Study on the Alliance between SFCL and Hybrid DC Circuit Breaker for Protecting HVDC Grid

Yacine AYACHI AMOR¹, Gaëtan DIDIER², Jean LEVEQUE² and Farid HAMOUDI¹

¹Laboratoire de Maîtrise des Energies Renouvelables (LMER), Faculté de Technologie, Université de Bejaia, Algeria.
²Groupe de Recherche en Énergie Electrique de Nancy (GREEN), Faculté des Sciences et Technologies Université de Lorraine, 54506 Vandoeuvre-lès-Nancy, France.

E-mail: yacineayachiamor@gmail.com

Abstract. Breaking the DC fault in HVDC grid is the greatest challenge for DC grid protection system. Although there are many scientific researches investigating the high voltage DC breakers, yet, there is still always a trade-off between the interruption time and the breaking capability. Therefore, combining between the superconducting fault current limiter (SFCL) technology with a fast DC circuit breaker could bring a solution to this limitation. In this work, an accurate model of resistive-type SFCL (r-SFCL) considering the electro-thermal behaviour, is proposed to be placed in series with ABB proactive hybrid DC circuit breaker (PHCB). To test the viability of the system, a pole-to-pole DC fault scenario was imposed in a HVDC grid. The numerical analysis was undertaken with (EMTP-RV®) software, while the simulation results show how effectively the SFCL can reduce the fault current below the maximum breaking capability. Also, it is concluded that there is a positive interaction between the r-SFCL and PHCB.

1. Introduction
The high voltage direct current (HVDC) transmission systems using voltage source converter (VSC) offer great potential for long-distance bulk power delivery [1]. However, the key obstacle of implementing a reliable HVDC grid is the lack of existing commercial protection devices that can withstand the huge rise of the DC fault current and isolate it completely from the grid. The DC fault current rises rapidly and surges tenfold within several milliseconds over the whole system, mostly this is due to three main causes: no zero-crossing point in the DC current, low DC side impedance, and huge discharge of the DC-side capacitors [2].

Recently, the DC breaker developed by ABB can cut off a 16 kA fault current within 2 ms while its rated voltage is 320 kV [3], and Alstom has developed a DC breaker that can cut off a 7.5 kA fault current within 1.6 ms while the rated voltage is 120 kV [4]. However, the rated ultimate breaking capacity is limited, which will not meet the requirement of constant increase in short circuit current level.

To this, the Superconducting Fault Current Limiter (SFCL) technology could bring a solution to this main bottleneck by offering a huge reduction of the DC fault current and can handle the substantial amounts of energy dissipated of the circuit breaker during the interruption process.
A few published papers are limited to the fault current behaviour and focused on the evolution of the impedance values without considering the thermal behaviour and the recovery characteristics of the r-SFCL, which is very likely to lead to a wrong transient response [5][6][7]. Energy dissipation of the circuit breaker is also a crucial design parameter that should be evaluated to determine the breaking capability of the circuit breaker [8].

In this work, the new generation of SFCL, called the second-generation high-temperature superconductor 2G HTS yttrium barium copper oxide (YBCO) coated conductors, have been accurately modelled considering both the electrical and thermal behavior, and the SFCL is proposed to work together with ABB proactive hybrid DC circuit breaker (PHCB) for fulfilling the HVDC grid safety. The whole system is carried out using Electro-Magnetic Transient Program (EMTP-RV®) software.

The paper is organized as follows: Section 2 explains the test-bed of the HVDC grid while section 3 is devoted to demonstrating in details the model of the proposed protection system that is r-SFCL in series with PHCB. Then, section 4 illustrates the discussion results and the conclusion is given in section 5.

2. HVDC Grid
The HVDC link test model is exhibited on figure 1. All the parameters are on the figure. The system has 2 stations, each station modelled by a three-phase voltage source in series with a short-circuit impedance, Modular Multilevel Converter (MMC) which is made up of 400 half-bridge sub-modules per arm, and finally the proposed protection system which is the main focus of this work and it will be explained in details in the next section.

The grid is used to operate in steady-state, where station 2 is representing the offshore wind energy feeding an onshore AC grid (station 1) through an HVDC cable. That cable is based on the bipolar underground transmission cables with a wideband modelling approach, where the cable data was taken from France-Spain HVDC link (the model is available in EMTP-RV®) [9].

![Figure 1. Schematic diagram of HVDC grid.](image)

3. Protection System

3.1. Resistive type superconducting fault current limiter electro-thermal model
The r-SFCL model used in simulations is based on the HTS coated conductor most often called HTS tape. Those tapes are based on the architecture illustrated in figure 2, i.e. a stack of buffer layer (oxides), and a superconducting layer, e.g. (RE)BCO, deposited on a mechanically strong metallic substrate (stainless steel and Hastelloy).

![Figure 2. HTS tape architecture.](image)
3.1.1. Electrical model. Each layer of the HTS tape can be modeled by a nonlinear resistance that depends on current $I$ and/or temperature $T$, 

$$R_{el}(J, T) = \frac{\rho(J, T)}{A} L \tag{1}$$

where $\rho(J, T)$ is the resistivity of the considered material ((RE)BCO, silver or Hastelloy), $L$ is the length of the tape and $A$ is its longitudinal cross-section. The current density $J$ is given by $J = I/A$ where $I$ represents the total current flowing through $R_{el}$. Except for the superconducting tape, the properties of all materials constituting HTS tape depend only on $T$ [10][11].

