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Superconducting Fault Current Limiter for Ship Grid Simulation and Demonstration

P. Tixador Pascal, A. Badel, G. Auran, and G. Santos Pereira

Abstract—The strong growth of electrical power on ships leads to modifications and optimizations of their electrical grid, from their architecture to their components. An emerging architecture is the dc grid, which outperforms the ac solution. Security and protection are two major concerns on a ship. Even with controllable static converters, fault currents may be very high. For security reasons there are in general a port grid and a starboard grid. They are not connected in normal operation: a fault (short-circuit) on one grid must have no influence on the other grid to avoid a total blackout. On the other side, a coupling between the two grids brings many advantages through mutualisation and a stronger grid. This coupling is possible using a superconducting fault current limiter (SCFCL). A SCFCL between the two ship grids appears as a promising solution to take benefit of the coupling under normal operation and the decoupling under a fault case. Simulations have been carried out using EMTP-RV to study the operation and the advantages of such SCFCL implementation, with consequences in terms of safety in addition to protection. These simulations show that the healthy grid does not nearly see the short-circuited one. The voltage of the dc bus only experiences a little transient drop (lower than 10%), whereas the ac voltage supplies for the propulsion motors are not affected at all. A demonstrator has been developed. It uses SuperOx REBCO pancakes. The rating is 500 A–800 V at 77 K using two 12-mm-wide tapes in parallel. The design of the demonstrator, of its SC element (design of the REBCO tape shunt) in particular and preliminary tests are presented in ac conditions but at temperatures higher than 77 K to fit the laboratory limited testing capacities.

Index Terms—Superconducting fault current limiter (SCFCL), ship grid, grid coupling.

I. INTRODUCTION

THE electrical energy has increased a lot in ships and became the first energy vector on board with the concept in particular of “all electric ship” including electric propulsion. This concerns the civil but also the military ships. They have specific demands in particular large pulse powers (electric weapons, electric launchers . . .). The DC marine grid brings a lot of opportunities and flexibility compared to the conventional AC one [1], [2]. With a DC grid the rotation speed of generators is, for example, no more fixed and the efficiency of

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the driving system (engine fuel for example) increases a lot at reduced loads.

DC grid is easily compatible with storage (batteries, capacitors, SMES . . .) and renewable sources (solar panels . . .). The today configuration mainly deals with a DC voltage bus with multi level converters using IGBT or IGCT. These converters may operate with an optimal power factor (one).

But DC grids also show some challenges. High fault DC currents are extremely difficult to cut: they do not cross zero. No practical HVDC breaker really exists [3]. By strongly lowering the currents to cut, SCFCL makes their interruption much easier and possible with today switching technology.

II. STUDIED MARINE GRID

A. Description of the Grid

Fig. 1 shows the marine grid studied using EMTP-RV [4]. EMTP-RV is dedicated to simulate and analyze power system transients. The studied grid is classical and simplified with the port and starboard grids. Each grid is composed by a 20 MVA generator represented here by a three phase voltage ideal source, which supply the ± 5 kV DC bus through a rectifier. One propulsion motor is connected on each grid through an inverter. It is represented here by a simple load (16 MW, 12 Mvar). The innovative element of this grid is the coupling of the port and starboard grids through a SCFCL. Due to the buses +5 kV and –5 kV two FCLs are required. The SC length is the same compared to a 10 kV grid but it unfortunately doubles the number of current leads. A switch can bypass each SCFCL (not represented).

In conventional configuration the two grids are never permanently coupled to keep a grid operational in case of a fault (short-circuit) on the other grid. The coupling of the two grids makes power-sharing possible, brings redundancy, possible re-configurations and improved availability. At half load the ship may use only one generator at full load when its efficiency is maximum. But this coupling is only possible with a device, which very quickly “isolates” the healthy grid from the faulty grid to be able to operate. This device can be a SCFCL as we will show. This bus tie coupling is already a classical location in AC grids [5], [6]. References [7]–[9] present SCFCL for ship electric AC grid and for marine battery protection. DC operation suits very well to superconductors since it does not show AC losses except due to current ripples. These remain low with multilevel converters. The use of a SCFCL, which reduces a lot the current amplitude makes the current interruption much easier all the more it is difficult to cut (no natural zero crossing).

