European Union Project FASTGRID

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Abstract

HVDC (High Voltage Direct Current) super-grids are one attractive solution for the transmission of bulk power of renewable electricity over long distances. Their protection is still an issue and Superconducting Fault Current Limiters (SCFCL) offer attractive perspectives. However, the actual superconducting tapes are not yet properly designed for operation at high voltages (> 100 kV): the electric field developed during the current limitation is still too low (approx. 50 V/m for 50 ms) and the limiter requires too long lengths of tape. The European project FASTGRID aims at improving the properties of the REBCO tapes to enhance significantly (by 2 to 3 times) the electric field limit and so the economical attractiveness of SCFCL. We use advanced THEVA tapes. Substantial improvements are also planned on the stabilizer (shunt) layer. Several shunt ways are under investigations. Other improvement on the tape properties will be carried out, namely the increase of the normal zone propagation velocity by at least one order of magnitude, with the help of the innovative Current Flow Diverter architecture. The optimized conductor will be used in a SCFCL module (≈ 1.5 kA – 50 kV) tested at 65 K. We will monitor the temperature along the conductor using an attached optical fibre. FASTGRID will also develop innovative tapes based on sapphire substrate, which can tolerate very high electric fields, in the range of kV/m. Validated on the laboratory scale, this game-changing technology needs to be implemented at long lengths with an industrial process. We will provide an overview of the project and its first results.

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I. INTRODUCTION

HIGH Voltage Direct Current (HVDC) Supergrids appear as one of the best solutions to integrate huge amounts of renewable energies, one key for the sustainable development. It must move considerable energies from offshore wind farms or photovoltaic farms to customers. As its name indicates it is a HVDC grid. DC is required inter alia due to the cables between the wind farms and the coast and HV results from a technico-economical optimization like in AC. If DC shows numerous advantages compared to AC, one of its main drawbacks is the difficulty to cut the fault currents since the current does not cross naturally zero like in AC. HVDC Supergrids link different energy sources to several points of the traditional AC grids and so are inherently multi-terminal. The fault current must be then cut on the DC side to provide selectivity; it means the isolation of only the faulty part. The “classical” half bridge power converters between the AC and DC sides cannot manage the fault currents. Full bridge converters could do this but are much more expensive and show higher losses. There is no consensus about the protection of HVDC Supergrids. One solution could be to associate an inductance to a hybrid breaker [1]. This solution remains expensive, shows losses and requires space. Several studies show that the Superconducting Fault Current Limiter (SCFCL) offers an attractive solution for the protection of HVDC grids [2][3]. The first economic calculations based on the Eccoflow conductor [4] with a limitation electric field of 50 V/m (50 ms) and a tape at 200 €/kA/m show prohibitive costs. That is the origin of the H2020 European FASTGRID project (Cost effective FCL using advanced superconducting tapes for future HVDC grids). FASTGRID [5] aims to develop “low cost” robust REBCO conductors for the SCFCLs by working on the conductor including a breakthrough solution (sapphire substrate) and its environment. The effectiveness of the solutions will be tested on a 50 kV – 1.5 kA module (designed as a basic element of a HV device). FASTGRID project started in January 2017 and gathers 12 academic or industrial partners: CNRS Grenoble (coordinator), SuperGrid Institute, CSIC/ICMAB, Oxolutia, THEVA, RSE, EPM, TAU, KIT, IEE, EPFL and STU.

II. RESISTIVE SCFCL (R-SCFCL)

The Resistive SCFCL (R-SCFCL) is simply a SC element immersed in a cryogenics fluid (liquid nitrogen) in a cryostat and connected to the grid through two connexions called current leads (Fig. 1) and a switchgear.

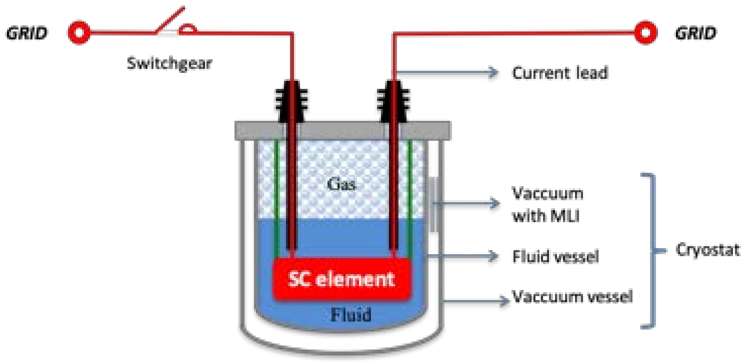

Fig. 1. Resistive SCFCL.

