A NOVEL DEVICE PROTECTING A SUPERCONDUCTING CABLE AND ITS CONNECTION TO A CONVENTIONAL DISTRIBUTION NETWORK

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ABSTRACT

A European Commission (EC) sponsored project (SLIM FORMER) is presently operating to design, build and evaluate a novel hybrid 100kVA demonstrator with features for protecting a superconducting cable from short circuit fault currents and providing connection to a conventional electrical system.

This paper describes the salient features of the device and its application together with details of a finite element model showing both normal operation and a fault current limiting scenario.

INTRODUCTION

Electric cables incorporating high temperature superconductors (HTS), which lose resistance at temperatures above the boiling point of liquid nitrogen, are considered to be economically viable for immediate use in applications where bottlenecks in the electrical network exist. For this reason several HTS cable application trials are currently being undertaken around the world e.g. the Albany Project, New York State (USA) in which a 350 meter long three-phase (34.5 kV, 800 A) HTS cable is presently supplying power to 70,000 households.

As with other equipment in an electrical network, HTS cables require protection from excessive short-circuit fault currents. If subjected to fault currents 10-20 times above the critical current (Ic) of the superconductor, the cables will lose their superconductivity and become resistive. Unless this fault current is quickly removed, the superconductor may be permanently damaged by excessive heating. Furthermore, in order to connect with conventional networks, HTS cables require high voltage terminations with current leads connected to the cryogenically cooled cable at 77K and a warm (~300K) conventional copper conductor. These terminations are complex in their construction and often suffer from high voltage insulation breakdown.

These issues are addressed through the use of a patented hybrid device, called a Self-limiting Superconducting Transformer (SLIM FORMER), which integrates a HTS cable termination with a HTS transformer, a fault current limiter and robust refrigeration. The device is to be designed to limit fault currents to safe levels within the first quarter cycle, thus protecting the HTS cable and other equipment in the network. Further, high voltage insulation problems are greatly reduced through the use of a transformer as an interface between a conventional network and a superconducting cable - separating the warm (copper primary) and cold (refrigerated superconducting secondary) conductors.

The SLIM FORMER project is part of the European Commission (EC) Sixth Framework Programme in the field of Sustainable Energy Systems. It brings together six partners from across Europe to design and build a prototype multi-functional SLIM FORMER. Preliminary work [1, 2] has demonstrated the principles of the fault current limiter on small bench top devices. The primary goal of the project is to develop system design and component fabrication procedures to a point where a hybrid 100kVA prototype can be constructed and critically assessed. At the time of writing a pre-prototype 20 kVA design is under construction.

The device will be suitable for connecting a conventional high voltage line (primary winding) with a high current superconducting cable system (secondary winding). There are additional features including a superconducting counter winding and a superconducting screen for protecting the superconducting cable against short-circuits faults. The schematic of the SLIM FORMER is shown in Figure 1.

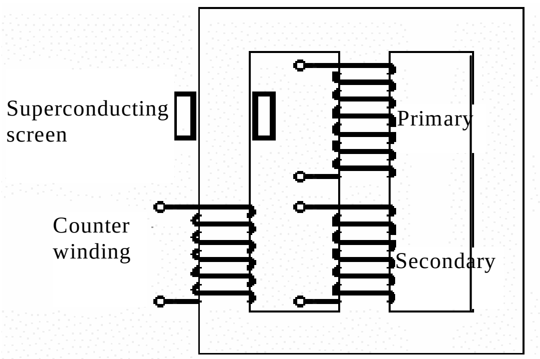

Figure 1. Schematic of SLIM FORMER

INTEGRATED FEATURES OF SLIM FORMER

The SLIM FORMER is a multifunction device that brings together three independent functions: current lead to a superconducting cable, current limitation and transformation between voltage levels. The technical viability of superconducting cables depends on the optimisation of cooling effectiveness and reliable current limitation. In a number of systems it has been considered necessary to use independent solutions for these functions, i.e. a high voltage termination operating between ambient temperature and cryogenic temperatures, transformation on the warm side of the circuit and fault limitation outside the superconducting cable.