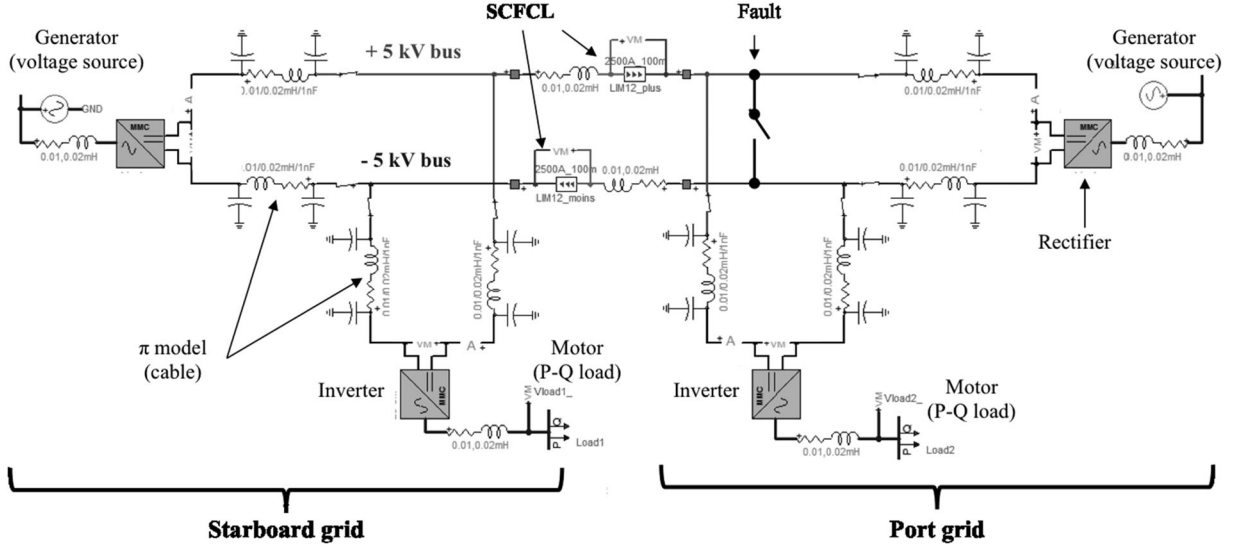


Fig. 1. Studied electrical marine grid with the port and starboard grids coupled through the SCFCLs.

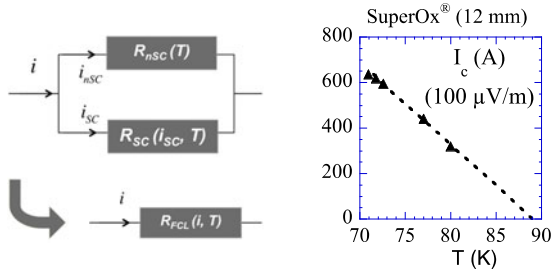


Fig. 2. Equivalent electric diagram of the SC block, $I_c(T)$ for a REBCO tape.

The cables are represented by π model (see Fig. 1). Rather complex EMTP-RV models simulate the power converters.

B. Model of the SCFCL

The SCFCL is at first modeled by a resistance ($R_{FCL}(i, T)$) [10], which depends on the current (i) under the critical temperature (T_c) and temperature (T). R_{FCL} is proportional to the length of the SC element (L_{SC}). This is the resistance of a single isothermal block. Its electrical diagram is two resistances in parallel R_{SC} and R_{nSC} (see Fig. 2). The resistance ($R_{nSC}(T)$), represents all the resistive materials (substrate, shunt . . .) in parallel with the SC layer. It only depends on the temperature. The resistance R_{SC} represents the SC layer. Its expression under the critical temperature (T_c) is:

$$T < T_c \quad R_{SC} = \frac{E_c}{I_c(T)} \left(\frac{|i_{SC}|}{I_c(T)} \right)^{n(T)-1} L_{SC}$$

I_c : critical current (electric field criterion E_c (100 $\mu\text{V/m}$)).

n : resistive transition index.

