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TESTING THE OPERATION OF HIGH T_C SUPERCONDUCTING FAULT CURRENT LIMITER IN A REAL SYSTEM

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Abstract

This paper presents the effects of an inductive type high-temperature superconducting fault current limiter (HTS FCL) on a three-phase system have been investigated both theoretically and experimentally in the case of a shunt and a subsequent series fault.

Calculations have been performed for different cases including those when currents in the faultless phases would increase. This may lead to an incorrect operation of the automatic protection elements even in the faultless phases. The calculations based on the method of symmetrical components.

To investigate the real physical processes, a measuring instrument was constructed to measure the transients due to the fast acting HTS FCL.

Keywords: high-temperature superconductor, fault current limiter, modeling, shunt and a subsequent series fault, symmetrical components.

1. Introduction

The increasing demand for electric power leads to the need to reinforce systems. As electric power systems grow and become more interconnected, fault currents (i.e. the currents that would flow during a short circuit) increase. It is well-known that the higher the currents in the network, the higher the dynamic and thermal loads of circuit elements. The higher the fault currents anticipated, the higher the equipment costs, not only for the breaker itself but also the high fault currents add to maintenance costs as they accelerate aging. In order to cut the dangerous values of current in transmission and/or distribution lines, various limiting devices are applied in electric networks. In this context, a protecting system composed of a High-Temperature Superconducting Fault Current Limiter (HTS FCL) and traditional circuit breaker seems to provide a promising solution for future power system operation.

The applied conventional methods for the limiting of the current:

- Reduction of looping the network, with rearrangement of the topology
- The insulation or slackening of the starpoint of the network with choke or resistor

- Series choke
- Air core reactors

These methods have been applied in the electric power supply but these are not ideal, they have more disadvantages.

The superconductor FCLs can provide:

- Negligible influence, low impedance in normal operating conditions of protected circuit
- High impedance in fault condition
- High-speed operation providing transient fault limitation of all types of fault currents
- Effective limitation of steady-state fault current
- Repetitive operation with short recovery time
- Absence of dangerous overvoltages across components of the circuit
- Short recovery time after fault
- No external trigger or external energy source

The main advantages of the fault current limitation by FCLs are in the reduction of weight, size and cost of electric power equipment, the possibility of using circuit breakers with lower current-interrupting capabilities and more effective schemes of the electric network. A superconducting FCL is essentially a variable impedance inserted into the circuit to be protected. An ideal FCL should exhibit zero impedance under normal operation, rapidly switch to a large impedance under fault conditions, and return to a zero impedance state quickly upon removal of the fault or operation of the circuit breaker.

We present in this paper the calculations and the measurements on our experimental models in order to prove the applicability of this device. The commercially available components make it possible to construct FCLs with the necessary parameters for power applications in the near future.

2. Device Development

2.1. SuperTech (ST) Fault Current Limiter

The simplified scheme of an inductive type FCL is shown in *Fig. 1*.

It consists of a primary coil coupled via a ferromagnetic core to an HTS ring (made of melt textured YBCO material with high critical current density) acting as a one-turn short-circuited winding.

A laboratory scale experimental inductive HTS FCL was designed and constructed (*Fig. 1* and *Fig. 2*). The experimental FCL incorporated two primary windings – ‘two devices in one device’ – to investigate various effects.

- The first device consists of a closed laminated iron core with a variable air gap, a primary copper core with different turn ratios and a secondary ‘coil’: the HTS ring.

- The second device belongs to the screening type FCL's. This device differs from the first one in that the secondary HTS ring is placed inside the primary coil.

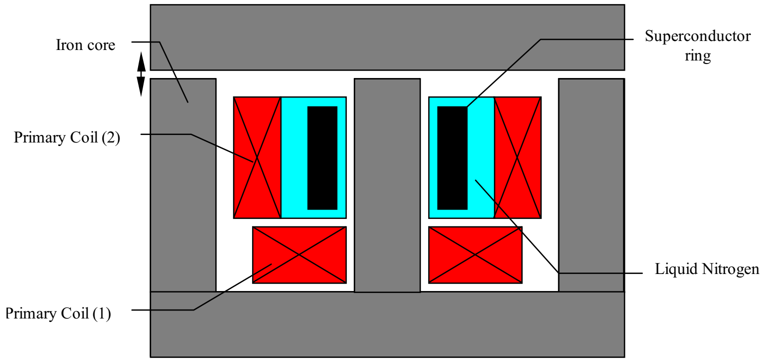

Fig. 1. The structure of the FCL

The next photos show the view of the HTS FCL (*Fig. 2*) and the measurement arrangement (*Fig. 3*).

