is very important to the normal operation of the power line protected by the SCSFCL, but there is little detailed analysis of the key factors affecting its non-limiting state reactance so far. In this paper, the effects of the height of AC coil, the turns of AC coil, the cross-sectional area of the iron core and the excitation of the DC coil on the non-limiting state reactance are analysed and verified by simulation with ANSYS Maxwell. Finally, the design suggestions are put forward, including the method of designing the DC excitation value of the superconducting coil and how the key factors affect the non-limiting state reactance.

1. Introduction

In recent years, the voltage level of the power grid has been continuously improved, and the scale of the power grid has been largely expanded. Besides, the interconnection degree of the power grids has been greatly strengthened [1-3]. As a result, the short-circuit fault current of the power grid keeps increasing and will even exceed the breaking capacity of the circuit breaker, which seriously threatens the safe operation of the power grid [4-7]. The traditional measures of limiting the fault current, such as transformers with high impedance, will affect the flexible operation of the power grid. So novel measures are urgently needed. The saturated-core superconducting fault current limiter (SCSFCL) is a new type of current limiting equipment, which develops rapidly recently [8-12]. When the power grid is in normal operation, it has almost no impact on the power grid. When the power grid has a short circuit fault, it can effectively limit the fault current.

The non-limiting state reactance is very important to the normal operation of the power line protected by the SCSFCL, but there is little detailed analysis of the key factors affecting the non-limiting state reactance of the SCSFCL. In this paper, the effects of the height of AC coil, the turn of AC coil, the cross-sectional area of the iron core and the excitation of the DC coil on the non-limiting state reactance of the SCSFCL are analyzed and verified by simulation with ANSYS Maxwell. Finally, the design suggestions are put forward, including the method of designing the DC excitation value of the superconducting coil and how the key factors affect the non-limiting state reactance.
2. The working principle of the SCSFCL

The SCSFCL is mainly composed of iron core, AC coil and superconducting DC coil, as Figure 1 shows. The AC coil is connected in series in the power grid. The DC coil is excited by an independent DC power source, and it can be cut off if needed. There are two typical working states for SCSFCL, namely the limiting state and the non-limiting state.

![Figure 1. The structure of the SCSFCL.](image)

When the power grid is in normal operation, the SCSFCL operates in the non-limiting state. In this state, a large DC current flows through the DC coil, and the DC magnetic field in the iron core is much larger than the AC magnetic field. As a result, the iron core is in deep saturation region of the $B-H$ curve, as shown in Figure 2, and the non-limiting state reactance is small enough not to influence the power grid. This is the state that the SCSFCL mostly works in, which is a very important aspect for design.

![Figure 2. The $B$-$H$ curve of the iron core.](image)

When the short circuit fault occurs in the power grid, the SCSFCL will operate in current limiting state. In this state, the DC coil power supply is cut off, and the short circuit current flows through the AC coil. In this state, there is only the AC magnetic field in the iron core, so the iron core is no longer kept in a state of deep saturation. As the iron core will work in the linear region of the $B$-$H$ curve, the reactance quickly increases and effectively limits the short circuit current.

3. Analysis of key factors affecting non-limiting state reactance of the SCSFCL

The main factors affecting the non-limiting state reactance of the SCSFCL include the height of the AC coil, the turns of the AC coil, the cross-sectional area of the iron core, and the excitation of the DC coil.

Before performing detailed analysis, it is necessary to present the calculating formula of the iron core reactor, as shown in Figure 3, whose iron core works in the linear region of the $B$-$H$ curve. This is the basis for subsequent research. The structure of the iron core reactor and the corresponding calculating formula are shown below. $\mu$ is the magnetic permeability of the iron core. $N$ is the turns of coil. $S$ is the cross-sectional area of the iron core. $\omega$ is $2\pi f$. $L$ is the equivalent length of the magnetic field path.

$$X = \frac{\mu N^2 S \omega}{L}$$  \hspace{1cm} (1)
The following analysis is carried out with ANSYS Maxwell, and the corresponding parameters of the SCSFCL are shown in Table 1.

### Table 1. SCSFCL parameters.

| Item                      | Parameter   | Item                      | Parameter   |
|---------------------------|-------------|---------------------------|-------------|
| DC column diameter (mm)   | 1500        | AC coil height (mm)       | 1300        |
| Iron core thickness (mm)  | 710         | AC coil inner diameter (mm) | 1150       |
| AC column diameter (mm)   | 710         | AC coil outer diameter (mm) | 1650       |
| Yoke height (mm)          | 1150        | Rated AC current (kA)     | 3           |
| Iron core window height (mm) | 2000      | DC coil inner diameter (mm) | 1900       |
| Iron core window width (mm) | 1500       | DC coil outer diameter (mm) | 1950       |
| Turns of the AC coil      | 40          | DC coil height (mm)       | 1070        |
| Rated DC excitation (A·Turn) | 700000     |                           |             |

3.1. The influence of the AC coil height

When the iron core works in the linear region of the $B$-$H$ curve, its reactance is independent of the height of the AC coil, as Equation (1) shows. However, for the SCSFCL, as there is large amount of magnetic leakage flux due to the saturation of the iron core, the higher the AC coil is, the smaller the non-limiting state reactance is. When the AC coil height is increased, the equivalent magnetic path of the AC magnetic field becomes longer, so the reactance of the AC coil becomes smaller. It can also be understood from another perspective. The magnetic flux of the AC coil becomes smaller when the height of the AC coil increases, so the reactance is reduced.

