HIGH TEMPERATURE SUPERCONDUCTOR BASED FAULT CURRENT LIMITER FOR DISTRIBUTION SYSTEMS

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ABSTRACT

In power system, the fault current levels are rising due to expansion and interconnection of the grids, requiring replacement of higher rated circuit breakers. A superconductor fault current limiter (SFCL) connected in series to a circuit breaker will reduce the fault current to the rated level of the circuit breaker, so that it can be operated safely. This feature of SFCL eliminates up-gradations of grids with the higher capacity breakers and the associated equipments. Also, as the fault current is limited, the electromagnetic and thermal stresses on the components would reduce resulting in reliability enhancement. To evaluate the SFCL performance as a protection equipment in 12 kV distribution system, CG Global R&D centre is developing a 12 kV, 200 A, three phase SFCL with stainless steel stabilized high temperature superconductor YBCO tape under the national prospective plan (NPP) of Ministry of Power, Govt. of India. This paper discusses the conceptual designs, cryogenic challenges and installation possibility of SFCL in the distribution system. The paper also describes the results of the current limiting tests conducted on the 440 V, 200 A conceptual prototypes.

INTRODUCTION

The global growth in power generation and interconnection in Transmission and Distribution (T&D) have resulted in the increase of fault levels in the network. T&D operators need to make large investments to upgrade the existing networks to match the fault levels. A superconductor fault current limiter (SFCL) connected in series to breaker will reduce the fault current below the rated short circuit level of the breaker, so that the breaker can be operated safely. This feature of SFCL eliminates up-gradations of grids with the higher capacity breakers and other associated equipments. Also, as the fault current is limited, the electromagnetic and thermal stresses on the components would reduce resulting in reliability enhancement. The installation of SFCL in such substations will increase the capacity of the substations and gives flexibility for further expansion and interconnection. Other advantage of SFCL could be the design of compact substations with under rated equipments. For example a 25 kA breaker could be used for 40 kA fault level using series connected SFCL designed to limit the fault from 40 kA to lower than 25 kA. The cost of SFCL in such systems will be justified with the lower investment for other equipments. In the nominal operation, SFCL is invisible to the system and do not contribute to the system losses, thus saves energy. High temperature superconductor (HTS) based SFCLs are being been developed for many years. Several types of SFCLs are developed and evaluated with different superconducting materials [1]–[6]. The resistive type SFCL based on second generation (2G), YBCO tapes are preferable because it limits the fault current within 1 or 2 ms and has low impedance during normal operation.

To evaluate the SFCL performance as a protection and control equipment in 12 kV distribution system, CG Global R&D centre is developing a 12 kV, 200 A, three phase SFCL under national prospective plan (NPP). This paper discusses the conceptual designs, cryogenic challenges and installation possibility of SFCL in the distribution system. The paper also describes the results of the current limiting testes conducted on the conceptual prototypes.

DESIGN AND DEVELOPMENT OF 12 kV, 200 A, 3 PHASE SFCL

In this research, selection of superconductor tape, design and evaluation of prototype coil and conceptual design of 12 kV SFCL were mainly performed. The cryogenics requirement and the installation possibility were explored.

I. Selection of Superconductor tape

The superconductor tape “coated conductor” architecture consists of a substrate with thickness of ~50–100 µm which is often ferromagnetic, one or more buffer layers, the HTS layer, a thin Ag layer ~1–10 µm, and a metal stabilizer layer ~50–100 µm. The buffer layers are thin insulating oxides.

The superconductor tape for SFCL application should address the two parameters; the critical current with high “n” value (steepness of transition from superconducting state to normal state) and the voltage drop developed per meter during the quench (V/m value). The critical current decides the number of parallel connections required to conduct the rated current during normal operation. The V/m value corresponds to the ability of HTS tape to sustain the energy during quench for few cycles, without getting damaged. The tape stabilized with resistive metal such as stainless steel is advantageous for the mechanical properties to face the electromagnetic stresses during the short circuits. In addition this will also help in current sharing for simultaneous quenching of HTS tapes. The Amperium wire procured from American Superconductor is used for the SFCL development. The parameters of the HTS tape are shown in Table 1.

