Current limiting characteristic of saturated iron core SFCLs

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Abstract. Saturated Iron Core SFCL (SIC-SFCL) provides an attractive option for the suppression of fault current level in a high voltage or an extra-high capacity electric power network. Different from traditional devices, such as air core reactors, high resistance transformers, etc., the impedance of SIC-SFCL can change from very low in normal power transmission to very high for fault current limiting. The eventual value of the apparent impedance of an SIC-SFCL also varies with the magnitude of the fault current. Therefore, investigating the progressive properties in the current limiting process is key to fully understand the working mechanism and the performance of an SIC-SFCL. A computer simulation model of a 35kV SIC-SFCL was developed to study the limitation progression, and the results of these studies are presented and discussed in this paper.

1. Introduction
Saturated iron core superconducting fault current limiter (SIC-SFCL), which is based on the principle of conventional iron core reactors, takes advantage of no-N/S transformation during the fault current limiting process, and thus are able to be used in high voltage and large capacity power grids. However, since the fundamental idea was proposed in 1982 [1,2], heavy weight, high costs, and huge volume are always the main obstacles for the application of this kind of SFCL. In recent years, Innopower Co. has made a dramatic breakthrough in designing an SIC-SFCL that is more compact and much cheaper, and we have also manufactured a three phase 35kV prototype, which has been run in a power grid for more than one and a half years, starting from Jan. 2008, in Puji substation, Yunnan, China [3-5]. The continued steady operation of and several man-made short circuit experiments [6] on the SIC-SFCL strongly proves that the device successfully realized the main functions of an SFCL: low impedance at normal time, high impedance at fault time and fast recovery of the circuit after the fault event. This will be a milestone in the industrialization progress of SIC-SFCLs.

From the viewpoint of manufacturing, the practicality of this new design of SIC-SFCL is enticing, while in the eyes of power utilities, the performance of SIC-SFCLs is the real selling point to be seriously considered. Since they are different from traditional devices, such as air core reactors, high
resistance transformers, etc., the impedance of SIC-SFCLs can change from very low in normal power transmission to very high for fault current limiting. Furthermore, the eventual value of the apparent impedance also varies with the magnitude of the fault current [7]. All these phenomena can be ascribed to the non-linear electromagnetic property of the iron cores, which might cause trouble in numerical evaluation for the setting of the relay protection system of the power grid. Therefore, investigating the progressive properties in the current limiting process is key to fully understanding the working mechanism and the performance of an SIC-SFCL.

Commonly, a fault current has two major effects that pose potential dangers for power equipment: one is the electrodynamic force; the other is the thermal effect. The maximum electrodynamic force is determined by the largest surge of the fault current, in other words, the highest peak of the current curve. On most occasions, this peak appears at the maximum of the first wave period after the fault current comes. The thermal effect is the heat accumulated during the whole fault process, and directly relates to the effective value and the duration of the fault current. Thus both the transient process and the steady-state should be taken into consideration when we analyze the effects of a fault current.

However, in most relay protection calculations of power grids, all the elements in the net are approximated as linear factors and only the effective values are considered. However, SIC-SFCLs are typically non-linear devices due to the demagnetization of their iron cores, especially in the current limiting state, which causes the styles of current and voltage waves to vary so much that SIC-SFCLs cannot be treated as linear devices. This paper develops a calculation method that can take into account the non-linear characteristic of the SIC-SFCL, and analyze its limitation performance.

2. Calculation module

The real circuit in which an SIC-SFCL is installed may be very complex. But no matter how intricate the circuit is, the intrinsic I-V property of an SIC-SFCL never changes, as it is only determined by the structural design of the device’s iron cores and ac coils. So it is reasonable to use a simple model to deduce the fundamental calculation equation, and then encapsulate it into a simulation module, which can be freely connected into various circuits. A simple circuit, comprising only an one phase ideal infinite voltage source and an SIC-SFCL, as shown in figure 1, is used to solve the characteristic I-V curve of the SIC-SFCL.

