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Resistive Fault Current Limiter Prototypes: Mechanical and Electrical Analyses

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Abstract. The problem of excessive short-circuit currents has become an important issue for power systems operators and there are clear indications for a growing interest in superconducting fault current limiter devices for MV and HV grids. In this work, we report on both simulation and electrical testing on single-phase SFCL prototypes developed in the framework of an Italian RTD project to be completed with a 3-phase SFCL unit by the end of 2005.

1. Introduction

In transmission and distribution (T&D) electric networks there is the need to provide effective and reliable protection to cables, transformers, switches, and equipment against over current faults. In fact, when power distribution networks are expanded or new generation is added, fault levels can increase beyond the capabilities of existing equipment, leaving circuit breakers and other substation components in an over-duty condition. The superconducting Fault Current Limiter (SFCL) is a new type of short-circuit current limiting device aimed to reduce, in extremely short times, very high prospective fault currents to lower levels so the existing switchgear can still protect the grid. The technical and economical benefits of SFCL have already triggered a considerable interest in utilities and suppliers of equipment for electric power networks and at present, SFCL development projects are worldwide [1-3]. These benefits include ability to connect new generators to the electric system avoiding up-grading of existing networks or additional reinforcement and increase of network flexibility and reliability. The use of high temperature superconductors (HTS) allows the fabrication of SFCL devices with different configurations and indeed, YBCO films, BSCCO wires and bulks have already been used for the construction of different prototypes of resistive or inductive SFCL. The most powerful SFCL demonstrator built and tested successfully uses BSCCO-2212 bulk material [2]. In this work, we report on both mechanical and electrical simulation and electrical testing results on 350 kVA single-phase resistive-type SFCL prototypes developed in the framework of the Italian RTD project LIMSAT to be completed, by the end of 2005, with a 3-phase SFCL demonstrator made by commercially available HTS, see Fig. 1a. In particular, silver-sheathed BSCCO-2223 and Ni-alloy sheathed MgB₂ conductors have been purchased, fully characterized and utilized to manufacture the SFCL prototypes. Short circuit testing of several HTS windings has been carried out at CESI facility to ascertain the potential of SFCL. In the presence of the SFCL, prospective peak short circuit current up to 15kA has been effectively reduced to 800-2200A depending of applied voltage.
2. Experimental details

2.1.1. Fault Current Limiter Prototypes. Insulated BSCCO-2223 multifilamentary tapes, produced by American Superconductor Corporation have been used for the construction of several SFCL windings. In fact, the electrical, thermal, mechanical and dielectric properties of reinforced and insulated commercial BSCCO-2223 tapes are fully satisfactory for small scale SFCL prototypes until other HTS conductors as YBCO coated-conductors and/or MgB2 tapes become readily available. Non-inductive single-phase SFCL, composed of 200m of HTS tape wound around a cylindrical support, have been built and preliminarily tested by dc current (self-field critical current Ic = 282A at 64K). The SFCL prototype has a solenoid winding design and is constituted by two HTS layers. Voltage drop across the inner and outer layer as well as from the whole HTS winding has been measured during the electrical tests. Pt100-type temperature sensors have been positioned on the cylindrical support and at different positions along the outer HTS layer to study and monitor the thermal heating and cooling mechanisms of the SFCL winding during the short-circuit electrical tests. SFCL prototypes have been placed in a cryostat and cooled by a Stirling machine with about 700W cooling power at 65K. The top flange of the cryostat allows the feed through of current leads for powering of the SFCL, of all instrumentation wiring and is equipped with a pressure gauge and a safety valve. The normal operating pressure inside the cryostat ranges between 176mBar and 1Bar and can safely be operated up to 3Bar.

2.1.2. Electrical Circuit and Testing Procedure. The short-circuit testing of the SFCL prototype has been carried out with the HTS winding immersed in a LN bath kept at 64K. Fig. 1b reports the simplified scheme of the employed electrical circuit where R LINE, L LINE and R LOAD, L LOAD are the line and the load impedance-components respectively. Suitably changing these components and the transformer turn ratio, the test voltage has been varied from 100V rms up to 2000V rms with nominal (I nom) and short-circuit (I sc) current values up to I nom = 155Arms (with cos nom = 1) and I sc = 15kA (with cos sc = 0.1 lagging). Short-circuit currents with a power factor cos sc = 0.1 lagging have been chosen in order to take into account the inductive nature of the large majority of faults on MV grids. Ic has been applied for 40-100ms on single-phase SFCL devices to evaluate their current-limiting performance. Typical testing cycles have been repeatedly applied to SFCL continuously monitoring, with a 20kHz sampling rate, temperature, limited current, voltage across SFCL models and released energy.