The R-SCFCL is based on the intrinsic highly non-linear characteristic of the electric field versus current density of a superconductor (Fig. 2). The critical engineering current density (J_{ce}) corresponds to a critical electric field (E_c). The international standard for HTS is E_c = 100 µV/m. The very high value of J_{ce} must be noticed. For comparison typical current densities in copper are about a few MA/m^2.

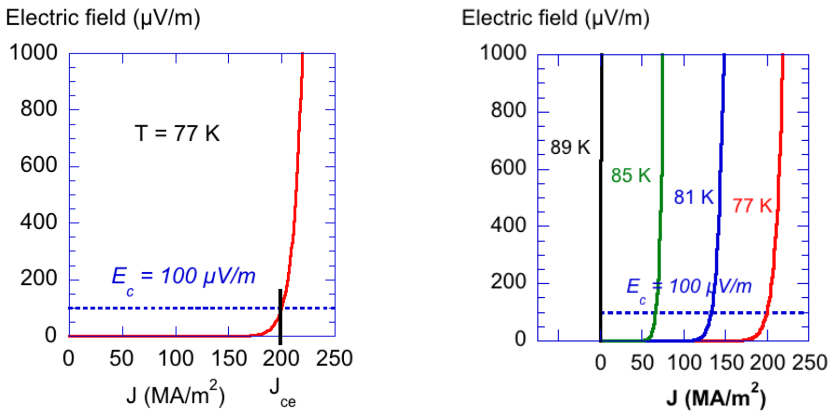

Fig. 2. Characteristic electric field versus engineering current density of a superconductor at 77 K (left) and at different temperatures (right)

Well under J_{ce} the electric field is non-detectable: this is the SC non dissipative state and the R-SCFCL is invisible since its impedance is ultra-low. The superconductor temperature remains constant. But as soon as the current density oversteps J_{ce} an electric field appears instantaneously and the superconductor becomes dissipative. It develops a large resistance, which limits the current. The temperature of the superconductor increases very rapidly. J_{ce} decreases and becomes zero at the critical temperature (89 K for Fig. 2). The E(J) characteristic changes and becomes linear at the critical temperature (Fig. 2). The superconductor is then in the normal state characterized by a high resistivity (this is why the E-J characteristic seems “vertical”). The dissipation is high and the superconductor should be isolated from the grid to prevent its damage by overheating. This is why a quick switchgear is in series with the SC element (Fig. 1). The fault isolating is mandatory anyway.

III. COST REDUCTION

A. Conductor cost for a SCFCL

The cost expression of the superconductor for a SCFCL is rather simple with very few parameters. It uses the cost of the superconductor per unit critical current and per unit length (C_{SC}) a classical data for REBCO tapes.

$$Cost_{SC} = C_{SC}\, I_c\, \ell_{SC} \tag{1}$$

The critical current (I_c) is higher than the rated current (I_a). The ratio ($k_a = I_c/I_a$) is given by grid studies in particular overcurrent operations. Typical value of k_a is between 1.5 and 2. The length is given by the ratio of the voltage across the SCFCL (V_{SC}) over the electric field under limitation (E_{lim}):

$$\ell_{SC} = \frac{V_{SC}}{E_{Lim}} \tag{2}$$

The voltage across the SCFCL is lower than the grid rated voltage. The expression of the SC cost becomes:

$$Cost_{SC} = \frac{C_{SC}}{E_{\mathrm{lim}}}\, k_a\, I_a\, V_{SC} \le \frac{C_{SC}}{E_{\mathrm{lim}}}\, k_a\, S_a \tag{3}$$

S_a is the rated power of the line to be protected by the SCFCL.

Since the grid fixes $k_a\, S_a$, there is only two parameters we can play to reduce the cost: lower C_{SC} and increase E_{lim}.

