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Comparative analysis of various superconducting and non-superconducting fault current limiting devices designed for operation in a 110 kV/100 MW power network

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Abstract

As it is known one of the most promising fault current limiting (FCL) devices for high-power electric networks can be the so-called transformer type superconducting fault current limiter (SFCL) with the primary winding connected to the load in series and the secondary one shortened by a fast-acting circuit-breaker. These devices when made of conventional materials can be very large and expensive – e.g., for a 100 MW circuit under protection the total mass of copper winding conductors can exceed 15 tons and the heat losses in a normal operating mode can be more than 200 kW. Therefore, using of high-temperature superconductors (HTSC) can be a solution which can sufficiently improve the mass, geometrical and operational characteristics of an FCL. Unlike other superconducting AC devices, the magnetic field in SFCL does not exceed 0.1 – 0.2 T what allows using HTSC windings even at a comparatively high level of AC losses existing nowadays. In this paper is performed a comparative analysis of various designs of SCFL with the non-superconducting FCL. It has been shown that the former have a mass by an order of magnitude lower than the latter and the rate of lowering of heat losses in a normal operating mode is the same. The equalization of costs of both designs is expected to be reached within the nearest 3 – 5 five years.

Keywords: fault current limiter; superconductor; transformer, short-circuit, AC losses; impedance.

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1. Introduction

The basic element of the fault current limiting device is a transformer connected in series and having a non-linear resistance in the secondary winding circuit. Note that as this non-linear resistance can be used any low-impedance fast-acting switching device, e.g. superconducting commutation elements, cryotrons, fuse-links, explosive I_S-limiters etc. The fault current limitation is realized by breaking the transformer secondary winding circuit. In the normal operating mode the transformer impedance is close to that one of the short-circuit mode and is minimal. But if any fault event occurs in the power transmission line connected in series to the primary winding the current of the latter increases, what leads to the subsequent increasing of the secondary winding current and, hence, to the acting of the commutation device. Thereafter the total transformer impedance significantly increases and becomes close to that one of the no-load mode and due to that occurs the fault current limitation in the load under protection [1 – 3].

2. Designs of normal and superconducting FCL for 110 kV power systems

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, I_1 and I_2, respectively are determined by the following system of equations:

$$L_1 \cdot \frac{dI_1}{dt} + M \cdot \frac{dI_2}{dt} + R_1 \cdot I_1 + L_{ld} \cdot \frac{dI_1}{dt} + R_{ld} \cdot I_1 = U_0 \cdot \sin(\omega t + \varphi_0), \tag{1a}$$

$$L_1 \cdot \frac{dI_2}{dt} + M \cdot \frac{dI_1}{dt} + R_2 \cdot I_1 = 0\,. \qquad 1(b)$$

where L_1, L_2, R_1, R_2 are the self-inductances and resistances of the primary and secondary windings, M is their mutual inductance and L_{ld} and R_{ld} 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 $L_1=L_2$ and $R_1=R_2$ at an accuracy of 1 – 2 %, system (1) may be rewritten in a form allowing an analytical solution. Assuming $I_2{\cdot}R_2=- I_1{\cdot}R_1$ and expressing dI_2/dt from (1b), we obtain:

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

From (2) one can see, that in a normal operating mode an FCL is a load with an equivalent inductance $L_e = L_1 - M^2/L_2$ and equivalent resistance $R_e = R_1 + R$. 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 $L_{ld}=0$ and $R_{ld}=0$. An analytical solution for the appropriate transient process has a form:

$$I_1 = \exp\left(-\frac{R_e}{L_e}\cdot(t-t_1)\right)\cdot\left[I_1(t_1) - \frac{U_0}{Z_e}\cdot\sin(\omega t_1 - \Delta\varphi)\right] + \frac{U_0}{Z_e}\cdot\sin(\omega t - \Delta\varphi), \tag{3}$$

where t_1 is the start time of the short-circuit mode and $I_1)$ is the current at this time, $Z_e = \sqrt{(R_e^2 + \omega^2 L_e^2)}$, $\Delta\varphi = \varphi - \varphi_0$, $\varphi = arctg(\omega L_e/R_e)$. 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 1×8mm, 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.

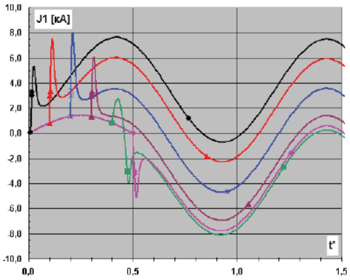

Fig. 1. Starting of the transient process in the FCL

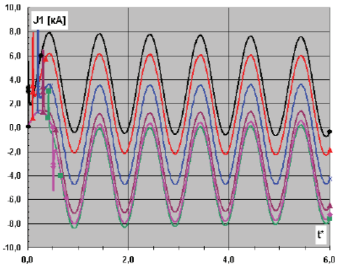

Fig. 2. Transient process in the FCL

Unfortunately, all the opportunities of the FCL design enhancement do not allow significant lowering of copper consumption and decreasing of heat losses in the normal operative mode. Further improvement of the FCL design described is possible when using superconducting materials only.

Using of superconducting windings in various magnetic systems of electric power devices would allow an approximate 100 times current density increasing at simultaneous zero Joule losses in DC mode and 10 – 50 times decreasing of them at 50 – 60 Hz.

As an example let us estimate possible characteristics of FCL with current-carrying elements made of modern HTSC of the second generation. As a prototype we choose the HTSC conductor SGS-12050 produced by [4]. It is a 12×0.0095 mm tape totally stabilized by copper with the filling factor 50 %. The critical current density of the tape calculated over its whole cross-section area is $J_c=220\ A/mm^2$. AC-losses at 50 Hz per unit of length 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. A) The winding has to be superconducting in a normal operative mode only. In this case at the exceeding of I_H 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 I_2 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 $I_c=1.2\cdot\sqrt{2}\cdot I_2=1.7\ kA$. B) 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 favorable, i.e. $I_c=3.6\ kA$. Additionally, we take into account that the conductor cross-section area is greater than that one of the prototype tape, 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: $j_c=150\ A/mm^2$, $P_{SP}=0.8\ W/kA{\cdot}m$. Based upon these values consider the HTSC cable cross-section area to be 2×12=24 mm^2. In this case, though the conductor length is reduced in 1.4 times only, its mass due to the cross-section area reduction is 20 times, and losses in the normal operative mode are 100 times lower. When estimating actual electric energy losses it should be taken into account that the heat transfer efficiency at the liquid nitrogen temperature does not exceed 10 %. However, even in this case the losses reduce by an order of magnitude.

3. Conclusions

In the normal operating mode the heat transfer power calculated only from the conductor’s outer surface in the SFCL winding is 0.066 kW/m^2. At the available opportunities of the winding cooling this value is negligible. In the transient mode a part of current exceeding I_c flows through the copper substrate. In this case the winding heating depends upon the conductor design but does not exceed 5 K due to the short duration of the process. It should be additionally noted that there is an opportunity to realize another SFCL design. If the secondary winding is made of a partially stabilized conductor with I_{cs} equal to the limitation current, the current decay in it occurs automatically, what is similar to the processes in a FCL with bulk HTSC rings considered in [5].

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