USING OF HIGH TEMPERATURE SUPERCONDUCTIVE IN SECONDARY WINDING OF TWO TYPES OF TRANSFORMERS: FAULT CURRENT LIMITER AND CURRENT INJECTION TRANSFORMER

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INTRODUCTION

The Types of applications in which superconductivity has the potential to be effective in an electric power system can be separated into two general classes. The first type includes those technologies in which superconductivity is simply a replacement of existing resistive materials, for example, cable, motor, generators, and transformer. The second type includes technologies that will be enabled by superconductivity and that have little or, at most, limited capability if conventional resistive or other materials are used. Examples are superconducting magnetic energy storage (SMES) and large fault current limiter (FCL) [1].

Superconductivity brings a variety of features that provide new functionality to the electric power system. For example, today, the ability to limit the maximum current in a system, one is SMES, the other is the advanced flywheel, which spins at a very fast rate and is supported and constrained by magnetic bearings that use superconductors.

The July 1997 issue of IEEE Spectrum was dedicated to recent developments in the applications of high temperature superconductivity (HTS) to electric power systems.

FCLs are used to limit the fault current to the level that is within the interrupting capabilities of the existing circuit breakers. They are expected to improve reliability and flexibility of power system. Various types of them have been proposed and studied [2-3].

The HTS provide the advantage of a higher temperature operation and they are applied to FCL. The FCLs based on HTS materials have been developed for many years now [4-6]. Prototypes have been manufactured and tested in existing power system [6-7].

In the other hand, current injection transformer (CIT) are within the major group of the standard type test equipments in electrical industry, their performance are very important, one of the critical problem in this type of transformer is thermal characteristics: hot-spot temperatures, warm and cooling periods, and aging [8]. Using superconductive solves above mentioned problems, but trade off between economical purposes and technical problems is a major discussion.

The purpose of this work is to study two types of transformers “FCL” and “CIT” using HTS coil. Simulations of Transient Characteristics and performances are considered for each type.

EQUIVALENT CIRCUIT OF TRANSFORMER USING SUPERCONDUCTIVE IN SECONDARY WINDING

Each of the conventional components of an electric power system can be replaced by a superconducting equivalent. A simple model of transformer by using of a superconductive in secondary winding is presented in Figure 1. In this model the superconductive is only introduced as a non linear or zero resistance. Analysis and simulations are based on this model.

HTS can be formulated by below Equations:

\[ R_{SC}(I_2, T) = 0 \quad I_2 < I_c(T), \quad T < T_C, \]
\[ R_{SC}(I_2, T) = \frac{R_{nc}}{\frac{I_c(T)}{I_2} - \frac{I_2}{\Delta I_2}}, \quad I_2 > I_c(T), \]  

where \( R_{nc} \) is the normal resistance of the superconductor, \( I_c(T) \) is the critical current, \( I_2 \) is the current flowing in superconducting winding, \( \Delta I_2 \) is the width of the transition.

HTS can be able to pass a high current in conditions \( T < T_C, I_2 < I_c(T) \). Especially, in high current issue, that hot spot is very important; using superconductive will solve thermal problems (CIT applications).

On the other hand, HTS can be limited the fault current in condition \( I_2 > I_c(T) \). According to above Equation, by
increasing of current, resistance of HTS is increased and fault current is limited (FCL application).

In presented model (Figure 1), \( L_m \) is the equivalent inductance of saturated and unsaturated cores. \( R_{sc} \) is a nonlinear resistor formulated the superconducting coil.

**FIGURE 1- Simple Model of Transformer by Using of a Superconductive in Secondary Winding**

**SIMULATION OF TRANSIENT CHARACTERISTICS OF FAULT CURRENT LIMITER TRANSFORMER**

In this section, the simulation of HTS FCL was carried out by Simulink module of Matlab software. Figure 2 illustrates the Equivalent circuit of the saturated FCL in power system [6]. The electrical parameters of the saturable power transformer, shown in this Figure, are taken into account in the Matlab software. Based on the measured result and simulation [9-10], all parameters are given in Table 1.