B. Superconductor cost (C_{SC})

This cost is given by the cost of the tape (material, process labour…) and its critical current (I_c). Increasing the critical current lowers C_{SC}. So there is an interest to decrease the operating temperature since the I_c then increases. This is the reason why FASTGRID intends to operate at 65 K: this is nearly the minimum temperature using liquid nitrogen, a fully industrial fluid. The critical current is approximately doubled when compared to I_c at 77 K therefore a reduction by 2 for C_{SC}. The cryogenic penalty is limited (15 % according to Carnot) and the operation at 65 K is not very complicated when compared to 77 K. It is difficult to think about another solution than a subcooled bath for insulating reasons (HV device). The pressure on the bath will be from 3 to 5 bars to improve the dielectric properties of the gas. The thermal exchange properties are significantly improved [6]. A quench at 77 K leads to vaporization of a given liquid volume. The bath temperature does not change but the transient pressure increase must be managed. With subcooled bath the liquid volume does not change (bubbles quickly collapse), but its temperature increases. The energy dissipation is absorbed by the specific heat instead by the latent heat. The consequences of the bath temperature increase must be evaluated in relation with the grid requirements (successive fault constraints).

C. Electrical field under limitation (E_{Lim}), conductor thickness

The electric field is given by the limitation / short-circuit regime. In adiabatic conditions the thermal equilibrium equation gives:

$$\frac{v_{SC}^2(t)}{\rho(T)\,\dfrac{\ell_{SC}}{A_{SC}}}\, dt = C_p(T)\, A_{SC}\, \ell_{SC}\, dT \tag{4}$$

C_p and ρ are the mean specific heat per unit volume and the resistivity of the SC conductor (cross section A_{SC}).

$$e_{Lim}^2(t)\, dt = \rho(T)\, C_p(T)\, dT \quad \Rightarrow \quad E_{Lim} = \sqrt{\frac{\int_{T_c}^{T_{max}} \rho(T)\, C_p(T)\, dT}{\Delta t}} \tag{5}$$

T_c is the critical temperature and T_{max} the maximum one reached after Δt (clearing time of the switch of the SCFCL).

Equation (5) shows that a high resistivity and/or a high specific heat favourably increases the electric field under limitation. FASTGRID objective is to overstep 100 V/m (clearing time of 50 ms); a significant increase compared to Eccoflow project (50 V/m, [4]).

But in case of a prospective current close to the I_c due to the inhomogeneities in term of I_c along the conductor and the low Normal Zone Propagation Velocity (NZPV), there is a "hot spot" regime. No current limitation occurs then since the hot spot zone is very short and extends very little: the grid acts as a current source. The current value is about I_c. The thermal equilibrium equation becomes:

$$\rho(T)\frac{l_{SC}}{A_{SC}}\, i^2(t)\, dt = C_p(T)\, A_{SC}\, l_{SC}\, dT \tag{6}$$

$$\rho(T)\, I_{c-w}^2\, dt = C_p(T)\, A_{SC}\, dT \qquad \left(I_{c-w} = \frac{I_c}{w}\right) \tag{7}$$

$$e_{SC} = I_{c-w}\sqrt{\frac{\Delta t}{\int_{T_c}^{T} \frac{C_p(T)}{\rho(T)}\, dT}} \tag{8}$$

I_{c-w} is the critical current per unit width of the conductor, a standard for REBCO tapes (w: conductor width). e_{SC} is the thickness of the conductor.

Equation (8) shows that a high resistivity required for a high E_{lim} leads to a thick conductor. An enhanced NZPV lowers the thickness. A thick shunt increases the recovery time and makes the winding more difficult.

IV. SC CONDUCTOR DESIGN

The SCFCL is designed to operate in any case from high to low prospective fault currents. We consider also a defect of the switchgear (no opening). This increases the fault clearing time from 20 ms to 40 or 50 ms with the back up. In what follows a clearing time of 40 ms is considered. With 50 ms the maximum temperature rise will increase by about12 % Fig. 3 shows the electrical circuit considered to design the conductor.

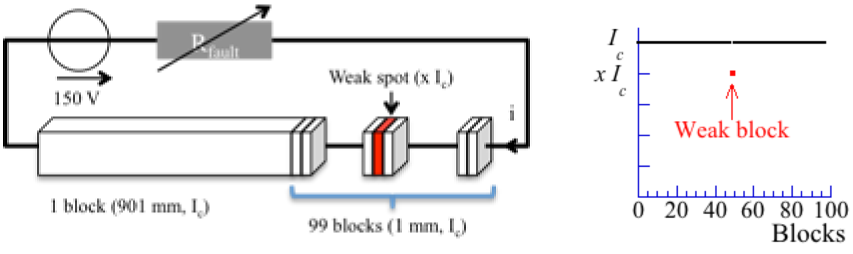

Fig. 3. Modelling of the SC length.

