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Computational Study on the Steady-state Impedance of Saturated-core Superconducting Fault Current Limiter

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Abstract

This paper presents the electromagnetic analysis of a high voltage saturated-core superconducting fault current limiter (SCSFCL).The numerical analyses of a three-dimensional (3D) model is shown, and the specific parameters are given. The model focus on the steady-state impedance of the limiter when connected to the power grid. It analyzed the dependence of steady-state impedance on the AC coil current, and the relationship between oil gap and coil inductance. The results suggest that, adding oil gap between slice of silicon steel can reduce the core cross-section, restrain the ultraharmonic and decrease the steady-state impedance. As the core cross-section of AC limb decreased from 4344 cm^2 to 3983 cm^2, the total harmonic distortion for voltage decreased from 2.4% to 1.8%, and the impedance decreased from 1.082 Ω to 1.069 Ω (I_{dc}=400A,I_{ac}=1296A).

*Keywords:*Steady-state impedance; Saturated-core superconducting fault current limiter; Oil gap

1. Introduction

With the development of high voltage power system, the installed capacities are increasing rapidly, moreover the short circuit current becomes larger. As a consequence, the efficiency and the reliability are taken more into account. The Saturated-core Superconducting Fault Current Limiter (SCSFCL) is an effective device to reduce the impact of fault current and increase the reliability of the power grid. According to the nonlinear property of the iron cores, it can reach a low value of inductance at normal state and a high value at limiting state [1]. In saturation condition of

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the SCSFCL, it still shows a small impedance to the outer circuit, therefore causes less voltage drop across the SFCL. As we know, the steady-state impedance of the SCSFCL mostly depends on the permeability of the magnetic core which varies with the exciting current. Even the iron core is in the deeply saturated station, the minimum value of the steady-state impedance is also limited by the air inductance of the AC coil. In the high voltage power system, the steady-state impedance will cause great loss even in a small level. Hence, it is critically important to investigate methods to calculate and decrease the steady-state impedance of the SCSFCL.

2. Working principle and structure of the SCSFCL

2.1. Working Principle of SCSFCL

A 500 kV SCSFCL mainly contains of two separate cores, two AC coils and one superconducting coil. The AC coils are made of copper wires, and would connect to the 500 kV electrical power system in series. The DC bias winding is made of superconducting tapes and powered by an independent circuit. When the power grid is in normal operation, the cores maintain deeply saturated due to large superconducting DC excitation. In this operation, the waveforms of both the induced voltage and the current on the ac windings are sinusoidal, and the impedance are small. As the fault occurs, the short-circuit is large enough to convert one of the iron cores into un-saturated region in every part of the cycle. Thus the inductive voltages appear to reduce the peak of the short circuit. The concept of SCSFCL was first suggested by B. P. Raju et al. in early 1980’s [2]. T. Verhaege, Y. Laumond discussed in detail on the saturated iron core concept fault current limiter in 1998 [3].The 500 kV SCSFCL has the same working principle . The schematic diagram of the SCSFCL is shown in fig.1(a).

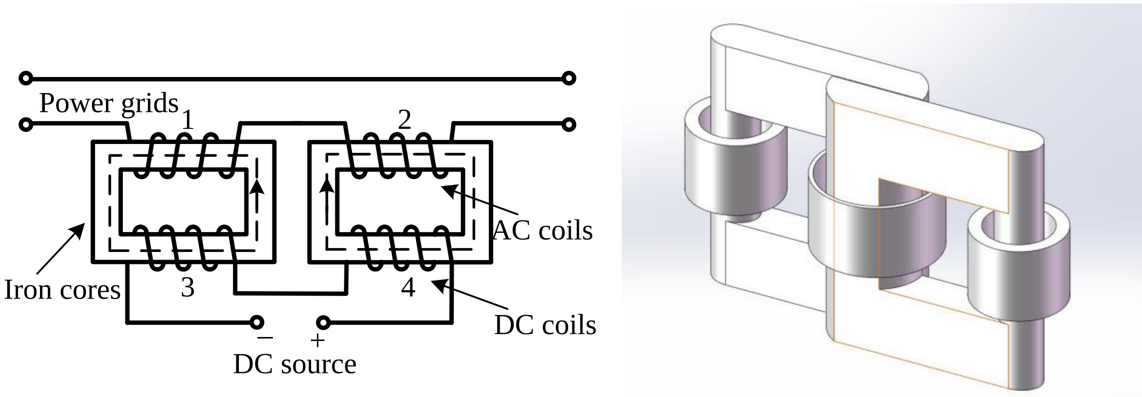

Fig. 1. (a) The schematic diagram of the SCSFCL; (b) 3D model of the SCSFCL.