**FIGURE 2- Equivalent circuit of the saturated FCL in power system [6]**

| TABLE 1- The Technical Parameter of the HTS FCL |
|------------------|------------|---------------|
| Items            | Units      | FCL [10]      |
| \( R_{p1} \)     | \( \Omega \) | 500           |
| \( R_{s1} \)     | \( \Omega \) | 0.1           |
| \( R_{1} \)      | \( \Omega \) | 5.7           |
| \( R_{2} \)      | \( \Omega \) | 0.0           |
| \( R_{ac} \)     | \( \Omega \) | 0.0012        |
| \( L_{p1} \)     | \( H \)     | 0.0           |
| \( L_{s1} \)     | \( H \)     | 0.0           |
| \( L_{1} \)      | \( H \)     | 0.2223        |
| \( L_{2} \)      | \( H \)     | 1.4e-6        |
| \( N_{1} \)      | –           | 343           |
| \( N_{2} \)      | –           | 1             |
| \( U_{s} \)      | \( V_{rms} \) | 40/\sqrt{2}   |

Both the nonlinear inductance \( L_{sat} \) of the iron-core and the nonlinear resistance \( R_{sc} \) of the superconducting secondary winding in Figure 2 are very complicated and need to be modeled carefully in the simulation model. \( L_{sat} \) is formulated by entering \((I, \Phi)\) pair in per unit, then the power system blockset of Matlab will convert the \((I_{pu}, \Phi_{pu})\) pair into standard units in saturation model of the saturable transformer block. In the simulation, the specified \((I_{pu}, \Phi_{pu})\) pairs are \([0, 0]; [0.02, 1.0]; [1.0, 1.30]\). \( R_{sc} \) is modeled by a controlled voltage source. In the simulation, the load \( R_{p1}, L_{p1} \) is short-circuited at 41 millisecond. Figures 3, 4, and 5 show the results of the primary short circuit currents with HTS FCL and without FCL respectively.

**FIGURE 3- Primary current waveforms of the model with saturated FCL when a load is short-circuited at 41 ms**

**FIGURE 4- Primary current waveforms of the model with unsaturated FCL when a load is short-circuited at 41 ms**
FIGURE 5: Primary current waveforms of the model without FCL when a load is short-circuited at 41 ms

Figures 6 and 7 illustrate the transient current waveform of superconducting tube \( I_2 \) when saturated and unsaturated iron-cores are employed.

FIGURE 6: Secondary current waveforms of the model with saturated FCL when a load is short-circuited at 41 ms

FIGURE 7: Secondary current waveforms of the model with unsaturated FCL when a load is short-circuited at 41 ms

To investigate clearly the influence of the saturation of an iron-core on the fault current limiting ability of the magnetic shield type FCL, various assumptions were considered.

Firstly, enlarging the magnitude of the nominal voltage of a power supply in Figure 2 by multiplying a factor \( k \), the primary current increases around \( k \) times consequently.

Secondly, transforming the actual primary current by multiplying a factor of \( 1/k \), then the primary current is illustrated in Figure 8 with \( k = 1.00, 1.25, 1.50 \) and 2.00 respectively.

FIGURE 8: Relationship between the over-voltage factor \( k \) and the converted primary current indicates the influence of the iron-core saturation on the effectiveness of fault current limiting.

As shown in Figure 8, with the increase of the saturation extent of the iron-core, the fault current limiting ability of the FCL obviously decreases. Meanwhile, the unsaturated FCL has the best performance (a linear transformer model with magnetization current 0.02 in per unit value).

DESIGN AND SIMULATION OF CURRENT INJECTION TRANSFORMER

Current Injection Transformer (CIT) are within the major group of the standard type test equipments in electrical industry and its thermal performance is very crucial. The CITs are used for testing equipments such as circuit breakers, that must carry short-circuit current. Secondary voltage of this transformer is usually low, (less than 5 volts) whereas, the output current is very high (1 kA-100 kA).

Previous investigation reported the simulations of copper and core losses of the CIT from which temperature rise of secondary windings together with thermal limitations were calculated [8]. it also explained a case study for a dry-type transformer with output current of 25kA and 5 volts secondary voltage and the short-circuit time duration was about 3 seconds at full load.