The voltage is 150 V and the SC length is 1 m (objective of 150 V/m). The resistance R_{Fault} varies to change the prospective current. The SC length is divided in 100 blocks, one long block (901 mm) and 99 short blocks (1 mm). All the blocks have the same cross section and I_c except one in the middle of the 99 blocks to model a weak spot whose critical current is xI_c ($x \leq 1$). A thermal conduction is considered between the blocks. The model is described in [7]. A more realistic I_c distribution among the 99 blocks does not change significantly the results and is more favourable for the hot spot regime. The I_c is 1000 A at 65 K (width: 10 mm). The final design will be given in section V. Here we will only study the relevant parameters.

Fig. 4 shows the maximum temperature of the weak spot block at the time of isolation (40 ms after the fault) versus the prospective fault current (I_{pros}) back to the critical current for three values of x (1, 0.9 and 0.7). The current I_{pros} varies by changing the fault resistance R_{Fault}. The hot spot regime is clearly visible when $x \neq 1$ for prospective fault currents close to I_c. The maximum temperature increases when the critical current inhomogeneity decreases (lower x). This maximum temperature is fixed by the conductor thickness (equation (8)). The weak zone plays of course no part when for high prospective fault currents compared to I_c since the full length then quenches.

The first conclusion is that the I_c must be as homogeneous as possible along the conductor.

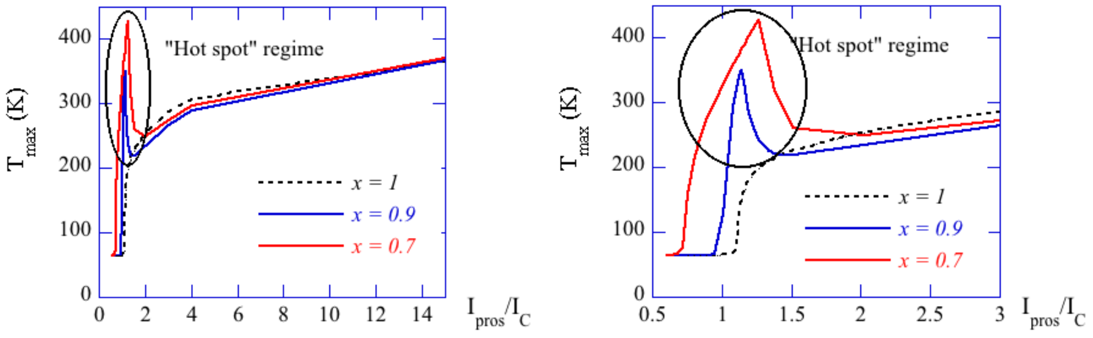

Fig. 4. Maximum temperature of the weak spot block 40 ms (Δt) after the fault versus the prospective current back to the critical one for three values of the critical current of the weak spot (I_c, $0.9\ I_c$ and $0.7\ I_c$).

Fig. 5 shows the influence of the thermal conductivity on the maximum temperature for the hot spot regime. When the thermal conductivity increases by two orders of magnitude the hot spot regime is significantly less problematic: the maximum temperature in the hot spot regime decreases. An increase of the thermal conductivity simulates an enhancement of the NZPV.

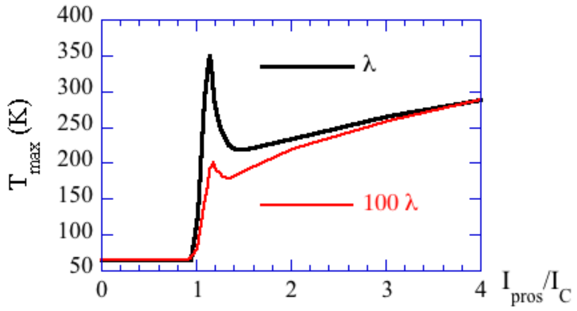

Fig. 5. Maximum temperature of the weak spot block 40 ms after the fault versus the prospective current back to the critical one for two values of the thermal conductivity along the blocks (x=0.9).