The resistivity of the superconducting layer is calculated by the well-known power law characteristics for the electrical field, i.e.

$$\rho_s(J, T) = \frac{E_c}{J_c(T)} \left( \frac{|J|}{J_c(T)} \right)^{n-1} \tag{2}$$

where $E_c$ is the electrical field criterion used to define the critical current density of the (RE)BCO superconductor $J_c$, and $n$ is the power law exponent.

The temperature dependence of $J_c$ can be evaluated by

$$J_c(T) = J_{c0} \left( \frac{T_c - T}{T_c - T_0} \right) \tag{3}$$

where $T_0$ is the temperature of liquid nitrogen bath, $T_c$ is the critical temperature of the (RE)BCO superconductor, and $J_{c0}$ is the critical current density in self-magnetic field at $T = T_0$.

The material parameters used for the superconductor are given in table 1 and the corresponding resistivity curves are illustrated in figure 3.

**Table 1: Parameters of the (RE)BCO superconductor**

| Parameters | Value         | Description                  |
|------------|---------------|------------------------------|
| $E_c$      | 1 $\mu$V cm$^{-1}$ | Critical electrical field criterion |
| $J_{c0}$   | 2.5 MA cm$^{-2}$ | Self-field critical current density |
| $n$        | 15 [12]       | Power law exponent           |
| $\rho_{Tc}$| 30 $\mu$Ω cm [13] | Normal state resistance at $T_c$ |
| $\alpha$  | 0.47 $\mu$Ω cm$^{-1}$ [13] | Temperature coefficient  |
| $T_c$      | 90 K          | Critical temperature         |
| $T_0$      | 77 K          | Temperature of the LN$_2$ bath |

**Figure 3.** (RE)BCO resistivity $\rho_{sc}(J, T)$ near the superconducting to normal operation transition occurring in the high electric field region ($E > 0.1$ Vcm$^{-1}$).
3.1.2. **Thermal model.** Taking into account the evolution of the temperature during the transition of the tape is crucial for achieving reliable simulations. As the model is developed in a power system environment (EMTP-RV), the simplest approach is to express the thermal model in terms of electric circuit elements by the use of “thermal to electrical” analogy [14].

To evaluate this mean temperature, the Joules losses $Q_j$ in each layer $j$ are computed by

$$Q_j(I, T) = R_{el}(I_j, T)I_j^2$$

(4)

The general thermal equation can be rewritten as a lumped model with average temperature $T$ and heat capacity $C_{th}$ by the use of the following equation

$$C_{th}(T) \frac{dT}{dt} = Q - Q_c = \sum_{j=1}^{n} Q_j(I_j, T) - Q_c(\Delta T)$$

(5)

where $Q - Q_c$ is the total internal heat gains minus the heat evacuated through convection noted $Q_c$. The cooling power $Q_c$ is evaluated by the use of the nonlinear Newton law $Q_c = h(T_s - T_0)S(T_s - T_0)$ where $T_s$ is the surface temperature of the tape (equal to the mean temperature $T$ in this model), $T_0$ is the cryogenic bath temperature considered equal to 77K (LN$_2$ bath), $S$ is the transverse cross section and $h(T_s - T_0)$ is an effective nonlinear steady state coefficient, expressed in W.K$^{-1}$m$^{-2}$. With equations (4) and (5), the evolution of the temperature $T(t)$ can be compute for a given current $I(t)$ imposed in the r-SFCL.

3.2. **Proactive hybrid DC circuit breaker model**

The proactive hybrid DC circuit breaker (PHCB) is innovated and developed by ABB [3]. Figure 4 shows the structure of the PHCB. This circuit breaker is a combination of mechanical switches and semiconductor switches. It is shown that the circuit breaker has two parallel branches: The primary branch consist of an Ultra-Fast Disconnector (UFD) in series with a group of semiconductor switches known as the Load Commutation Switch (LCS). The secondary branch is the main DC breaker, consisting of a string of semiconductor switches connected in parallel groups with a large bank of varistors that used to limit the transient recovery voltage (TRV).

![Figure 4](image-url)

**Figure 4.** Schematic diagram of the proposed protection system (r-SFCL in series with PHCB).

During normal operation, LCS and UFD are closed and conducting the nominal current whereas the main breaker is open. When the fault is detected, the LCS is turned off and the LCS’s snubber circuit charges [15] and produces a voltage to commutate the current from the primary branch into the main breaker. Once the current is fully commutated to the main breaker, the UFD will open effortlessly with minimum arc. Now, when the main breaker is switched off to break the fault current, a TRV appears across the circuit breaker, which is limited by the surge arresters. This latter must be rated to deal with the peak of TRV.
4. Simulation Results & discussion

In order to validate the performance of the proposed protection system, a pole to pole DC fault is imposed with a low impedance of 0.1 Ω at the endpoint HVDC cable close to station 1 (see figure 1). This type of fault is considered as the worst scenario case that could be occurred: the fault appears at t=1s and vanish at 1.1s.