![Figure 1. A simple circuit with one phase SIC-SFCL](image)

If the iron eddy current and ac losses are negligible, equation 1 can be deduced from this circuit.
\[ U = e + L \frac{di}{dt} + Ri \]  

(1)

In which, \( e \) is the induced voltage of the SIC-SFCL, \( L \), \( R \) are the inductance and resistance, and \( U, i \) are the voltage of the source and current in the circuit. \( e \) is generated by the ac coil with an iron window. In equation 2, \( N \) is the number of turns of the ac coil, \( S \) is cross-sectional area of the coil and \( B \) is the magnetic inductance.

\[ e = NS \frac{dB}{dt} \]  

(2)

\( B \) is directly related with the non-linear magnetic property of the iron core, whose \( B-H \) curve can be written as equation 3. \( H \), the magnetic force, is generated by the ac current in the coils ( in this case, only the limitation state of SIC-SFCL is considered, so there is no dc current in the dc bias coil ). According to ampere circuital theorem, \( H \) can be calculated using equation 4, in which \( l \) denotes the magnetic path.

\[ B = f(H) \]  

(3)

\[ HI = Ni \]  

(4)

Equation 4 represents the relationship between electric current \( i \) and magnetic force \( H \), and equation 3 reflects the non-linear property of the iron core. Combining these equations, we can deduce the fundamental I-V property of SIC-SFCL as described in equation 5.

\[ i = \int (U - Ri) \left/ \left( \frac{N^2 S}{l} f' \left( \frac{Ni}{l} \right) + L \right) \right. \frac{di}{dt} \]  

(5)

It is convenient to create an SIC-SFCL calculation block according to equation 5 in Matlab/SimPowerSystems. This block can be easily incorporated into various circuits modeled in SimPowerSystems and has the characteristic of nonlinear U-I curve similar to real SIC-SFCL, as long as the correct parameters are inputted. Using this block, we can study the limiting characteristic of SIC-SFCLs in a complex power grid.

3. Analysis

3.1. Simulation circuit

The limitation performance of an SIC-SFCL was studied using the simulation circuit shown in figure 2, which was composed of a three-phase transformer, an SIC-SFCL, a RLC branch, a RLC load, and a breaker. The parameters were set according to the real circuit of the 35kV SFCL prototype operating in Puji substation, Yunnan, China. The transformer worked as an ac current source with 35kV output voltage, and the impedance of the RLC branch was a combination of the internal resistances of the
transformer and the SIC-SFCL. In the normal power transmission state, the breaker was open and the current in the RLC load was about 800A. Then the breaker closed to short the RLC load and simulate the transition process of a 3-phase fault. Table 1 lists out the parameters of the circuit.

![Simulation circuit of a 35kV SIC-SFCL](image)

**Figure 2.** Simulation circuit of a 35kV SIC-SFCL

| Items                              | Parameters |
|-----------------------------------|------------|
| turns of the ac coil              | 60 turns   |
| length of magnetic path           | 6 m        |
| cross section of iron core        | 707 cm²    |
| dc resistance of SFCL             | 0.03 Ω     |
| leakage inductance of SFCL        | 0.4 mH     |
| rated phase voltage               | 35 kV      |
| rated normal current             | 800 A      |
| max. fault current without SFCL   | 40 kA      |
| limited current                   | < 25 kA    |

**Table 1.** The parameters of the simulation circuit

3.2. limitation effect

Figure 3 shows fault current curves of a 3-phase short without limitation. The short point was set at the end of the first wave cycle, at which the current angle of phase A was 0°, phase B was 120°, and phase C was -120°. It was obvious that the amplitude of first wave period of the fault current was much bigger than subsequent periods, and the value of its peak was closely related with the phase angle. Generally, the highest surge peak will appear when the short occurs at the current zero point, because at this moment the corresponding voltage is at its maximum value for an inductive circuit. It takes the fault current several wave periods to reduce down to a steady value, meaning there is a damping dc component in the transition process. This kind of current spike is a typical phenomenon, and is caused by a sudden change of voltage on inductive equipment in the circuit, especially on transformer, electromotor, etc. To weaken the damaging force of fault currents, it is necessary to lower both the surge peak and the rms. value of the fault current.
3. Limitation stage