The second conclusion is that an increase of the NZPV reduces the hot spot regime temperature and then the shunt thickness. Since the NZPV is proportional to the square of the thermal conductivity, an increase of the thermal conductivity of 100 is expected to simulate then an increase of the NZPV by a factor 10. Simulations show that this is the possible gain provided by the Current Flow Diverter (CFD, [8] and [9]) developed by EPM. The industrialization of the CVD for REBCO tapes is one of the objectives of FASTGRID.

The SC conductor is made by a REBCO tape and a shunt bonded to the tape. First, we will consider the REBCO tape.

V. REBCO TAPE

A. *Hastelloy substrate "basic" Tape*

The tape for FASTGRID is a REBCO ISD process tape from THEVA [10]. The 100 µm thick substrate is Hastelloy which shows high mechanical properties and high resistivity (1.2 µΩm). The $GdBa_2Cu_3O_{7-\delta}$ superconductor is deposited on MgO buffer layers using ISD technique (Fig. 6). A 1 µm thick Ag layer surrounds all the tape. Optimization of process parameters led to I_{c-w} higher than 500 A/cm-w at 77 K and 1000 A/cm-w at 65 K with a standard variation lower than 5 % over the length required for the module.

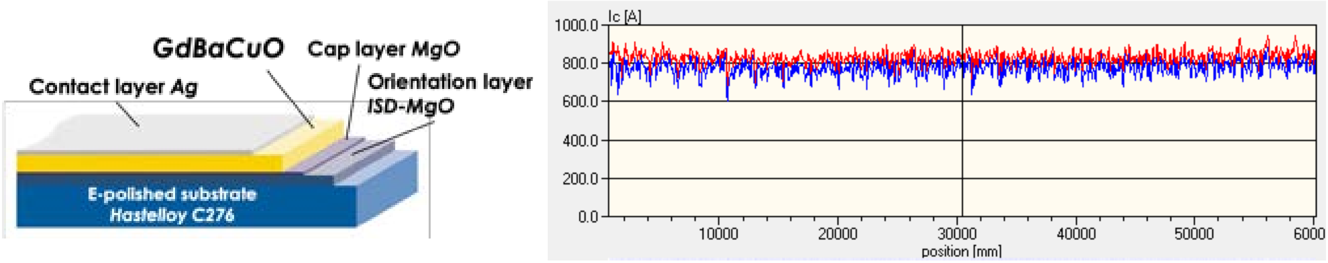

Fig. 6. Cross section of a THEVA tape and variation of its Ic along its length (12 mm wide tape) at 77 K.

B. *Hastelloy substrate CFD Tape*

Fig. 3 has clearly shown the advantage to increase the NZPV. FASTGRID aims at using the CFD concept (Fig. 7) to achieve this goal, which requires a strong increase of the contact resistance between the SC and Ag layers.

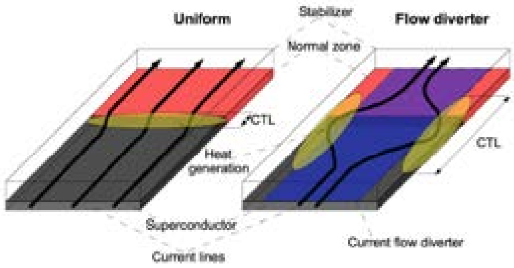

Fig. 7. CFD concept: reduction of the contact surface between the superconducting and the contact Ag layers by an electrical isolated layer in the middle of the tape.

ICMAB and OXOLUTIA have developed a process to deposit a thin (100 nm) Y_2O_3 insulating layer the GdBaCuO layer of THEVA tapes (shipped with no Ag layer). The insulating layer covers about 90 % of the tape surface. The Ink Jet Printing

(IJP) is particularly suitable to achieve this goal [11]. After the CFD deposition, Ag is deposited to cover the whole tape surface (Y_2O_3 and the exposed GdBaCuO on both edges, as shown in Fig. 8). The latest CFD samples processed in this way showed critical currents very close to THEVA standard tapes.

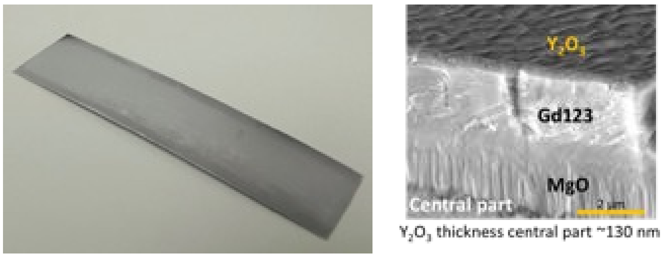

Fig. 8. CFD REBCO tape with its Ag layer. The Y_2O_3 central part used as current flow diverter (CFD) can be distinguished in the middle.