2.2. Calculation methods of the SCSFCL steady-state impedance

There are several methods to calculate the steady-state impedance of the SCSFCL. One method is to calculate the current waveform and voltage waveform of the SCSFCL by using the simplified electric circuit equation and magnetic circuit equation to simulate the practical condition of the power grid. This method can roughly estimate the steady-state impedance in the power grid by the voltage-drop in the power grid.

Another method is to build the model of SCSFCL by using Finite Element Method（FEM） software to calculate the time-evolutional voltage and current. By using the FEM software, we can take advantage of the proper function-fitting magnetization curve to calculate various electromagnetic properties, thus help predict the performance of practical value. In this way, we can get the inductance of each AC coils which varying along the core limb with different permeability. In this paper, we will use the FEM analysis to study how the different permeability and magnetic path affect the steady-state impedance.

2.3. 3D modeling process of the SCSFCL

A 3D SCSFCL model is designed for the simulation by using Finite Element Analysis(FEA) software. The specific geometry parameters are shown in Table 1. Fig.1(b) exhibits the 3D SCSFCL model studied in this work. This design uses two single magnetic cores, and the air gap between two cores is set as 20mm. In this way, the DC bias coils would form a closer DC magnetic circuit. The cross-section of the yoke is 1.8 times as the AC limb, and the DC limbs are two times of that.

Table 1. Specific parameters of the SCSFCL.

Parameter	FCL element	Value
AC limb length, mm	Core	4275
AC limb cross-section,cm^2		4344
DC limb cross-section,cm^2		8688
Current, Ampere(rated)	AC coil	1800
Turns, number		42
Turns, number	DC coil	780
Current, Ampere(rated)		600
DC limb length, mm		4275

After this model, we have designed another model which was modified on the basis of the former one. As we all know, the iron core was fabricated by the stacked silicon steel. There are negligible crevices between each slice of the steel. Furthermore, as this design will work on the 500kV voltage class, we should set oil gap aside for the huge heat generated on the cores. Hence, We added five oil gaps on each core, which was set as 5 mm, and changed the lamination factor from 0.97 to 0.93. By modifying these parameters, the cross-section of the DC limb reduces from 8688 cm^2 to 8543 cm^2 , and AC limb from 4344 cm^2 to 3983 cm^2.

2.4. Results and Discussion

We have performed twelve kinds of the transient FEM simulations for AC coils. The current passing through the DC coils is kept as 490A in the first six conditions and 600A in the second six conditions. As two iron cores keep in a relatively saturated state, the RMS current of the AC coils varies from 533A to 1289A. The simulation results of steady-state impedance is shown in fig.2.(a-b).

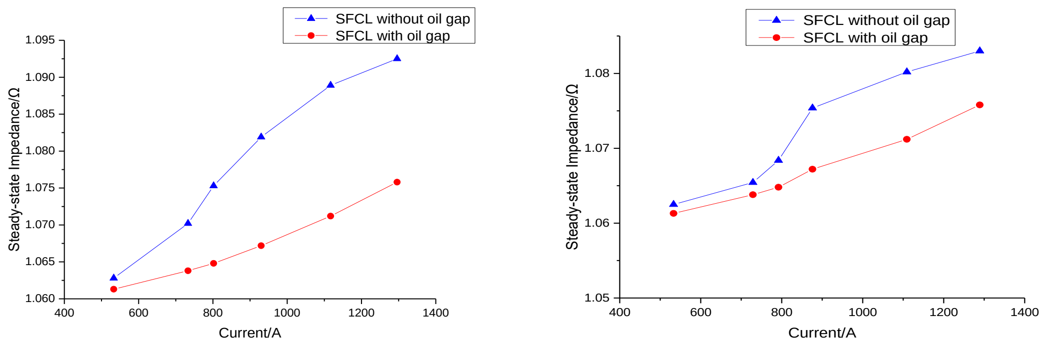

Fig. 2. (a) Steady-state impedance with different AC current;(I_{dc}=490A) ;(b) Steady-state impedance with different AC current;(I_{dc}=600A) .