The SLIM FORMER core has three limbs with a conventional copper primary winding located on the middle limb. The secondary winding consist of two coils connected in series and made from HTS tape, of which one is wound on to the middle limb (Secondary Winding) and the other wound in a counter direction on to an outer limb (Counter winding in Figure 1). With this configuration the induced voltages in the two coils are in series opposition. An HTS screen is placed with the counter winding to prevent magnetic flux entering that limb of the core. As a result, the output voltage is due only to the unshielded part of the secondary winding and the SLIM FORMER operates in conventional transformer manner. In the event of a short-circuit fault in the power system, the HTS shield quenches (loses its superconducting properties and becomes resistive) and flux enters the left outer limb resulting in fault limitation.

DESIGN CONSIDERATIONS

Normal transformer operation

In normal operation the SLIM FORMER must behave as a conventional, efficient transformer. As already stated, the flux is excluded from the left limb of the core, thus the right outer limb and the middle limb operate as a standard transformer (see Figure 1). The fundamental design in terms of turns ratio and iron cross-section is determined using standard transformer design equations. However, additional constraints are imposed by the use of both the superconducting screen and the superconducting cables.

Superconducting cables

The SLIM FORMER is proposed as a means of interfacing a superconducting cable with a conventional power line and a means of protection. The copper primary circuit operates at high voltage and low current. The SLIM FORMER transforms this to a low voltage, high current in the superconducting secondary circuit. Superconducting windings made using silver sheathed BSCCO -2223 tapes exhibit low loss and carry current at a density more than ten times larger than that in copper windings. Thus, transferring to the high current mode using highly efficient superconducting cables is attractive.

The SLIM FORMER has two secondary windings. Each secondary must be housed in a cryostat. This leaves the challenge of connecting the two windings together via a cable crossing from one cryostat to the other. The development of suitable current leads to achieve this connection without compromising the minimal resistance of the superconducting windings is an important aim of this project.

The secondary windings impose an additional design constraint on the SLIM FORMER in that they must not be allowed to exceed their critical current and quench either during normal operation or in a short circuit scenario.

Superconducting screen

The superconducting screen consists of a small number of

HTS cylinders. These form a short circuit around one outer limb. As such there are no connections to be made with this superconducting winding.

The proposed cylinders are made from a ceramic compound, BSCCO-2212, using a melt cast process (MCP). The existing manufacturing process is capable of producing rings up to a diameter of 400mm.

In order to reduce eddy-current loss, the HTS cylinders and HTS secondary windings are housed in Glass Reinforced Plastic (GRP) cryostats.

For the 20 kVA pre-prototype three BSCCO-2212 cylinders of 200mm diameter and height 100mm will provide a critical current of around 6000 A. This imposes an upper bound on the allowed current in the superconducting screen during normal operation. Since the superconductor will cancel out the flux induced by the counter winding this also limits the amp-turns in the counter winding.

FINITE ELEMENT MODEL

The preliminary design of the SLIM FORMER can be based on traditional transformer equations. However, the need for a third limb with a counter winding and superconducting screen means that the flux distribution in the iron core requires extra analysis. The SLIM Electromagnetic Engineering suite of finite element (FE) software has been used to gain further insight into the behaviour of the SLIM FORMER.

The 2D finite element mesh is shown in figure 2. This shows the geometry of the iron core and the locations of the windings and superconducting screen. The primary winding is connected to a voltage source and the secondary winding is connected to the load resistance. This external circuit (Figure 3) is interfaced with the SLIM FE model so that the software simultaneously calculates the required winding currents and their flux linkage to achieve the imposed primary voltage.

The finite element calculations demonstrate that during normal operation magnetic flux is excluded from the outer limb with the superconducting screen. This means that the resultant flux circulates around the middle and right side limb as in Figure 4.