C. *Sapphire substrate Tape*

A sapphire substrate shows the unique advantage to be electrically insulating and have a thermal conductivity ten times higher when compared to Hastelloy. The electric field can be ultra-high, higher than 1000 V/m whereas the hot spot regime is no longer an issue due to the very large NZPV. Electric fields overstepping 2 kV/m have been even measured on 1 mm thick sapphire substrate. 3 kV/m is expected. Sapphire substrate really brings a breakthrough for SCFCL. FASTGRID wants to find ways to push the development of this emerging game-changing technology ([12] and [13]) to implement it at industrial length scales.

REBCO on epi-polished sapphire wafers has been successfully developed a long time ago but the sapphire tapes show more roughness. This is a difficulty with chemical deposition methods but solutions have been found. The REBCO is deposited through CeO_2 and YSZ layers.

The hot spot regime maximum temperature can be modulated by the thickness of shunt and its resistivity (equation (8)). FASTGRID mainly investigates two approaches for the Hastelloy substrate tape: a metallic shunt soldered of the Ag layer of the tape and an electrically insulating shunt bonded to the tape.

VI. SHUNT / HEAT CAPACITY LAYER

A. *Electrical conducting shunt*

This is the basic solution of FASTGRID. Equation (8) shows the interest of a high resistivity to reach a large electric field. Hastelloy shows a very high resistivity and the absence of thermal differential contraction with the tape (95 % Hastelloy) is a decisive advantage taking into account the thermal cycling of the conductor (soldering, limitation…). The only drawbacks are the rather high cost of Hastelloy and the required layers (Ni + Sn) for its soldering. THEVA has developed the soldering process using a lamination machine. The Hastelloy shunt for FASTGRID is 500 µm thick. FASTGRID about 620 µm thick conductor is stiff but still acceptable. KIT has measured a critical bending diameter much lower than the winding diameter in the pancakes.

Fig. 9 shows a limitation test in subcooled Nitrogen at 66.5 K on a 0.27 m long conductor carried out in Grenoble in AC for practical reasons (no high power DC source available). Two electric fields (0.197 m and 0.129 m in the middle) are plotted and show very close values. The curve deformations are due to the inrush current in the transformer connected at the time of test. The maximum and mean calculated temperatures [14] at the time of isolation are very close (317 K and 304 K (Fig. 9)). This is another indication for the homogeneity of the quench. These temperatures are in good agreement with the calculations. The behaviour in hot spot regime will be carried soon.

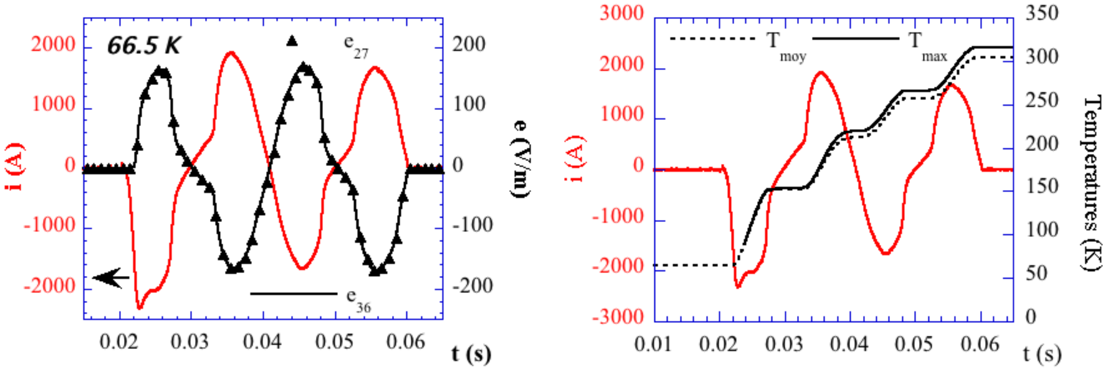

Fig. 9. Electrical tests on a 27 cm long FASTGRID conductor sample at 66.5 K, current (inversed) and two electric fields versus time (on the left), current, mean (zone 27) and max temperatures versus time (on the right).

