Fault current limiting devices for a 110 kV/100 MW power network: a comparison of superconducting and conventional technologies

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Abstract

It is well known that a so-called transformer type superconducting fault current limiter (SFCL) with the primary winding connected in series to the load and the secondary one shortened by a fast-acting circuit breaker can be one of the most promising fault current limiting (FCL) devices for high-power electric networks. For a 100 MW protected circuit, the total mass of copper winding conductors may surpass 15 tons, and the heat losses in normal operation mode can be more than 200 kW, making conventionally constructed versions of these devices excessively bulky and costly. The use of high-temperature superconductors (HTSC) is therefore a potential answer that may significantly enhance the FCL's mass, geometry, and functioning. Since the magnetic field in SFCL does not exceed 0.1–0.2 T, HTSC windings may be used even with the relatively substantial AC losses that currently exist, which is not the case with other superconducting AC devices. In this work, we examine the similarities and differences between SCFL and regular FCL. The former have been found to have a mass that is an order of magnitude less than the latter, and the rate of reduction of heat losses while running normally is the same. In the next 3–5 years, we should see a levelling out in prices between the two designs.

Keywords:

Superconductor; transformer; fault current limiter; short circuit; alternating current losses; impedance.

Introduction

A series-connected transformer with a non-linear resistance in the secondary winding circuit is the foundation of the fault current limitation device. Keep in mind that any fast-acting switching device, such as superconducting commutation elements, cryotrons, fuse-links, explosive IS-limiters, etc., may make advantage of this non-linear resistance. The secondary winding circuit of the transformer is broken to achieve the fault current restriction. The impedance of a transformer in its regular working state is very close to its impedance in it short-circuit mode. However, if a fault develops in the power transmission line that is in series with the primary winding, the current in the primary winding will rise, which in turn will cause the current in the secondary winding to increase and the commutation device to function. After then, the fault current limitation in the protected load occurs [1-3] because the total impedance of the transformer approaches its value in the no-load state.

110 kV FCL designs using conventional and superconducting materials

Basic operational characteristics of the FCL are given in Table 1.

Table 1. Basic operational characteristics of the 110 kV FCL

Characteristic	Value
Rated voltage	110 kV
Current in the normal operative mode	1000 A
Relay protection system actuation current	5000 A
Relay protection system actuation time, no more than	~3 ms
Short-circuit striking current	12000 A
Relay protection system disconnection time, no more than	100 - 120 ms
Recovery time of the system	2 s
Number of subsequent relay protection system actuations	3

Striking short-circuit currents were estimated by the analysis of transient processes taking place at the fault event. In a normal operation mode (i.e., in a steady-state power network operating mode before a short-circuit occurs) the secondary winding of the FCL is shortened, and the currents of the of the primary and secondary windings, I1 and I2, respectively are determined by the following system of equations:

$$L_1 \cdot \frac{dI_1}{dt} + M \cdot \frac{dI_2}{dt} + R_1 \cdot I_1 + L_{ld} \cdot \frac{dI_1}{dt} + R_{ld} \cdot I_1 = U_0 \cdot \sin(\omega t + \varphi_0),$$
$$L_1 \cdot \frac{dI_2}{dt} + M \cdot \frac{dI_1}{dt} + R_2 \cdot I_1 = 0\,.$$

Where L1 L2, R1 R2 are the self-inductances and resistances of the primary and secondary windings, M is their mutual inductance and Lld and Rld are the self-inductance and active resistance of the load connected to the power network. Generally, there can be obtained only a numerical solution of system (1). However, since for an FCL device are valid approximate equalities L1=L2 and R1=R2 at an accuracy of 1 – 2 %, system (1) may be rewritten in a form allowing an analytical solution. Assuming I2˜ R2=- I1˜ R1 and expressing dI2/dt from (1b), we obtain:

$$(L_1 - \frac{M^2}{L_2}) \cdot \frac{dI_1}{dt} + (R_1 + R_2) \cdot I_1 + L_{ld} \cdot \frac{dI_1}{dt} + R_{ld} \cdot I_1 = U_0 \cdot \sin(\omega t + \varphi_0).$$

From (2) one can see, that in a normal operating mode an FCL is a load with an equivalent inductance Le= L1-M2 /L2 and equivalent resistance Re= R1+R. When a fault event (short-circuit) occurs there is an uncontrolled short-circuit mode instead of the previous normal one. The former can be described by (1) or by approximate equation (2) at Lld=0 and Rld=0. An analytical solution for the appropriate transient process has a form:

$$I_1 = \exp\left(-\frac{R_e}{L_e} \cdot (t - t_1)\right) \cdot \left[I_1(t_1) - \frac{U_0}{Z_e} \cdot \sin(\omega t_1 - \Delta\varphi)\right] + \frac{U_0}{Z_e} \cdot \sin(\omega t - \Delta\varphi),$$

where t1 is the start time of the short-circuit mode and I1) is the current at this time,

$$Z_e = \sqrt{(R_e^2 + \omega^2 L_e^2)}\,, \quad \Delta\varphi = \varphi - \varphi_0,\ \varphi = arctg(\omega L_e / R_e).$$

Basic parameters for a 110 kV FCL are given in Table 2.