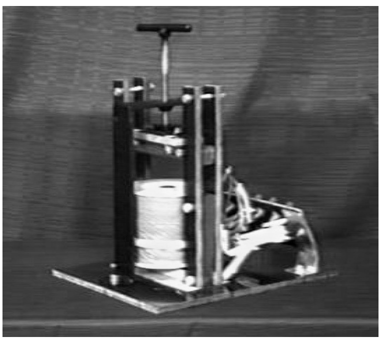

Fig. 2. The view of the FCL

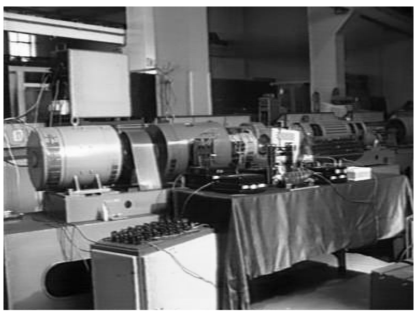

Fig. 3. Photo of measurement

2.2. *Experimental Setup*

The operation of the FCL corresponds to that of a current transformer with a short-circuited secondary winding, so that the leakage reactance of the device will be connected in series with the network (*Fig. 4a*). Under fault conditions, however, the superconducting ring goes as a fast transition into the normal state because the induced current in the ring exceeds the critical value. This operation of the FCL corresponds to the one of a current transformer with an open secondary winding. As a result, the main field reactance will appear in the network (*Fig. 4b*). Thus the current limiting behavior of the inductive FCL is based on the large impedance change of the device between short-circuit and no-load conditions.

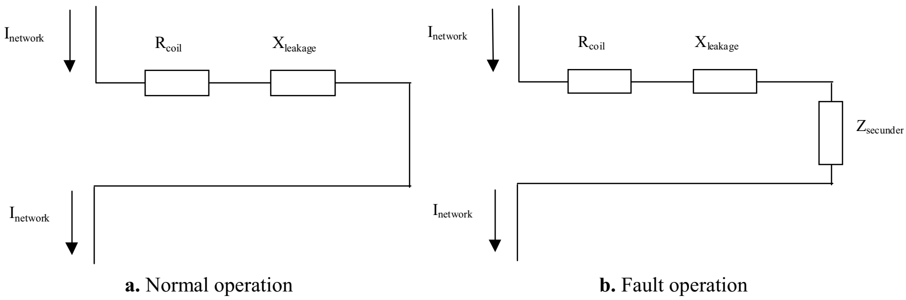

Fig. 4. The schema of the inductive FCL operation

The SuperTech FCL was measured to define the parameter of the equivalent circuit.

The parameters of the ST FCL:

- The turns ratio is $n = 100$
- The activation current is $I_a = 3.5$ A
- The resistance of the coil is $R_{\text{coil}} = 0.16\ \Omega$
- The FCL impedance in normal operation is $Z_{\text{normal}} = 0.457\ \Omega$
- The FCL impedance in fault operation is $Z_{\text{fault}} = 3.238\ \Omega$
- The impedance ratio is $z = \dfrac{Z_{\text{fault}}}{Z_{\text{normal}}} = 7.083$

3. Theoretical

3.1. *Modeling the Device*

In normal condition of the protected circuit, the superconducting ring of the HTS FCL is in the superconducting state. Under fault conditions the induced current in the ring exceeds the critical current very quickly. The secondary superconducting coil becomes resistive. Thus, the FCL impedance increases and limits the fault current. This process is a combination of a shunt and a subsequent series fault (simultaneous fault).