B. *Heat Capacity layer*

This second solution uses a “heat capacity layer” electrically insulating layer with large heat capacity. It makes possible to reach higher electrical fields under limitation compared tothe Hastelloy. Heat capacity layer prepared from epoxy-ceramic filler composite coated on the SC tape are under investigation by IEE and STU. Measurements of mechanical and thermo-physical properties (thermal expansion, Cp, thermal diffusivity) revealed composites of Stycast 2850 FT with 20 vol. % SiC [15] and Araldite with 40 vol. % SiC as suitable materials for this purpose (Fig. 10). Both composites in form of approx. 200 µm thick coating are flexible and they can be bent at room temperature up to bending diameter of 8 cm without damage. The limitation behaviour is better for the modified THEVA tape with the composite coating 2850FT – 20 % SiC compared to the reference THEVA tape. The temperature rise for a given energy is lower, about 15 to 20 % as shown in Fig. 11. Simular effect can be achieved also with coating layer from Araldite epoxy and 40 % SiC.

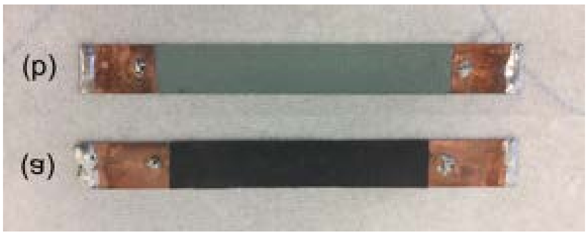

Fig. 10. Prepared short samples of epoxy-ceramic filler composite coated on the SC tape: (a) Stycast 2850FT - 20 % SiC (b) Araldite - 40 % SiC

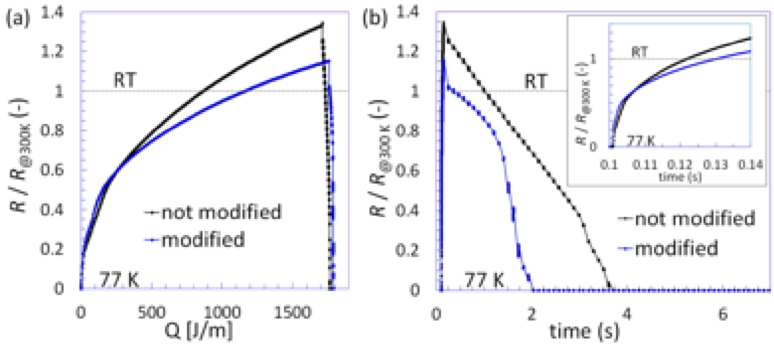

Fig. 11. Normalized electrical resistance (indicating tape temperature) as function of Joule heat absorbed by the sample (a) and time (b) measured during limitation test (50 ms DC pulse, 100 V/m) of not modified and modified THEVA tape with Stycast 2850FT – 20 % SiC.

VII. 50 KV – 1.2 KA MODULE

The module will consist of 10 sub modules connected in series. Each sub module (Fig. 12) is one bifilar coil made of two conductors in parallel. The two bare conductors are separated by two corrugated fibre glass tapes with a fibre glass tape between. This configuration provides the HV isolation and an efficient cooling. The critical current is about 2.6 kA.

Every pancake will be tested individually and the module will be tested.

Optic fibres will be placed on the conductor to have a distributed temperature sensor interrogated with a dedicated Raleigh back scattering technique.

Fig. 12. FASTGRID pancake prototype (5 kV / 1.5 kA, Øe = 880 mm).

VIII. CONCLUSION

FASTGRID aims for SCFCL applications to significantly reduce the cost of the REBCO conductor cost and improve its robustness. Works deals with REBCO tapes with enhanced $I_{c\text{-}w}$ and its homogeneity along the length. 1000 A/cm-w is already overstepped at 65 K (foreseen operating temperature) with a standard deviation of about 5 %. The CFD concept is under implementation using IJP to enhance the NZPV for improved robustness. FASTGRID will use a REBCO tape with Hastelloy substrate for the 50 kV – 1.5 kA module. This conductor shows an electric field higher than 130 V/m for a clearing time of 50 ms. FASTGRID explores new routes such as electrically insulating heat capacity layer or REBCO tape on sapphire substrate. These show extremely high electric fields (more than 2 kV/m for 1 mm thick substrate).

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