Table 1

Parameters of YBCO tape

Parameter	Unit	Value
Tape width	mm	11.9-12.3
Tape thickness	mm	0.22-0.28
Stainless steel lamination	mm	0.75 per side
Minimum I_c (manufacturer)	A	275
'n' value (measured)	-	~ 42

II. Development of 440 V, 200 A prototype coil

Rated voltage and rated current of the grid determine the length and width of the superconductor tape. Two pancake coils each rated for 200 A, 220 V are manufactured. The HTS tape length of 6.2 m is evaluated considering the voltage per meter criterion of 65 Vpeak/m with 10% over voltage margin. Both the coils are wound with two parallel YBCO tapes such that their substrate side is facing each other and superconductor side is exposed outside. Each turn in pancake coil is separated by insulating GFRP rods, located radially in the specific slots. This interturn arrangement ensures that proper cooling reaches to superconductor in each turn. Both the coils are assembled one above the other with a gap of 25 mm. They are series such that the current flow in one coil is in opposite direction to that of the other coil. This arrangement will substantially cancels the magnetic field. The inductance of each coil is ~25 µH and when connected in the flux cancelling configuration the net inductance measured is ~25 µH. This ensures that there is 50% flux cancellation. If the gap between the coils is further reduced the flux cancellation will be more. However in the present case due to mechanical tolerance, the minimum gap achieved is 25 mm. The SFCL assembly is bath cooled in double-walled laboratory cryostat of 200 L capacity. The cryostat has a vacuum level of 1×10^{-3} mbar with multi-layer insulation to minimize the radiation losses. The cryostat top cover is also double walled with vacuum 1×10^{-3} mbar and is provided with liquid nitrogen filling port, level sensor port, temperature sensors port, vent valve and current lead space. American Magnetics level sensor and liquid level monitor Model 185 is fitted for continuous level-indication. Level monitor is set to high and low level alarm warning indicators. Three Lakeshore Cernox temperature sensors and Lakeshore temperature monitor model 218 is used for temperature measurement.

Continuous current test at 220 A

The SFCL is tested for continuous current up to 220 A. The setup schematic is shown in Fig. 2. The continuous current experiments are conducted using low voltage step down transformer 230 V / 5 V, 1250 A connected in series with SFCL. The source voltage to the step down transformer is applied with a variac. The divisions in variac are adjusted to get desired level of current. The applied current values are measured using current measuring shunt of 1 kA / 75 mV rating. A scope corder is used to capture the experimental data (voltage and current).

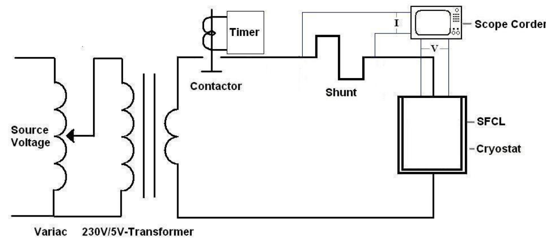

Fig. 2. Schematic for ac continuous current test setup.

Short circuit test at 440 V

The short circuit fault current measurements at 440 V were conducted at 50 kA short circuit laboratory at CG Global R&D centre. The schematic is shown in Fig. 3. A vacuum circuit breaker with timer is used to control the fault duration. A variable load is used to adjust the desired value of short circuit current.

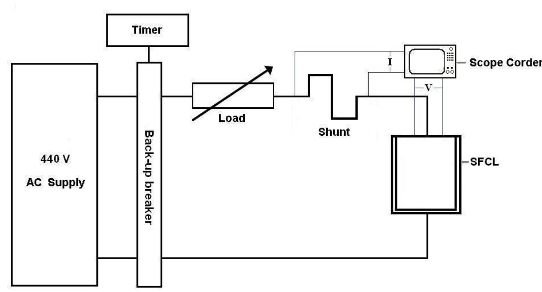

Fig. 3. Schematic for ac short-circuit test at 440 V.