Figure 5 shows that the current is successfully interrupted within 5 ms, while the breaking current capability kept below the maximum breaking current capability of the PHCB when the r-SFCL is applied. It is observed from the figure that the fault interruption time is reduced by 0.5 ms when the r-SFCL is applied. This is due to the fact that the interruption time of the circuit breaker depends on the current density that flows into it. If the current density is larger, the energy dissipated in its surge arrester bank is greater and consequently requires more time to make zero current.

![Figure 5. Positive pole current of the station 1 (I1p).](image)

Figure 6 demonstrates the station 1 voltage behavior: during the interruption time different peaks appear in the DC grid voltage. The first peak is the transient voltage peak due to the sudden increase of r-SFCL resistance. The second peak appears at 2 ms when the fault current is fully commutated to the main breaker and the UFD is opened. The third peak occurred when the PHCB is fully interrupted the fault current and it is called transient recovery voltage.

It is clear from the zoomed part of the figure that all peaks didn't exceed 1.6 p.u of the nominal voltage in the presence of r-SFCL, assuming that the peak transient overvoltage on the system is 2 p.u [15].

![Figure 6. Station 1 voltage (Vdc1).](image)

To see the behavior of the faulty current through the PHCB, the current flowing in each branch has been sensed individually as shown in the figure 7.
From the figure it is shown that, in the normal operation the majority of the current flows in the primary branch, and the current in the main breaker is zero. Once the fault occurs, the current keep flowing in the primary branch, at 2 ms the LCS is triggered and the current is fully commutated from the primary branch to the main breaker. Once the current in the primary branch has reached zero, the UFD is opened. With the mechanical switch in open position, the main breaker interrupts the current.

**Figure 7.** Station 1 current flowing in both branches of PHCB\(_{1\text{p}}\).

4.1. The influence of PHCB on the r-SFCL performance

The thermal behaviour of SFCLs located on the positive pole of station 1 (SFCL\(_{1\text{p}}\)) was measured assuming homogeneous quenching of the tape. The test was carried out with and without PHCB. It is noticed from figure 8 that for all cases the maximum admissible temperature (350 K) is respected. For the case where the PHCB is not applied (blue curve), the r-SFCL quenches almost instantaneously when the fault occurs and the temperature starts to increase until reaching 206 K at 1.1 s, which is the time when the fault disappears. After that, the SFCL\(_{1\text{p}}\) starts to recover and, for this case, the SFCL recovery is not seen because it has a much longer time constant.

When the PHCB is applied, the maximum temperature of SFCL\(_{1\text{p}}\) reaches 107 K when the fault cleared at 4.5 ms (red curve), then the temperature recovers in 60 ms.

From the cost investment point of view, reference [16] represents an economic visibility of the r-SFCL and gives some hypotheses on the cryogenic system and cryostat sizing. The authors emphasize the cost evaluation of the r-SFCL with respect to the circuit breaker clearing time. It is found that the faster the DCCB can clear the fault, the lower the investment cost. For example, the total investment cost of 2G HTS r-SFCL 77 K is about 1.7 M€ for clearing time equals to 5 ms, while it is about 3.1 M€ for clearing time equals to 100 ms.

**Figure 8.** SFCL\(_{1\text{p}}\) thermal behaviour.
4.2. The influence of r-SFCL on the PHCB performance
In order to visualize the impact of the r-SFCL on the PHCB, the dissipated energy in the main breaker is calculated using equation (6).

\[ E_{dissipated} = \int P \, dt = \int V_{arrester} \, I_{main \, breaker} \, dt \] (6)

Figure 9 shows the dissipated energy in the PHCB surge arresters for both cases with and without r-SFCL. The highest energy dissipation was observed in the surge arresters when the circuit breaker operates without SFCL was calculated as 49 kJ. With the contribution of the r-SFCL, the dissipated energy dramatically reduced down to 17 kJ, and therefore the PHCB with r-SFCL showed the best performance with a 65.3% energy reduction. As the energy dissipation reduces, the sizing and the dimensioning of the surge arrester bank is reduced as well, and correspondingly leads to a lower cost investment.

![Figure 9. PHCB1p surge energy dissipation.](image)

5. Conclusion
In this work, an electro-thermal model of the 2G HTS resistive type superconducting fault current limiter (r-SFCL) is applied in HVDC grid considering the fast protection system proactive hybrid DC circuit breaker (PHCB). The analysis was validated with a time-domain simulation using EMTP software and the results show that the fault current could be reduced up to 70%, a value that facilitate the breaking capability of the PHCB.

It is concluded that there is a positive interaction between the r-SFCL and PHCB. On one hand, the time duration for fault clearance has an effect on the quenching temperature of SFCL. It is therefore a shorter fault clearance that implies a reduced recovery time and lower cost investment for the cooling system. On the other hand, with the help of r-SFCL, there is a remarkable reduction in the energy rating of the surge arresters, which implies lower sizing, hence lower cost also.

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