2.1.3. Electrical and Mechanical Numerical Analysis. Since in the event of fault the abrupt increase of current in the SFCL winding gives rise to i) electrodynamic forces acting on the HTS conductor and to ii) Joule heating and hence thermal expansion, an axial symmetric finite element model (FEM) was developed to study SFCL mechanical behaviour under operating conditions. The main goals of numerical analyses were to evaluate the coil temperature evolution and radial displacement during the fault current event in order to assess all technical solutions to be taken to avoid any damaging of HTS.

**Figure 1**: Schematic 3D-view of a 3-phase SFCL prototype (a); scheme of the electrical circuit used for short-circuit testing on SFCL prototypes. T.O. = testing object, i.e. the SFCL prototype (b).
conductors. Since the computation of HTS displacement needs the simultaneous solution of electrical, thermal and mechanical problems, the FEM program to be used requires the multiphysics mode: at any time all data at each mesh node must be available at every numerical solver of the relative field equations (full coupling). In this way, it is possible to use material properties (thermal and electrical conductivity, specific heat, dilatation coefficient, elastic modulus) as function of temperature. At this purpose we have used the commercial program FEMLAB [4] that, beside the multiphysics property, allows the use of vector (“edge”) elements, necessary to solve the highly non linear Maxwell equations in presence of the power law of HTS electrical conductivity. Output of simulations, i.e. current density, temperature, stress-strain tensor and displacement, have then been used for the SFCL design.

3. Short-circuit testing results and discussion
Considering the possible introduction of SFCL devices in real electrical networks, it has been decided to test its effective limitation capacity under several typical fault conditions, e.g. double-fault events. Moreover, in order to estimate heating phenomenon and possible physical degradation of HTS at high currents ($I_{\text{nom}} >> I_{\text{c}}$), we applied nominal current $I_{\text{nom}}$ between two consecutive faults. Fig. 2 shows the time evolution of $I_{\text{lim}}$ and total voltage drop ($V_{\text{AD}}$) across a SFCL prototype, initially kept at $T_{\text{in}} = 64$K, during a typical fault testing cycle (50ms at $I_{\text{sc}} + 300$ms at $I_{\text{nom}} + 50$ms at $I_{\text{sc}}$). It can be noticed, no voltage drop across the SFCL before the fault and no over-voltages; the reduced $I_{\text{lim}}$ peaks during the second fault event state an increased limitation capacity due to the increased HTS temperature and consequently higher effective SFCL resistance. Fig. 3 shows, for the same experiment, the evolution of calculated SFCL resistance ($R_{\text{tot}}$): a steep increase during the first fault event, a small $R_{\text{tot}}$ reduction at $I_{\text{nom}}$ during the 300 ms between the two subsequent faults (partial recovery, owing to the thermal exchange with the liquid nitrogen bath) and a further resistance value increase in correspondence of the second fault. After the second fault event the higher HTS temperature associated with the dissipated power by joule effect at $I_{\text{nom}}$ determine the continuous increase of resistance.

4. Prospective ($I_{\text{sc}}$) and SFCL-limited currents.
4. Mechanical and Electrical Analysis: Numerical Results

Finite element modeling has been applied to predict stress-strain and heating effects on HTS windings subjected to short-circuit testing. Fig. 4 shows the comparison between SFCL-limited and unlimited short-circuit current \( I_c = 15\text{kA} \) as obtained experimentally: the limiting action of the SFCL reduces the first current peak to \( I_{lim} = 2100\text{A} \). Fig. 5 shows the experimental limited current \( I_{lim} \) used as input to calculate the tape temperature rise from \( T_{in} = 64\text{K} \). Being \( I_{lim} \) well above the HTS transition value, it causes a steep increase of the winding temperature, with a \( \Delta T \) of about 103K after 60ms. As a consequence, the HTS coil is subjected to pure thermal expansion and its initial radius enlarges by 0.33 mm, see curve 1 in Fig. 6. Since each turn of the inner HTS layer is facing a turn of the outer layer with opposite current, the repulsive electromagnetic force generates an internal stress whose angular component reaches 68MPa at the first peak, see Fig. 7. However, the corresponding force, i.e. 80N, is well below the maximum HTS tape tension of 230N, as given by the tape manufacturer. The radial component generates time oscillating displacements in opposite directions and, in absence of thermal expansion, they are given by the curves 2 and 3 in Fig. 6, whereas the combined displacement is given by curves 4 and 5. The most remarkable result is the prevalence of thermal expansion over the electromagnetic displacement. Since the final radius increment is comparable to the tape thickness, in order to prevent the coil entanglement, tape pre-tension and external bindings have been considered as possible practice. These technical solutions have been included in our latest FEM simulations and the results compared with simulations performed by the ABAQUS code.

5. Conclusions

Test results and simulations are very important to study the behavior and to give useful hints to the design of practical SFCL devices. Short-circuit test results on SFCL single-phase prototypes showed the excellent current limiting capability of the HTS winding since it provides fault current limiting actions in the first half of cycle \( (t<5\text{ms}) \), reducing effectively short circuit currents to much smaller current amplitudes.

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