It can be observed that SFCL with oil gap has a higher impedance when contrasted with the model without oil gap. When the AC current is in the interval of 533A to 729A, the gap between two models grows gradually, while in the interval of 729A to 930A, the gap becomes larger. As the AC current reaches to 1100A, the gap tends to be stable. Due to the non-linear property of the iron cores, the SCSFCL keeps in deep saturation when AC current is low. The effect of the oil gap becomes evident with growing AC current. The oil gap and lamination factor decrease the cross-section of the iron core with increasing the magnetic resistance and decreasing permeability. Therefore, the gap between two models grows big. Actually, as the AC current increase continually towards the rated current, one of the iron core starts to demagnetize in each half cycle.[4] And the induced voltage on two AC coils would appear a phase-difference. Accordingly, the ultraharmonics would exaggerate the inductance of the AC coils. By increasing the oil gap can reduce the ultraharmonics and decrease the steady-state impedance. Fig.3(a) exhibits the 3D model with oil gap. The magnetic field distribution is shown in fig.3.(b)- fig.3.(c).

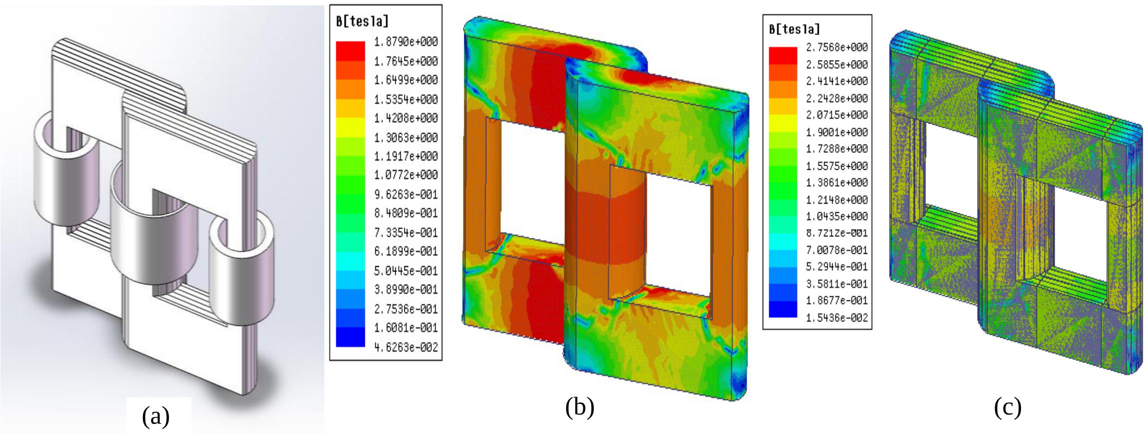

Fig. 3. (a)3D model of SCSFCL with oil gap; (b) Magnetic field distribution of Iron core without oil gap(I_{dc}=400A,I_{ac}=1296A) ; (c) Magnetic field distribution of Iron core with oil gap(I_{dc}=400A,I_{ac}=1296A)

3. Conclusion

The steady-state impedance of SCSFCL were computed by using the FEM software, which was combined with the qualitative analysis. The methods of calculating and decreasing the inductance of the AC coils were investigated, which allows the improvements in the efficiency and reliability of the limiter. According to the simulation results, it is found that decreasing the cross-section of the iron core can promote the decrease of the steady-state impedance in the saturated region. It is predicted that the phase-difference would appear as the AC current grows, and the utilize of oil gap can restrain the ultraharmonic, and reduce the steady-state impedance. According to the simulate result, as the core cross-section of AC limb decreased from 4344 cm^2 to 3983 cm^2, the total harmonic distortion for voltage decreased from 2.4% to 1.8%, and the impedance decreased from 1.082 Ω to 1.069 Ω (I_{dc}=400A,I_{ac}=1296A).

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