Calculations for the steady-state fault currents were performed by the method of symmetrical components for the cases of a generator supplying a three-phase load (*Fig. 5*). In these calculations the one-phase-to-ground and the overload fault cases have been produced in a real system (the generator–FCL–load system). *Fig.5* shows the equivalent circuit of the measuring arrangement, whichever has been calculated. The equivalent circuit of the FCL contains a non-linear element representing the superconductor.

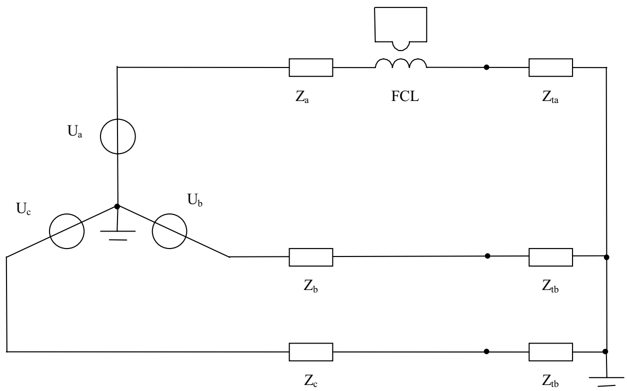

Fig. 5. The equivalent circuit of the measured system for the calculation

The positive, negative and zero sequence circuits of the generator–FCL–load system are demonstrated in *Fig. 6* where U is the generator voltage, Z_1, Z_2 and Z_0 are the impedances of the network, F_{FCL1}, F_{FCL2} and F_{FCL0} are the impedances of the fault current limiter and Z_{t1}, Z_{t2} and Z_{t0} are the impedances of the load in the different sequence circuit.

3.2. Calculations of the FCL and the Synchronous Machine: One-Phase-to-Ground Fault

In the one-phase-to-ground fault case the faulty phase has two types of faults:

- The first type is a one-phase-to-ground fault. The following expressions hold for the current and voltage components:

$$I_1 = I_2 = I_0,$$
$$U_1 + U_2 + U_0 = 0,$$

  where the indices 1, 2 and 0 refer to the positive, the negative and zero sequences, respectively.
- The second type is the series insertion of the impedance of the FCL into the network. The following expressions hold for the current and voltage components:

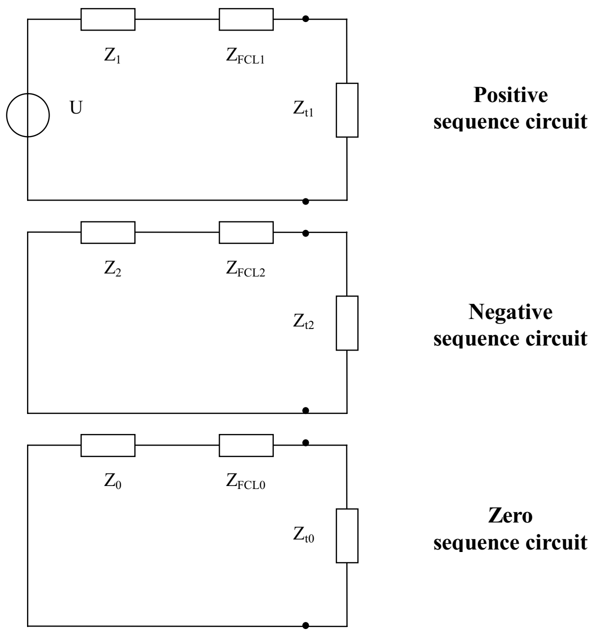

Fig. 6. Equivalent circuits for positive, negative and zero sequences

$$V_1 = V_2 = V_0 = \frac{Z}{3} \cdot I,$$
$$I_1 + I_2 + I_0 = I.$$

The next figure shows the equivalent circuit for the simultaneous fault indicating the equivalent circuits for the positive, negative and zero sequences (*Fig.*7).

3.3. Calculations of the FCL and the Synchronous Machine: Overload

In the overload fault case the faulty phase has one type of fault:

- This type is the series insertion of the impedance of the FCL into the network. The following expressions hold for the current and voltage components:

$$V_1 = V_2 = V_0 = \frac{Z}{3} \cdot I,$$
$$I_1 + I_2 + I_0 = I.$$

The figure shows the equivalent circuit for the simultaneous fault indicating the equivalent circuits for the positive, negative and zero sequences (*Fig.*8).