The assembly of two series connected SFCL coil is tested for fault currents at 440 V, for 5 cycles. In total, 15 over current tests are performed with increasing current amplitude. Fig. 4 shows one of the plots with maximum amplitude of current during the test. The prospective current of 15.28 kA_{peak} is limited to 1.94 kA_{peak} within 1 ms. The current is limited by 87.3 %. There is a finite dc component in the plots. The voltage developed in the SFCL is marginally increased from first peak to the fifth around 424 V (600 V_{peak}); this is because the voltage drop across SFCL is already reached to maximum input voltage value in the first peak. The corresponding rise in the resistance is also plotted and the increase of resistance is clearly observed in the figure. After the short circuit tests are over, SFCL is tested again for 220 A continuous current with repetitive results. This ensures that the HTS tapes in SFCL have not degraded and are performing well.

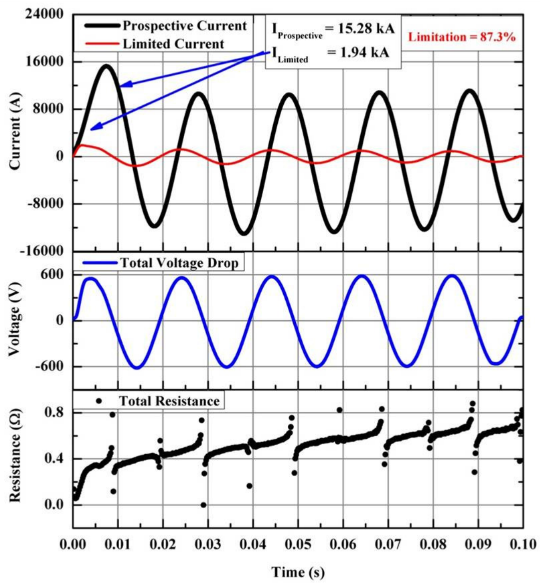

Fig. 4. Current limitation of SFCL coils.

III. Conceptual design for 12 kV, 200 A SFCL

The majority of 12 kV distribution systems are operated in a radial configuration. The system have continuous current ratings less than or equal to 600 A and fault current rating less than 20 kA [7]. The SFCL is designed to withstand 20 kA of short circuit level with continuous current rating of 200 A. In certain circumstances the overloading of current could go up to 1.5 times for a specific time. Therefore SFCL should not quench in the overloading current levels. The current sharing in the parallel connected HTS tapes is not same and varies. Therefore the SFCL should be designed to work with 50% overloading conditions with current sharing margin. The 12 kV SFCL is designed with the rated current of 200 A. The SFCL can carry 300 A, without quench during the over loading events. Two parallel HTS tapes with critical current of 275 A are proposed in the design. The tape length of 266 m is calculated from the 65 Vpeak/m for 100 ms parameter of the tape. The SFCL specification is given in the Table 2.

Eight set of coils with 33.25 m length of parallel connected superconductor are proposed to be arranged one above other and connected in series with current flow in opposite direction. Due to this the magnetic fields arising from the currents are largely cancelled out. The cancellation of magnetic fields also minimise ac losses.

Table 2

Parameters of 12 kV SFCL

Specification	Parameters
Rated voltage	12 kV
Rated current	200 A
Overloading current	300 A
Max fault current	20 kA
Fault hold time	<100 ms
Operating temperature	77k
Insulating and cooling medium	Liquid nitrogen

CRYOGENIC CHALLANGES

The cryogenics in SFCL has two elements, the cryostat that holds the coil in cryogenic environment and the cryocooler or cryogen that generates and maintains the cryogenic temperature. The selection of using cryocooler or cryogen depends on the designer and the economics of the system. The cryogen method is widely applied to various HTS apparatus because its thermal stability is higher than that of the cryocooler. Furthermore, the cryogen not only performs cooling but also insulates electrically.The cryocooler requires cooling power of 15-20 W to compensate heat load of 1 W. Some time it also requires backup water chiller unit that consumes power separately. Whereas the liquid nitrogen storage unit can be designed with automated system with level sensor, solenoid valves connected to level controller. The AC loss is an important factor for the SFCL design that dictates the capacity of the cryogenic cooling system. The YBCO tapes have ac losses typically in the range of 0.2-0.5 mJ/m/cycle at 50 Hz. Hence for a system having 500 m of YBCO tape the losses would be about 12.5 W. The factors such as heat conduction through current leads, measurement leads, heat leak through cryostat etc are a part of heat load.

