**Superconducting Fault Current Limiter**

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**ABSTRACT**

The inductive-type superconducting fault current limiters (LSFCLs) mainly consist of a primary copper coil, a secondary complete or partial super-conductor cylinder & open magnetic iron core. Complete performance of these devices significantly depends on the optimal selections of its materials and dimensions of construction, electrical, magnetic, thermal, and parameters. It is important to identify a comprehensive model describing the characteristics of LSFCL in a power system prior to its fabrication. When any fault occurs, the dynamic model will characterize the overall phenomena to compare the simulation results by varying LSFCL parameters to maximize the merits of a FCL while minimizing its drawbacks. The principle object of this paper is to achieve a full penetrative approach of design of LSFCLs by means of multi criteria decision-making techniques.

**Keywords**—Analytic hierarchy process (AHP), inductive superconducting fault current limiter (LSFCL), multi criteria decision making (MCDM), Pareto optimality.

**I. INTRODUCTION**

Day by day increment in the power supplied by the energy grid and the demands of energy system by the new paradigm in power markets in the world have led to the occurrence of faults that have caused a great deal of damage in the system, with an interruption of service to the customer being the result. Faults occur on transmission lines as a result of lightning strikes, severe weather, errant tree branches, and the occasional squirrel or metal pole. Regardless of the cause, the impact of fault currents and their effects on transmission equipment cannot be underestimated in terms of cost and loss of service. Because of this, it is desired that the fault current be limited or clipped so that the current may be interrupted sooner by a circuit breaker.

Fault current limiter (FCL) is expected to be installed in A power systems in order to reduce large short-circuit fault currents. Manu types of FCL have been researched and developed where the superconducting phenomena are applied. Parallel, technology that can make Yttrium barium copper oxide (YBCO) superconducting thin films of relatively low cost by the metal-organic deposition (MOD) method has been developed. The MOD method can produce large YBCO thin films having with critical current density without vacuum technique of evaporation method.

This paper describes the development of a superconducting fault current limiter (SFCL) using these Yttrium barium copper oxide (YBCO). Experiments were performed using over current phenomena to derive the data required to design the SFCL like V / I characteristic and withstand voltages of the superconducting elements. Superconducting elements was constructed using two parallel & six series connected elements and tested to discuss the quenching process of over-current element.

**II. ELECTRICAL AND THERMAL MODELING OF LSFCLs**

High temperature Superconducting Fault Current Limiter (SFCL) have been categorized into following types i.e. resistive, inductive and hybrid Moreover, some authors have divided the inductive SFCLs into quench and no quench types. The quench types are the magnetic shielding, transformer, and ring types, whereas the no quench types are the saturation reactor and dc reactor types.

Since no transition S/N exists in no quench SFCLs, only quench LSFCLs are considered as inductive SFCLs in this paper. As stated in Section I, except for the minor difference in the normal condition, the inductive-type SFCLs have common characteristics in the fault condition. In that sense, a common model can be considered for the current-limiting regime.

A magnetic-shield-type LSFCL shown in Fig. 1 is a passive device that consists mainly of a closed (open) iron core inside a superconductor tube, around the outside of which is wound a copper coil. Under normal conditions, the shielding capability of a superconductor tube keeps the inductance low; thus, no flux penetration into the iron core occurs. Under fault conditions, the high current in the copper coil exceeds the shielding capability.
of the superconductor tube, and a jump in impedance occurs because the flux profile in the superconducting screen penetrates into the iron core.

![Fig1: Magnetic-shield-type superconductive fault current limiter](image1)

Fig1: Magnetic-shield-type superconductive fault current limiter

### III. YBCO SUPERCONDUCTING THIN FILM ELEMENTS

Configuration and picture of the Yttrium barium copper oxide (YBCO) superconducting thin film element is shown in fig 2. The element has a rectangular shape, 30 mm wide and 210 mm long, where Yttrium barium copper oxide (YBCO) thin film of about 200 nm in thickness is coated on sapphire substrate with cerium dioxide cap-layer by the metal-organic deposition method and covered by a protective metal (Au-Ag alloy) coat.

The sapphire substrate of 1 mm (thickness) is characterized by high thermal shock resistance and potential for large area element. The CeO₂ cap-layer of 40 nm in thickness was inserted for mismatch relaxation of the Yttrium barium copper oxide (YBCO) crystal with the sapphire for epitaxial growth of the Yttrium barium copper oxide (YBCO).