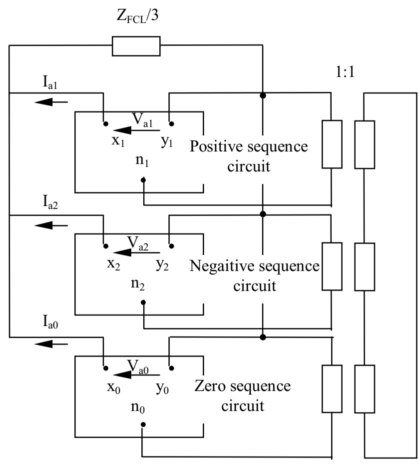

Fig. 7. One-phase-to-ground equivalent circuits for positive, negative and zero sequences

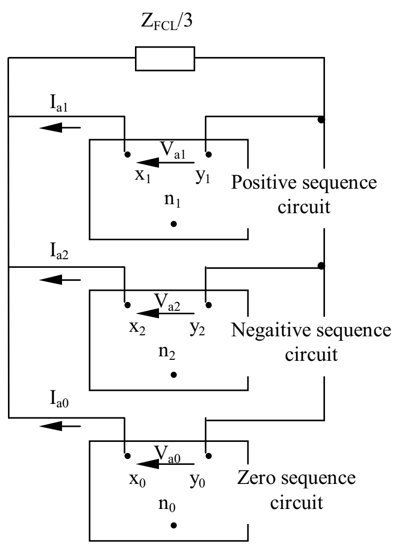

Fig. 8. Overload equivalent circuits for positive, negative and zero sequences

4. Results of the Calculations

The calculation is based on the method of symmetrical components and the steady-state condition in the generator–FCL–load system.

The first calculation involves the generator–FCL–load system without HTS FCL in the normal operation. After that the calculation was completed with the fault current limiter in different fault conditions (one-phase-to-ground and overload fault) and with different loads.

The results of the calculations are shown in the next table and figures.

In the table the calculation of the generator–load system can be seen in normal operation with different loads (*Table 1*). Phase currents of the system in the normal operation case are indicated with I_a, I_b and I_c.

Table 1. The normal operation with different loads

Normal	**Resistive load**	**Inductive load**	**Capacitive load**
$\|I_a\|$ [A]	3.182	2.25	9
$\|I_b\|$ [A]	3.182	2.25	9
$\|I_c\|$ [A]	3.182	2.25	9

Table 2. The one-phase-to-ground fault operation with different loads in non-limited case

1 Ph. F.	**Resistive load**	**Inductive load**	**Capacitive load**
$\|I_a\|$ [A]	7.709	13.5	6.443
$\|I_b\|$ [A]	2.112	6.397	2.371
$\|I_c\|$ [A]	2.317	6.397	2.371

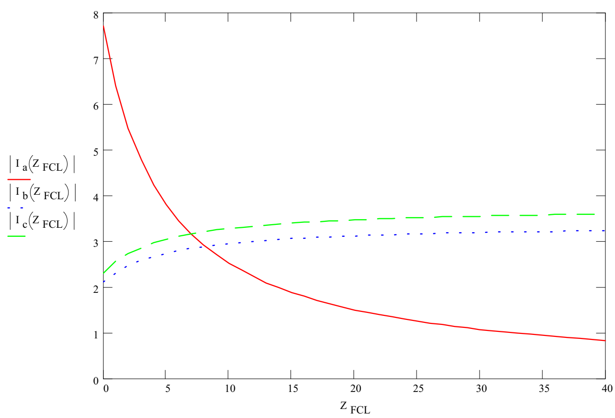

Fig. 9. One-phase-to-ground fault with resistitve load

The next figures show the calculated results of the three phase currents versus variable FCL inductance by the generator–FCL–load system in different fault conditions.