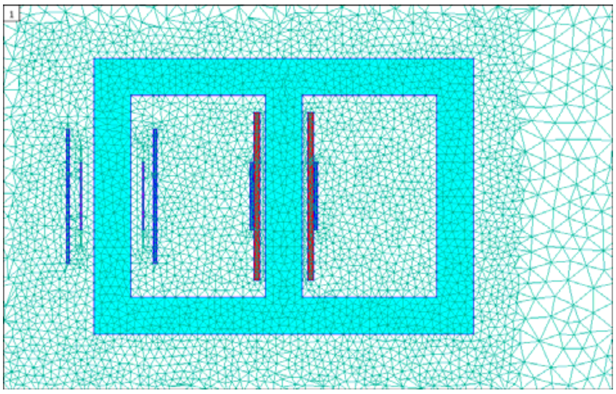

Figure 2. Finite element mesh

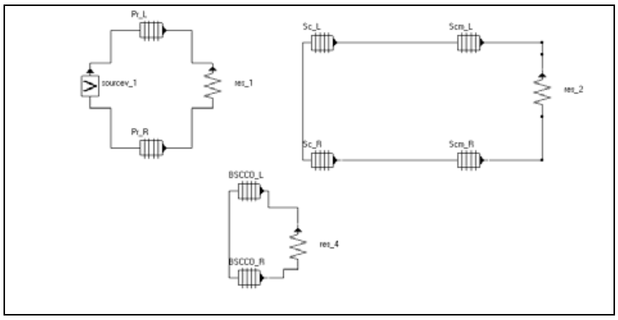

Figure 3. External circuit

When a fault occurs in the secondary, the current flowing in the counter winding increases rapidly, resulting in a corresponding increase in current in the superconducting screen. Eventually the superconducting screen reaches its critical current and then goes on to quench. At this point the screen current reduces dramatically as the BSCCO-2212 cylinders become resistive. Magnetic flux is then no longer excluded from the left outer limb (Figure 5) and the flux now linking the counter winding acts to reduce the secondary current, thus protecting the superconducting cable.

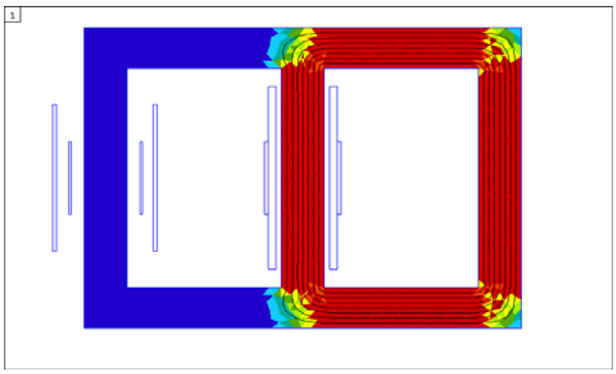

Figure 4. Flux distribution in normal operation

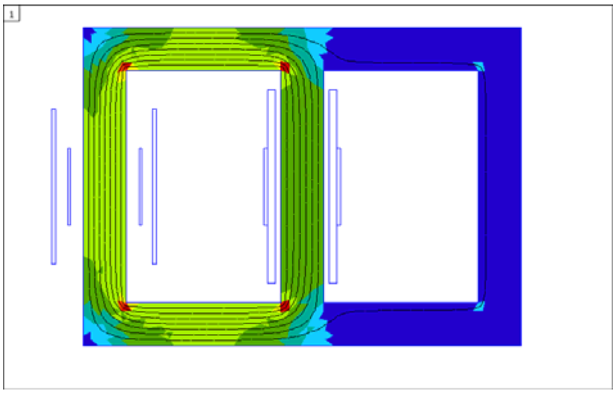

Figure 5. Flux distribution in fault mode

An example curve of secondary current during a fault is shown in Figure 6.

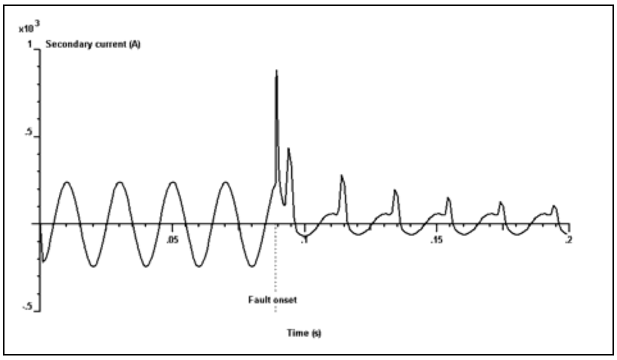

Figure 6. Secondary current variation

FUTURE WORK

At the time of writing the pre-prototype 20 kVA design is under construction. Over the remaining life of the project a 100 kVA prototype will also be built. These two prototypes will enable confirmation of the theoretical design and also give familiarity with the practical challenges of incorporating superconducting technology into operational equipment.

Acknowledgments

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Further information on SLIM FORMER can be found at www.slimformer.info.

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