It requires the current through the SC layer (i_{SC}). It is calculated from the total current (i) by solving circuit equations. I_c is supposed to decrease linearly up to T_c ($T_c = 89$ K) in good agreement with measurements (see Fig. 2). Above T_c the SC

block is represented by only the tape resistance (R_{tape}). R_{tape} only depends on the temperature. The measurement of this resistance per unit length above T_c gives more accurate values than its calculation from the resistivities and the thicknesses.

The temperature is calculated by solving the thermal equation in adiabatic conditions, justifiable under limitation:

$$R_{FCL}(i, T) i(t)^2 = c_p(T) A_{FCL} L_{FCL} \frac{dT}{dt}$$

c_p is the specific heat per unit volume. We have considered the c_p of Hastelloy [11], 95% of the total volume. L_{FCL} and A_{FCL} are respectively the length and the total area of the SCFCL (several tapes in parallel).

This simple model of the SCFCL suits well for faults with high prospective currents, but it is not sufficient for low prospective current faults. The distribution of the critical current along the SCFCL plays then an important part. This can be taken into account by modeling the SCFCL by several blocks in series with different critical currents [12]. F. Sirois *et al.* [13] have developed still a more advanced model for EMTP-RV.

C. SCFCL Design

For the SC element we considered the experimental data ($R_{\text{tape}}(T > T_c)$) of the Y-Ba-Cu-O tape used for the Eccoflow project [14] and operating at 77 K ($I_c = 320$ A/cm-w). The bare tape is about 105 μm thick (100 μm Hastelloy substrate, 4 μm Ag). Other tape optimizations could be performed but it would not change the main results and conclusions.

The length L_{FCL} is determined to reach 350 K when the SC element is cleared. The clearing time (Δt) is 80 ms so the length is 100 m for each SCFCL (50 V/m). The total width of the wire (w_{FCL}) is given by the critical current divided by the critical current per unit width ($I_c = 320$ A/cm-w). The rated current of each grid is 2 kA (20 MW, 10 kV). We have considered the case where the generator of one grid must supply the engine of the other grid at full load. The current through the SCFCL

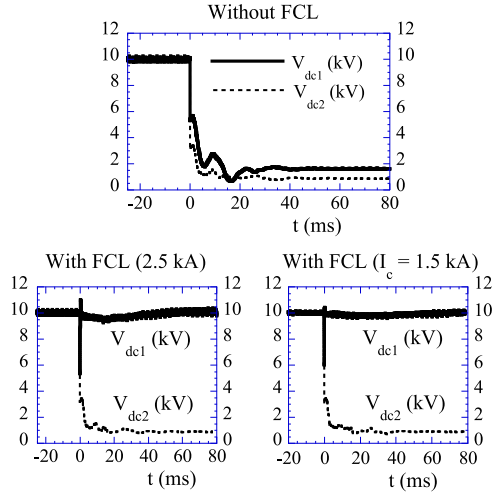


Fig. 3. Generator rectifier output voltages without (upper) and with SCFCL ($I_c = 2.5$ kA/1.5 kA) (below) for a short circuit on the port grid.

is then 2 kA and its critical current is 2.5 kA (0.5 kA margin, $w_{FCL} = 78$ mm). However in that case the limitation function is not absolutely required and the SCFCL may be then bypassed by a switch. We have also considered the case when a single generator supplies the two engines at half load. The limitation function should be then guaranteed but with a current capacity of the SCFCL of 1 kA. With the same 0.5 kA current margin the critical current is then 1.5 kA ($w_{FCL} = 47$ mm). A lower critical current reduces the cost of the SCFCL and reinforces the limitation (higher resistance). It has a beneficial effect on the current lead losses, the main thermal load especially for a DC SCFCL (400 W for 2 kA, 200 W for 1 kA (50 W/kA for a current lead)). These losses with the connections losses will be the main contributions to the total losses. The AC losses due to the current ripples will be fully negligible [15].