INSTALLATION POSSIBILITY IN 12 kV DISTRIBUTION SYSTEM

The SFCL should be coordinated with the background power system in order to improve the total efficiency, controllability and stability in a power system. In the normal condition of a power system, SFCL works with zero resistance and negligible ac losses. When a fault occurs in the power system, SFCL acts as a fault current limiter due to quench of SFCL windings, which improves the transient stability of the power system. The SFCL has no interrupting ability; the circuit breaker is required in series to interrupt the fault current which is limited by the SFCL. The opening time of breaker should be kept as minimum as possible as

the length of HTS tape in SFCL depends on the V/m value of the fault hold time. The breaker's transient recovery voltage is damped and its rate of rise also reduces with series connected SFCL [7].
The Recovery of HTS tape after interrupting the fault current is an important design issue for integrating SFCL to the distribution power networks. The breaker reclosing time should be matched with the HTS tape recovery time. If not properly matched, the HTS tape may burnout due to quench; even if the fault is ended and rated current is flowing in the circuit. The recovery time depends on the thermal energy absorbed by the HTS tape during the fault hold time.

CONCLUSION

The most important benefit of SFCL in distribution systems is the possibility to upgrade the electric grid to higher distribution capabilities while maintaining existing fault current limits for transformers and circuit breakers. This could save utilities' money because they will no longer have to upgrade or retrofit existing equipment on their lines when they want to increase their transmission and distribution ratings.
To prove the feasibility and applicability of 12 kV SFCL, a 440 V, 200 A demonstrator is developed and evaluated. The limitation of current by 87% within 1 ms is attractive and based on the experience the development of 12 kV SFCL is under consideration.

Acknowledgments

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REFERENCES

[1] M. Noe and M.Steurer, 2007, "High temperature superconductor fault current limiters: concepts, applications and development status", *Supercond. Sci. Technol,* Vol 20, R15-R29.

[2] H. P Kraemer., W Schmidt, H. W Neumueller., A Otto., D Verebelyi., U Schoop., A. P. Malozemoff, 2008, "Test of a 2 MVA medium voltage HTS fault current limiter module made of YBCO coated conductors", *Journal of Physics, Conference series*, Vol 97, 1-6.

[3] H. Kang, C Lee., K Nam, Y S Yoon, H .M. Chang, T. K. Ko and B. Y. Seok, 2008, "Development of a 13.2 kV/630 A (8.3 MVA) high temperature superconducting fault current limiter", *IEEE Transactions of applied superconductivity*, Vol 18, 628-631.

[4] J. Sim, K.B. Park, H.R. Kim, J.S. Kang, B.W. Lee, H.M. Kim, I.S. Oh, O.B. Hyun, 2007, "14 kV single-phase superconducting fault current limiter based on YBCO films", *Cryogenics,* Vol. 47, Issue 3, 183-188.

[5] M. Chen, W. Paul, M. Lakner, L. Donzel, M. Hoidis, P. Unternaehrer, R. Weder and M. Mendik, 2002, "6.4 MVA resistive fault current limiter based on Bi2212 superconductor," *Physica C*, vol. 372, 1657 - 1663.

[6] M. Dixit, S. Kedia, S. Kulkarni, S. Patil, L. Andrews, A. Gupta and P. V. Balasubramanyam, 2012, "Development of 440-V 800-A Resistive-Type Modular Superconducting Fault Current Limiter with YBCO Tapes", *IEEE Transactions of applied superconductivity*, Vol. 22, No. 5, 5603305.

[7] L. Ye, M. Majoros, T. Coombs and A.M. Campbell, 2007, "System studies of the superconducting fault current limiter in electrical distribution grids", *IEEE Transactions of applied superconductivity,* Vol. 17, No. 2, 2339-2342.