High Temperature Superconducting DC Fault Current Limiter Using Soft Magnetic Composites

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***Abstract* — In this paper, a magnetic core direct current (DC) fault current limiter (FCL) saturated by high temperature superconducting (HTS) DC bias winding is presented, which is applied to a large DC power transmission system. The FCL has no influence on DC system at normal operation, when fault occurs, which will produce a high short circuit impedance because the core works in non-saturation state. In order to extend the duration of current limiting in which the circuit breaker may work successfully, a new type of magnetic material, soft magnetic composites (SMC), is used as magnetic core. Considering the size of Dewar flask vessel and insulation distances, the structural parameters of core is determined. The transient short-circuit current is investigated using both 3-Dimensional (3D) finite element analysis (FEA) and equivalent circuit model. The influences of magnetomotive force (MMF) by HTS winding, the copper winding turns and core diameter are discussed thoroughly.**

I. INTRODUCTION

With the extensive application of DC power systems, suppression of DC fault current is very important to system reliability [1]. The HTS FCL is one type of fault current limiting devices, which uses the special characteristics of superconductor. Many researches are being performed for high voltage application and commercialization at distribution power system [2].

Saturated core HTS FCL offers a rapid and effective fault current limitation and saturated core FCL (SFCL) has a fast response, very high stability and reliability and the first current peak can be effectively limited in AC power system [3]-[4]. The FEA considering E-J characteristics of superconductor has also been developed to simulate the magnetic shielding type FCL [5]. The energy capacity of magnetic core is expanded to several times using Reverse Magnetization Bias (RMB) method. An SFCL with RMB circuit can reduce fault current to same level of that of air core SFCL. RMB circuit restrains core magnetic field saturation for short but enough time, Moreover, it has smaller size and lower cost [6].

In this paper, the design principle of DC HTS FCL and application of SMC are discussed in details, and a large amount of simulation computation and analysis are carried out to verify the DC FCL design.

II. DESIGN PRINCIPLE OF DC HTS FCL

The schematic diagram of saturated core DC HTS FCL is shown in Fig.1. In Fig. 1, U_s is the equivalent voltage source and R_s is the resistance of DC system. The equivalent circuit of DC power transmission system is in the left and DC bias circuit is in the right, whose loss can be neglected because the winding in series is made of HTS tapes. If copper windings and DC HTS bias windings are wound in the same core column, the structure can be suitable to greatly reduce leakage magnetic flux. However, if copper winding is surrounded by DC HTS bias winding and Dewar flask vessel, the larger volumes of them are demanded, and vice versa. This paper presents a DC HTS FCL in which the copper winding and HTS bias winding are mounted on two different core legs respectively.

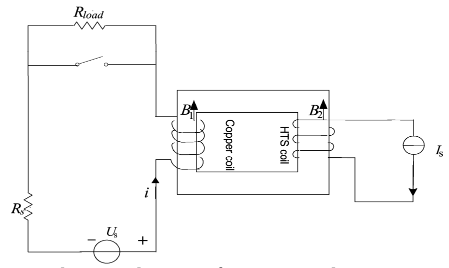


Fig.1 Schematic diagram of DC saturated core HTS FCL

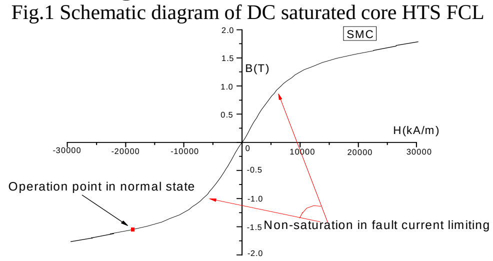


Fig.2 *B-H* curve of SMC core

DC bias current flows through superconducting coil in bias circuit to saturate the core at the operation point as shown in Fig.2, and the optimum operating point is given on the B-H curve of core. The DC HTS FCL has no influence on DC power transmission system in normal state. When fault occurs, current will increase to a very high level in a short time, and the operation point will locate at non-saturation section of *B-H* curve of magnetic core, where the core has high permeability and the copper winding may provide large inductance to limit the fault current.

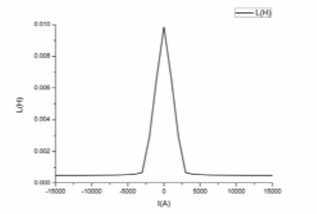
III. APPLICATION OF SOFT MAGNETIC COMPOSITES

Because the induced voltage of copper winding is zero at DC operation, the copper winding works only when fault occurs and the current will increase unidirectional to very large value in very short time. Selection of core is important to expand the current limiting time.