Silver sheets of 10 mm (thickness), 30 mm (width) and 10 mm (length) were deposited on both terminals of the Yttrium barium copper oxide (YBCO) film in order for connecting leads of current. Thus, the total length of the Superconducting Fault Current Limiter element is 190 mm. Current leads made of copper braided wires of 14 mm are solder-mounted with indium on the silver sheets as shown in Fig.2 (b)

![Fig2: Adopted YBCO thin film element. (a) Configuration; (b) appearance](image2)

![Fig2: Adopted YBCO thin film element. (a) Configuration; (b) appearance](image3)

Fig.2. Adopted YBCO thin film element. (a) Configuration; (b) appearance

### IV. VOLTAGE-CURRENT CHARACTERISTICS

Voltage-Current (V/ isc) characteristics obtained for Superconducting Fault Current Limiter element before breakdown is summarized in Fig. 3. From a small current carrying property, the apparent critical current of Superconducting Fault Current Limiter element is estimated to be 43 A (reference voltage: 10 mV across the electrodes (length between electrodes is 18 cm) in our experiments.

For E=3.6 kV , after the first peak of the current isc, the voltage (Vsc) almost linearly decreases as the current isc decreases. The slope of (Vsc – isc) characteristic expresses the resistance generated in the element. The resistance is evaluated to be around 7.8 ohm from slope valve which corresponds to 95% of the resistance of the protective metal coat (room temperature). This suggests that most of the Yttrium barium copper oxide (YBCO) thin film undergoes transition to the normal state. Therefore the current (isc) does not flow through the Yttrium barium copper oxide (YBCO) film, but through the protective gold-silver alloy layer.
A magnetic shield type was located at an outgoing feeder in a single-phase 11.5-kV distribution substation. Suppose a short-circuit fault occurs close to the substation, the model for a single-phase equivalent circuit is shown in Fig. 4.

The inductive superconducting fault current limiter (LSFCL) model was defined as a component in a PSCAD/EMTDC environment. Simulations were carried out with a fault occurring at t = 300 ms and cleared after t = 200 ms. To overcome the transient faults, the total simulation time was 2 s, which is enough for quenching and restoration of the HTS. 10 μs time was sufficient to observe the transient pattern. System characteristics and the selected LSFCL parameters are shown in Table I.

TABLE I
CHARACTERISTICS OF THE SYSTEM AND LSFCL

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>RMS Phase voltage</td>
<td>11.5 kV</td>
</tr>
<tr>
<td>RSL</td>
<td>Resistance of the system and the line</td>
<td>2 Ω</td>
</tr>
<tr>
<td>LSL</td>
<td>Inductance of the system and the line</td>
<td>10 mH</td>
</tr>
<tr>
<td>f</td>
<td>System frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Tc</td>
<td>Critical temperature for HTS</td>
<td>90 K</td>
</tr>
<tr>
<td>T0</td>
<td>Temperature of LN2</td>
<td>77 K</td>
</tr>
<tr>
<td>I0</td>
<td>Critical current in T=Tc</td>
<td>520 A</td>
</tr>
<tr>
<td>Rd</td>
<td>Shunt resistance to HTS</td>
<td>0.1 Ω</td>
</tr>
<tr>
<td>Cp</td>
<td>Specific heat of HTS</td>
<td>1.0 MJ/m²K⁻¹</td>
</tr>
<tr>
<td>P</td>
<td>Cooling power</td>
<td>200 kV</td>
</tr>
<tr>
<td>VSC</td>
<td>Volume of HTS</td>
<td>0.004 m³</td>
</tr>
<tr>
<td>ASC</td>
<td>Cross section of HTS</td>
<td>1.5e-4 m²</td>
</tr>
<tr>
<td>h</td>
<td>Height of iron core</td>
<td>0.5 m</td>
</tr>
<tr>
<td>μr</td>
<td>Relative permeability of iron core</td>
<td>250</td>
</tr>
<tr>
<td>rc</td>
<td>Radius of iron core</td>
<td>0.1 m</td>
</tr>
<tr>
<td>rs</td>
<td>Radius of HTS cylinder</td>
<td>0.14 m</td>
</tr>
<tr>
<td>rp</td>
<td>Radius of cooper coil</td>
<td>0.2 m</td>
</tr>
<tr>
<td>a</td>
<td>Turn ratio of transformer (N1/N2)</td>
<td>50</td>
</tr>
<tr>
<td>Psc</td>
<td>Maximum AC loss calculated from (9)</td>
<td>1.09 W</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

Over-current tests were performed on a superconducting fault current limiter (SFCL) using Yttrium barium copper oxide (YBCO) films prepared by metal-organic deposition (MOD). Following results were obtained:

1) The superconducting elements of 210 mm long (length not including the electrode is 190 mm) consisting of YBCO thin film covered by a protective Au-Ag coat can withstand high voltage stress of 1045 V.
2) All elements connected in parallel and series can transit to normal state by over-current without any trouble.
3) A 6.6 kV class single-phase SFCL was developed by connecting the YBCO elements: two-parallel & twelve-series. SFCL task was successfully limited the fault current from 11.3 kA peak (8 kA RMS) to 4.5 kA under full system voltage conditions.
4) A cubicle-type 6.6 kV–400 A three-phase SFCL will be manufactured by using parallel- and series-connected YBCO elements without regarding any major improvement.

REFERENCES