Table 2. Comparison of various 110 kV FCL designs (each device per phase)

Parameter	Type of the FCL		
Design	With an iron core	Without an iron core	With superconducting windings
1. Secondary winding voltage, kV	35 for all three variants		
2. Winding conductor design	5 copper tapes 20×40 mm each, total cross-section 22×40 mm,		Superconducting composite 1×6mm, filling factor k_{cu}=0.45
3. Current-carrying element cross-section area	400	400	8
4. Current density in the normal operative mode, A/mm^2	2.5	2.5	125
5. Current density in the fault current limitation mode, A/mm^2	7.5	7.5	375
6. Cooling agent	Transformer oil	Transformer oil	Liquid nitrogen
7. Total impedance in the normal operative mode, Ohm	1.2	2.5	0.3
8. Total impedance in the fault current limitation mode, Ohm	32	34	39
9. Total mass of the magnetic system, tons	116+8.22	15	0.64

The calculations of the FCL were performed by the numerical integration of system (1), and the results are given in Fig. 1 and 2.

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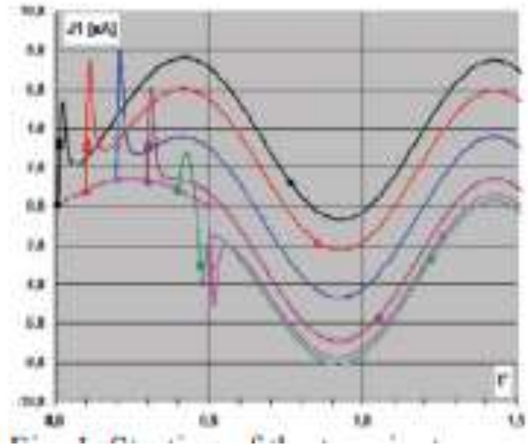
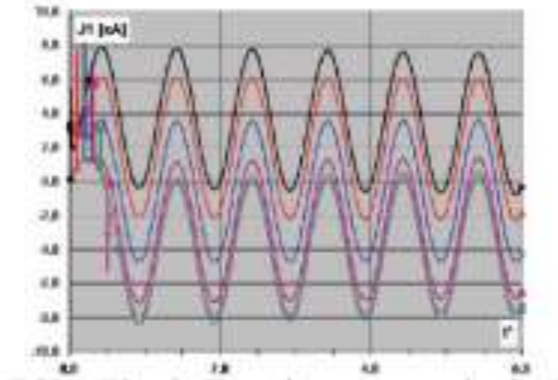


Fig. 1. Starting of the transient process in the



FCL Fig. 2. Transient process in the FCL

While there are several ways to improve the FCL's design, none of them result in appreciable reductions in copper usage or heat losses during typical operation. Using solely superconducting materials, the mentioned FCL design may be improved upon further. If superconducting windings were used in electric power devices' magnetic systems, the current density could be increased by a factor of 100 with zero Joule losses in DC mode and by a factor of 10 to 50 with lower losses at 50 to 60 hertz.

Let's use a hypothetical FCL with current-carrying components fabricated from state-of-the-art HTSC of the second generation to illustrate how this estimation works. The SGS-12050 HTSC conductor from [4] was our first choice for a prototype. It's a 12 mm x 0.0095 mm tape with a 50% filling factor and copper stabilization. The tape has a critical current density of Jc=220 A/mm2 when considering its whole cross-section area. In terms of length, the 50 Hz AC losses are

$$P_{sp}=0.4\ W/kA\cdot m.$$

The maximal piece length is 600 m with the warranted inhomogeneity of characteristics over the length 5 %. To ensure the better comparability assume the winding inner diameter and the current-carrying element design to be the same as of the normal conductor. There are two solutions of the problem what the necessary critical current value should be.

The winding has to be superconducting in a normal operative mode only. In this case at the exceeding of IH the excessive current is displaced into the copper substrate what, due to the full conductor stabilization, does not disturb the FCL performance. Additional losses in copper are not essential, since the I2 exceeding modes are assumed to have a short duration. In this case, taking into account a 20 % reliability margin, the critical current should be established as

$$I_c=1.2\cdot\sqrt{2}\cdot I_2=1.7\ kA.$$

The winding has to be superconducting up to the current at which the circuit breaker actuates. In this scenario, assuming the same reliability margin we have

$$I_c=1.2\cdot I_0=3.6\ kA.$$

Adopt the second scenario to be the most favourable, i.e.

Ice=3.6 kA. Additionally, we take into account that the conductor cross-section area is greater than that one of the prototype tapes, and, hence, the own field increases what in turn lowers the critical current density and enlarges AC-losses. In terms of this, assume these values to be worse than ones of a single tape and equal to: j.c.=150 A/mm2 ,

$$j_c=150\ A/mm^2,\ P_{SP}=0.8\ W/kA\cdot m.$$

The area of the cross section of an HTSC cable may be calculated as 212=24 mm2 using these numbers. Even though the conductor length is only cut by a factor of 1.4, its mass is cut by a factor of 20 owing to the decrease in cross-section area, and losses in the typical operating mode are cut by a factor of 100. Heat transfer efficiency at liquid nitrogen temperatures does not exceed 10%, hence this should be taken into consideration when assessing real electric energy losses. Losses are still mitigated by a factor of ten in this scenario.

Conclusions

When the SFCL winding is in its typical working state, the heat transfer power is 0.066 kW/m2 when based only on the conductor's outside surface. This cost is little when considering the winding cooling possibilities provided. In the transient mode, the copper substrate receives current that is greater than Ic. Due to the brief period of the procedure, the windings may become as hot as 5 K, depending on the conductor design. Another SFCL design may be realized, which is something to keep in mind. Current degradation happens automatically in a secondary winding consisting of a partly stabilized conductor if Ics is equal to the limiting current, as in the processes in an FCL with bulk HTSC rings examined in [5].

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