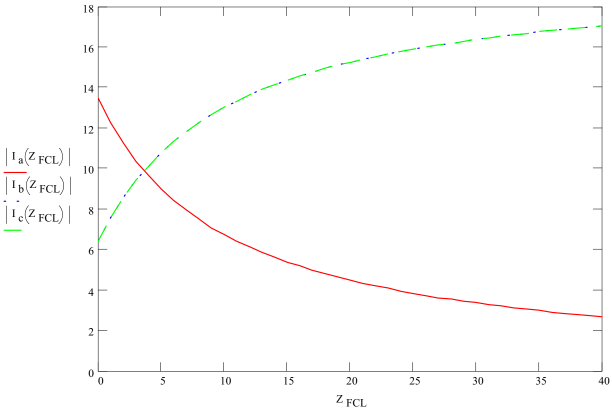

Fig. 10. One-phase-to-ground fault with inductive load

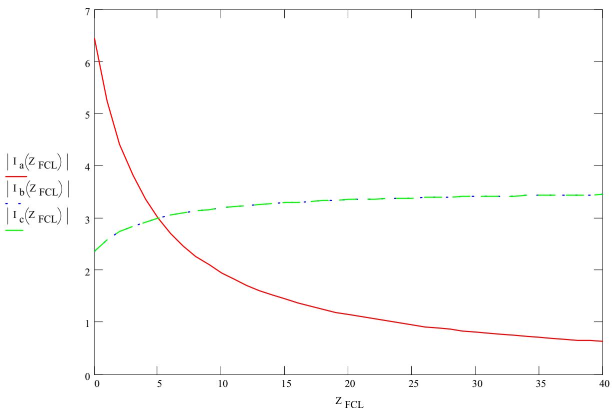

Fig. 11. One-phase-to-ground fault with capacitive load

The first three graphs demonstrate the one-phase-to-ground fault case with different loads. The current in the faulty phase has a very high value when no FCL was inserted (non-limited case) – in that point of the graph the FCL impedance is equal to zero. The RMS values of the fault currents in non-limited case are presented in the *Table 2*.

Fig. 9, *Fig. 10* and *Fig.11* show the calculated results of the three-phase currents (in RMS) versus variable FCL inductance in cases when the load is resistive, inductive and capacitive, respectively.

The next three graphs depict the overload fault case with different loads. In this case the current increases in each phase, but the limitation has been only in one phase. In 'a' phase FCL has been inserted, the 'b' and 'c' phases have no limitation.

The calculation results of the overload can be seen in the next figures when

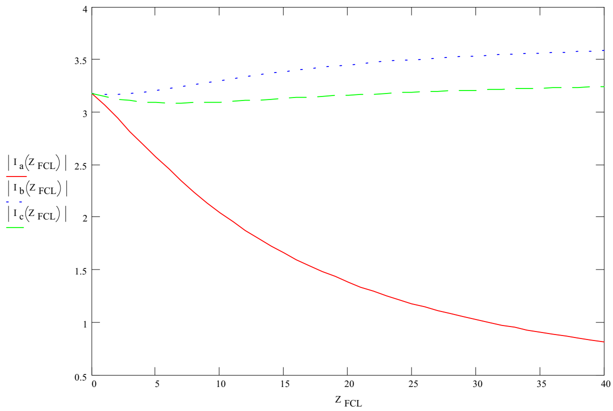

Fig. 12. The overload fault with resistive load

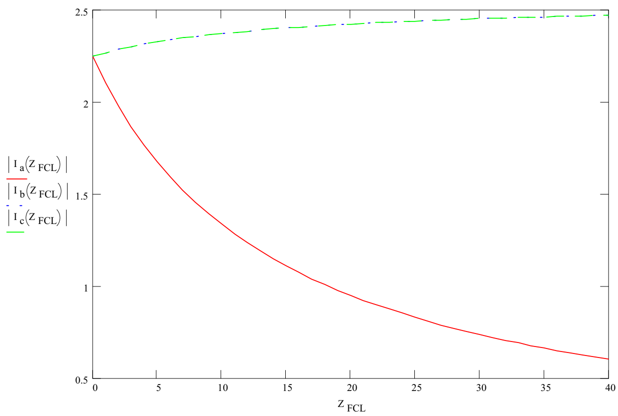

Fig. 13. The overload fault with inductive load

the load is resistive (*Fig.* 12), or inductive (*Fig.* 13), or capacitive (*Fig.* 14). The graphs show the three-phase currents (in RMS) versus the variable FCL inductance.