In AC the inductance of the SCFCL should be minimized to limit the voltage drop under normal operation. In DC this constraint disappears and the SC length can be arranged on the contrary to have a rather high inductance. Of course this means a magnetic flux density so a possible reduction of the tape I_c and an increase of the tape number. The EMC (ElectroMagnetic Compatibility) should be also studied.

III. SIMULATIONS

Fig. 3 shows the voltages at the generators rectifiers outputs in case of a short circuit between the DC buses on the port grid (see Fig. 1) with and without the SCFCL for the two I_c values (2.5 and 1.5 kA).

This illustrates the very effective SCFCL “isolation” effect of the fault on the port grid: the DC voltage only see a little and transient voltage drop. The voltage on the engine side even experiences no variation (see Fig. 4). Of course the voltage drop is lower with smaller I_c value and becomes nearly negligible.

Fig. 5 shows that the SCFCL is very effective to limit the current in the bus tie coupling. Without SCFCL the peak current oversteps 100 kA but is limited to 12 kA with a SCFCL. The current is less than 4 kA after 4 ms. Without FCL the fault current

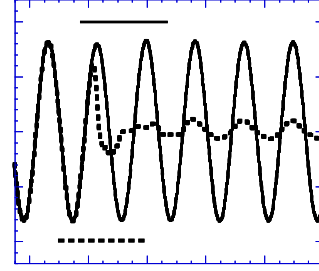


Fig. 4. AC load voltages (kV, phase a) on the starboard grid without and with SCFCL ($I_c = 2.5$ kA) for a clear short circuit on the port grid.

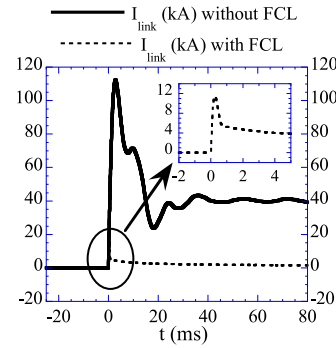


Fig. 5. Clear short-circuit current on the link between the two grids without and with SCFCL; zoom of the current with SCFCL ($I_c = 2.5$ kA).

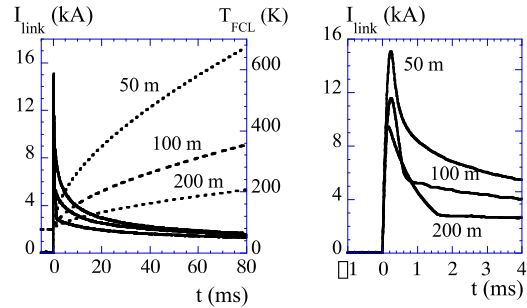


Fig. 6. Current through the link and SCFCL temperature for different lengths of each SCFCL (one SCFCL per bus, 100 m rated length).

stabilizes at 40 kA. This strong current reduction facilitates its interruption. The fault current depends only a little on the capacitance of the cables (see Fig. 1).

We have also studied faults with low prospective currents. These faults also have no consequence for the operation of the healthy grid: the load voltage amplitude only sees little perturbation.

We have investigated the effect of the SC length (L_{SC}). Fig. 6 shows the current and temperature time evolutions for three different lengths of each SCFCL (50 m, 100 m (rated length) and 200 m) in case of a fault on one grid. A longer length decreases the peak fault current, but above all the temperature. The break in slope for the current time evolution is when the temperature reaches about T_c . Similar behaviors have been experimentally recorded. A length of 50 m is definitely too short since the

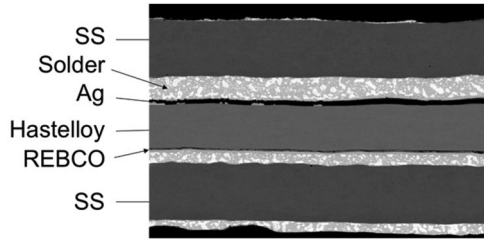


Fig. 7. Cross section of the REBCO conductor used for the demonstrator.