The corresponding simulation result with ANSYS Maxwell is shown in Figure 4, which is in consistent with the above analysis. The AC coil height expansion factor is the multiple of the AC coil height in Table 1.

![Figure 4. The influence of the AC coil height on the reactance of the SCSFCL.](image)
3.2. The influence of the AC coil turns

It can be seen from Equation (1) that for iron core working in the linear region of the $B$-$H$ curve, when the other parameters are constant, the reactance is proportional to the square of turns of the AC coil. So the larger the turns of the AC coil are, the larger the reactance is.

For the SCSFCL, when the turns of the AC coil are small enough, the reactance is approximately proportional to the square of the turns of AC coil. This is the same as the situation of the Equation (1). However, after the turns increase to a certain extent, the reactance increases sharply and much larger than the square of the turns of AC coil. This is because the demagnetization effect of the AC magnetic field on the iron core increases, and the magnetic working point of the iron core on the $B$-$H$ curve gradually approaches or even enters the linear region. As a result, the increasing speed of the reactance gradually goes up.

Figure 5 shows the simulation result, which is just as the above analysis. In the figure, the abscissa is the turns of AC coil and the ordinate is the reactance value.

![Figure 5](image)

**Figure 5.** The influence of the AC coil turns on the reactance of the SCSFCL.

![Figure 6](image)

**Figure 6.** The influence the iron core’s cross-sectional area on the reactance of the SCSFCL.
3.3. The influence of the cross-sectional area of the iron core

It can be seen from Equation (1) that when the other parameters are constant, the cross-sectional area of the iron core \( S \) is proportional to its reactance. So the larger the cross-sectional area of the iron core is, the larger the reactance is.

However, different from the iron core reactor shown in Figure 1, the SCSFCL has AC coil and DC coil. When \( S \) is large enough, it is the same situation as Figure 1. But when \( S \) is not large enough, the saturation situation changes when the cross sectional area of the iron core changes. This is why the extreme value occurs.

Figure 6 shows the simulation result. This is by keeping the other parameters of the SCSFCL constant, and changing the cross-sectional area of the iron core \( S \), including the cross-sectional area of the AC and DC coil proportionally. The abscissa is the multiple of the cross-sectional area value in Table 1, which refers to zoom factor in Figure 6.

3.4. The influence of DC coil excitation

The basis of the above parameter analysis is that the excitation of the DC coil is sufficiently large. The standard of “sufficiently large” means that at the peak value of the AC current in demagnetization state, the iron core column inside the AC coil operates in the saturation region of the \( B-H \) curve. When the DC excitation is large enough, even though the excitation is increased, the reactance reduction merely changes. That is to say the effect of reducing the reactance of the AC coil is small. This principle is the theoretical basis for designing excitation of the DC coil.

However, when the DC excitation is not large enough, the reactance increases significantly when the DC excitation decreases. This is because the current in the AC coil is in the negative value, the magnetic operating point of the iron core enters the non-linear region of the \( B-H \) curve, where the magnetic permeability is much larger.

The reactance under different DC excitations is shown in Figure 7. In the figure, the abscissa is the number of ampere turns of the DC coil, i.e. the DC excitation.

![Figure 7. The influence of DC coil excitation on the reactance of the SCSFCL.](image)

4. Conclusions

1) The method of designing the DC excitation value of the superconducting coil: at the peak of the rated AC current, when the direction of the AC magnetic field is opposite to the direction of the DC magnetic field, the iron core inside the AC column should work in the saturation region of the \( B-H \) curve. This is very important measure of designing the SCSFCL.
2) When the DC excitation is sufficiently large, the steady-state reactance of the SCSFCL is approximately proportional to the square of the turns of AC coil. When the turns of the AC coil increase beyond a certain extent, the AC excitation will reduce the saturation level of the iron core, so the reactance increases sharply with the turns of the AC coil.

3) There is a minimum value for the steady-state reactance of the SCSFCL when the cross-sectional area of the iron core changes. When the sectional area is large, the reactance increases linearly with the cross-sectional area; but when the sectional area is small, the reactance decreases as the cross-section decreases. This is due to the lack of DC excitation in the AC column. In addition, the higher the AC coil is, the smaller the reactance of the SCSFCL is.

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