Fig. 14 demonstrates the resonance between the capacitive load and the system impedance.

4.1. *FCL Measurements in the Real System*

The FCL can be inserted into the real system. In our case we tested the current limiting operation of the experimental FCL in a special 12 kVA three-phase generator–FCL–loads system as it can be seen in the photos (*Fig.*3).

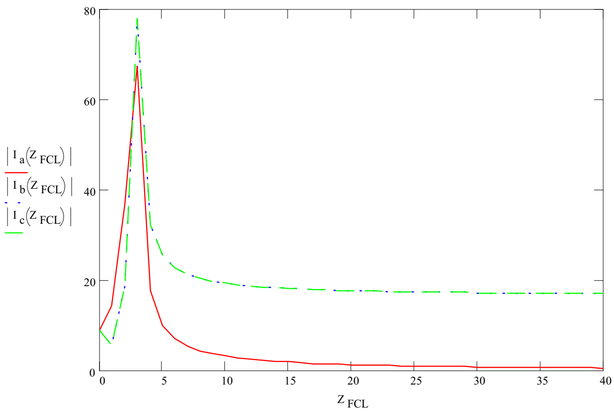

Fig. 14. The overload fault with capacitive load

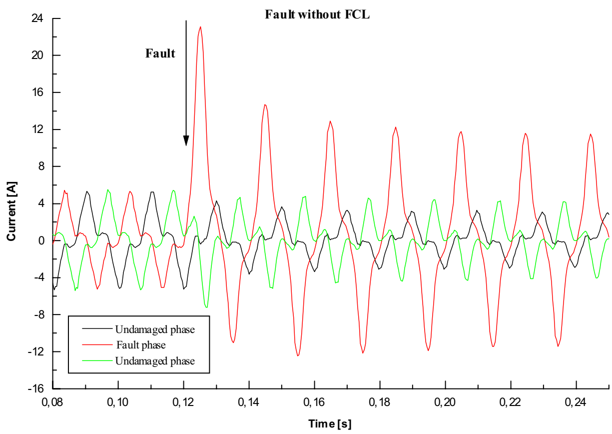

Fig. 15. The fault currents without FCL in the case of one-phase-to-ground fault

4.1.1. Test Results

In all of our measurements the currents in the three phases and the voltage on the FCL were measured as a function of time. In each measurement the data acquisition took place in a few periods before and during the fault event as well as for a few periods after the fault was cleared. The fault was always a sudden short-circuit fault in the phase with the FCL. The next figures show the fault current without FCL (*Fig.* 15) and with FCL in the case of one-phase-to-ground fault (*Fig.* 16).

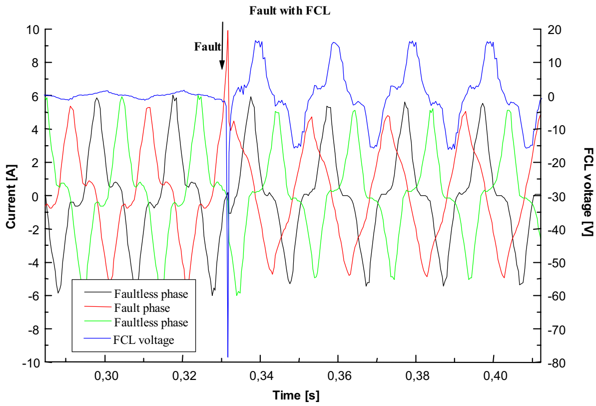

Fig. 16. One-phase-to-ground fault in a synchronous generator-FCL-load system

5. Conclusions

The inductive type FCL in a three-phase system has been successfully tested.

Calculations and tests were performed for the case of a one-phase-to-ground fault and the overload case in order to investigate the processes in the faulty and faultless phases.

The calculations showed that the fault current for the non-limited case ($Z_{FCL} = 0$) was 7.7 A. The calculated steady-state fault current peak value is 10.89 A. In the limited case the current is 3.91 A and the calculated peak value is 5.51 A. The analysis of *Fig. 9*, *Fig. 15* and *Fig. 16* reveals that the correspondence between calculated and measured values is rather good, the difference was in the range of 6%.

This simulation represents very well the operation of the fault current limiter in the different faults of the network.

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