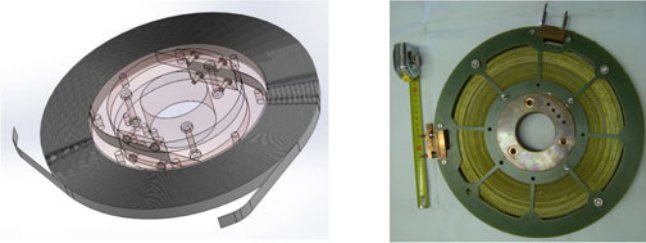


Fig. 8. 3-D drawing of one pancake and one realized pancake.

temperature oversteps 650 K. With 100 m the temperature reaches 350 K when the fault is cleared as designed.

We have studied other faults such as DC bus-earth fault, on the AC side and a short circuit of a rectifier branch. In all the cases the SCFCL has fulfilled its function.

IV. DEMONSTRATOR

We have designed and built a SCFCL demonstrator based on two pancakes (800 V/about 500 A) operating at 77 K in order to investigate several options in terms of currents and voltages but also in terms of inductances. Indeed whereas the inductance of the SCFCL should be minimized in AC to lower the voltage drop, a SCFCL with an inductance can be interesting in some cases in DC. The current rise and maximum amplitude are lowered. Nevertheless the current is more difficult to cut since the magnetic energy has to be dissipated. Because of these different configurations the rated current is not known accurately (about 500 A) since the magnetic field amplitude and orientation vary in function of the configuration.

The pancakes use REBCO conductor 12 mm wide from SuperOx company [16] with a Hastelloy substrate of 60 μm . Two stainless steel laminations 75 μm thick are welded (see Fig. 7). The tape design can be found in [12]. The 300 K resistance per unit length is about 87 m Ω /m. With this design the electric field reaches 44 V/m for a clearing time of 50 ms. The very thin polyimide isolation is favorable for short recovery. Its critical current is 450 A (± 10 A) at 77 K, self-field (100 $\mu\text{m}/\text{m}$ criterion, Fig. 2).

Fig. 8 shows a 3-D drawing of a pancake and a realization. The pancakes uses two 18 m long SC conductor fixed on the central Cu piece. There are two external contacts. The two conductors are separated by a special spacer developed by KIT to optimize the cooling in the context of the Ecoflow project [14]. The flanges are widely perforated to improve the cooling. This design makes possible to study different connection configurations for

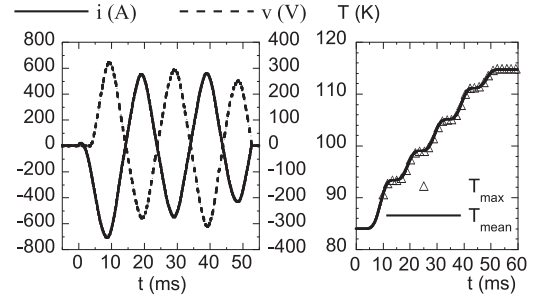


Fig. 9. Short-circuit test at 84 K, current and voltage versus time.

several pancakes (series or parallel, more or less inductance). For each pancake the conductors are connected in parallel.

The tests have been carried out in the laboratory but the power is limited. We kept the rated voltage but reduced the critical current. For that we increased the pressure on the bath and we tested only one conductor. First measurements at 84 K showed that the triggering current is about 200 A, in agreement with the I_c (T) plot (see Fig. 2).

Fig. 9 shows the test of an asymmetrical short-circuit at 84 K (no-load voltage of 800 V_{rms}). Our low short-circuit power led to only 300 V across the SCFCL but this represents a low prospective current fault, which is often the most severe for the tape [10]. The pancake quenched with a peak current of 720 A and a triggering current of 200 A, in agreement with other results. The maximum power and total energy dissipated in this test reached 230 kW and 3.7 kJ. The calculations of maximum and mean temperatures (see Fig. 9) show that the quench is homogeneous [17].

V. CONCLUSION

A SCFCL makes possible to couple the two port and starboard marine grids for a better and more efficient overall operation. It perfectly fulfills its function of quick and natural isolation of the two grids in case of fault: the healthy grid is little affected by the fault. Low prospective faults should be investigated using an improved model (multi block).

We have designed SC pancakes to investigate several configurations. They have successfully passed the first low power tests and should be tested in real DC conditions.

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