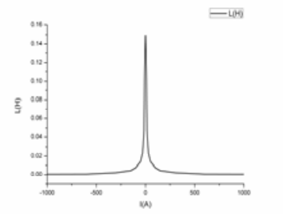
Soft magnetic composites (SMC) are made of small iron particles mixed with dielectric materials that provide dielectric insulation and particle bonding. The *B-H* curve of SMC ascends smoothly and has wider non-saturated range than other silicon steel materials. Thus, the core can work longer in non-saturation state and get better effect on current limiting when short-circuit fault occurs.

IV. SIMULATION AND DESIGN OF DC HTS FCL

In this paper, the numerical simulation using both 3D finite element analysis (FEA) and transient nonlinear circuit model is presented to evaluate the performance of the saturated core DC HTS FCL. Because of the existence of the iron core, the inductance of the HTS FCL is associated with the current flowing through the copper winding. The nonlinear inductance of the FCL and L-I curve are calculated by the energy perturbation method [7] based on FEA. The calculation results of *L-I* curve in SMC and normal silicon steel are respectively calculated and shown in Fig. 3.



(a) SMC

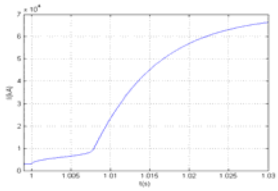


(b) Silicon steel

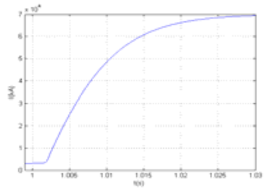
Fig. 3 *L*-I curve of two kinds of materials

The transient short circuit current could be acquired from the solution of equivalent nonlinear circuit model according to L-I curve.

The limitation results based on the same parameters of two kinds of core materials are compared as shown in Fig. 4.



(a) SMC



(b) Silicon steel

Fig. 4 Limitation results of two kinds of core materials

The influences of bias MMF of HTS winding, the core diameters and the turns of copper winding on the performances of FCL are presented in Fig. 5, 6 and 7, which illustrate the limiting current with respect to the MMF, the core diameters and the turns of copper winding, respectively.

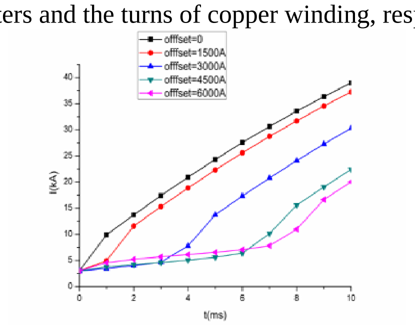


Fig.5 Short-circuit currents under different MMF

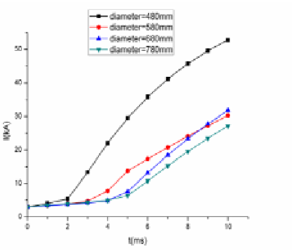


Fig.6 Short-circuit currents under different core diameter

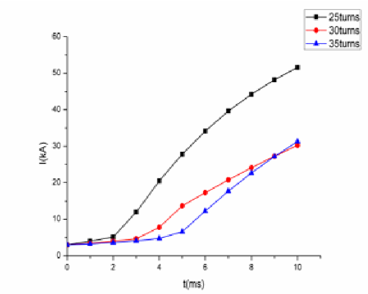


Fig. 7 Comparison of short-circuit current in different turns

The Change of MMF has almost no effect to the structure of the core. However using larger DC bias may increase the cost of HTS tapes when MMF exceeds 4500A. The Change of the copper winding turns and core diameter have large influence on the size of the FCL. Furthermore, the copper winding turns and the core diameters are all the major factors to determine the peak value and the bossing width of L-I curve.

V. CONCLUSION

In this paper, the magnetic core made of soft magnetic composites can extend the fault current limitable time so that the circuit breaker may work in longer time. The design principle of saturated core DC HTS FCL is researched and its transient performance is analyzed using 3-dimensional FEA and transient nonlinear circuit model. The influences of MMF by HTS winding, the core diameter and the copper winding turns are simulated and discussed thoroughly so as to provide reference for DC FCL design. The results reveal that the saturated core DC HTS FCL has rapid response to limit large fault current. HTS coil may maintain its superconducting state at both normal and fault operation.

VI. REFERENCES

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