We redesign this transformer as below:

Previous Design without Superconductive in Secondary Winding

In this section we review the previous design of the CIT that it followed with the thermal problem. Secondary voltage of the CIT, \( V_2 = 5[v] \) and output current is, \( I_2 = 25[KA] \rightarrow Q_2 = V_2I_2 = 125[KVA] \)

If the voltage per turns be as: \( E_t = 5[v/turns] \)
Maximum flux density obtains as:

\[ \phi_m = \frac{E_i}{4.44f} = \frac{5}{4.44 \times 50} = 22.5 \text{[mT]} \]

For flux density \( B_{\text{max}} = 1.6 \text{T} \) we have

\[ A_i = \frac{22.5 \times 10^{-3}}{1.6} = 0.014 \text{[m}^2\text{]}, \quad K_f = 0.9 \to A_c = \frac{0.014}{0.9} = 156.2 \text{[cm}^2\text{]} \]

\[ A_c = 12.5 \times 12.5 \text{[cm}^2\text{]} \]

Because magnetic fluxes become half for left and right legs, cross section of each one is half of central leg. 

\[ b = 2a \to a = 6.25 \text{[cm]} \]

If the current density \( \delta = 2 \times 10^6 \frac{A}{m^2} \) windows area, \( A_w \) 

obtained as:

\[ Q = 2.22 \times f \times B_m \times K_w \times \delta \times A_j \times A_w \]

\[ 125 \times 10^3 = 2.22 \times 50 \times 1.6 \times 0.27 \times 2 \times 10^6 \times 0.014 \times A_w \]

\[ A_w = 930 \text{[cm}^2\text{]} \to H_w = 45 \text{[cm]} \]

\[ D_w = 21 \text{[cm]} \]

\[ H = H_w + 2H_y = 45 + 12.5 = 57.5 \text{[cm]} \]

\[ W = 2D_w + 2b = 67 \text{[cm]} \]

According to this design, with the help of finite element method (FEM) simulation, flux distribution is showed in Figure 10.

**New Design with Superconductive in Secondary Winding**

Now, the CIT is redesigned by using of superconductive as secondary winding, so we haven’t thermal limitation. Like above design, we have:

\[ b = 2a = 12.5 \to a = 6.25 \text{[cm]} \]

But the current density can be assumed as below:

\[ \delta = 2 \times 10^7 \frac{A}{m^2} \]

(because there is no thermal problem)

Windows area, \( A_w \) obtained as:

\[ Q = 2.22 \times f \times B_m \times K_w \times \delta \times A_j \times A_w \]

\[ 125 \times 10^3 = 2.22 \times 50 \times 1.6 \times 0.27 \times 2 \times 10^7 \times 0.014 \times A_w \]

\[ A_w = 93 \text{[cm}^2\text{]} \to H_w = 13.63 \text{[cm]} \]

\[ D_w = 6.82 \text{[cm]} \]

\[ H = H_w + 2H_y = 13.63 + 12.5 = 26.13 \text{[cm]} \]

\[ W = 2D_w + 2b = 2 \times 6.82 + 2 \times 12.5 = 38.64 \text{[cm]} \]

Size of CIT is decreased in case of superconductive as secondary winding. Furthermore, flux distribution is improved (Figure 11). However, it is necessary trade off between economical and technical aspects in this case.

**CONCLUSION**

Each of the conventional components of an electric power system can be replaced by a superconducting equivalent
for more performance, downsizing, reducing system losses to a minimum and so on.

We have studied two types of transformer: “FCL” and “CIT” using HTS coil. The simulation of those transformers is carried out by Simulink module of Matlab software and Ansys software.

For FCL, the transient response, especially the primary short circuit current was obtained. The influence of the saturation of an iron core and the specified structure of the magnetic circuit was analyzed. Using HTS in secondary winding of FCL considering its linear characteristic in temperature more than critical temperature has advantages include stable apparent impedance during the occurrence of a fault, shorter recovery time and lower voluminal energy dissipation during controlled – transition.

For CIT, it is suggested using HTS due to reducing size and voltage drop. We have designed the 25kA CIT using HTS and compared with previous design of the CIT. Furthermore with the help of FEM simulation leakage fluxes distribution of the HTS CIT was simulated. Results of simulations and redesigned present that we can have a portable CIT with suitable characteristics: thermal and mechanical force.

Consequently, we described performance of superconductive in designing and construction of transformers with studying two case studies (FCL and CIT).

REFERENCES