A distinct attribute of the limited current curve is a small limitation stage appearing at the current zero line. This phenomenon is indicative of the nonlinear electromagnetic characteristic of the iron core. Equation 5 can be re-written in the form of equation 6, in which $\frac{di}{dt}$ is the slope of the current curve. When $i=0$, the value of $\frac{di}{dt}(i=0)$ is determined by $f'(0)$ (see equation 7), which is the magnetic
permeability $\mu$ of the iron core. When the iron core is unsaturated (the magnetizing current $i=0$), $\mu$ is so large that $\frac{di}{dt}(i=0) \to 0$. So, it is understandable there are a small limitation stage near the area of $i=0$. After the iron core is saturated, the ac coil works more like an air core coil, the current increases sharply, and the resulting current wave is more like a sine curve.

$$\frac{dt}{dt} = \frac{U - Ri}{N^2S f'/(N_0)} + L$$

$$\frac{di}{dt}(i=0) = \frac{U}{N^2S f'(0) + L}$$

3.4. Non-linear impedance

On one hand, for a certain size of iron core, number of turns of ac coil, and length of magnetic path, a fixed amount of ac magnetic force is needed to make the iron core saturated. This means that no matter how much the fault current is, the SIC-SFCL can only consume a certain part of magnetic force, and then the ac coils will work as air core coils. On the other hand, for a special circuit with a SIC-SFCL, the larger the fault current is, the lower the impedance is, and at that condition, even the ‘air core coils’ of the SIC-SFCL can play an important role in current limitation. So the limitation action in a SIC-SFCL may be roughly categorized into two different mechanisms, which might be termed iron limitation and coil limitation. Iron limitation is strongly related with the structure of the SFCL reactor part, including the iron cores and coils, and has a marked effect when the fault current is relatively small, while the effect of coil limitation will be more obvious when the fault current becomes very large.

The intrinsic non-linear characteristic of the iron core causes the SIC-SFCL to have no permanent impedance under different fault currents. Figure 5 shows the calculated impedance and limited current of the 35kV SIC-SFC exponential curve. When the fault current is less than 10kA, the impedance decreases sharply with the increasing fault current. This indicates that the iron limitation is the major factor in limiting the fault current in this range. When the fault current is larger than 10kA, the impedance decreases slowly and approaches 0.4 $\Omega$. The fault current is obviously large enough to easily saturate the iron core, and the SIC-SFCL can not only still limit the fault current, but is even more effective, because the remaining impedance of the circuit after the short is comparable with the inductance of the coils when the iron cores are saturated. From the limited current curve, it is clear that the larger the fault current, the higher the apparent limitation effect. When the fault current is less than 10kA, the limitation ratio is about 77%, while when the fault current is 40kA, the limitation ratio decreases to 56%. 
These results suggest that both the iron cores and the ac coils contribute to the current limitation, but the iron cores have a greater effect on limiting low fault current, while the coils have a greater effect on limiting a high fault current. In the design of a SIC-SFCL, one of the most important steps is to tune the impedance to a reasonable value, which can suppress the maximum fault current to under an acceptable level. For this 35kV prototype, the requirement is to cut 40kA fault current to 25kA limited current. We can choose different sets of structure parameters and calculate out series of limited current curves like those shown in figure 5. From these curves, an optimized set of parameters will be used for the final design.

4. Summary
A calculation module, containing the nonlinear features of iron cores, is developed to study the characteristic of the fault current limitation of an SIC-SFCL. The results show:
A. SIC-SFCLs can lower down both the maximum fault current peak and the steady fault current, thus reducing the danger of the electrodynamic force and thermal effect. However, it is more effective in decreasing the rms. value of the fault current than the maximum value.
B. The limitation current curve of SIC-SFCLs has flat stages near \( i=0 \). This phenomenon is caused by the demagnetization of the iron cores. After the iron core is saturated by ac current, the curve behaves more like a sine curve.
C. SIC-SFCLs have two kinds of limiting mechanisms, iron limitation and coil limitation. When the fault current is relatively small, iron limitation has a greater contribution, while when the fault current is very large, coil limitation has a greater effect.
D. An SIC-SFCL has no permanent impedance when subjected to differing fault currents. The larger the fault current is, the higher the apparent limitation effect is.

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