Enhancement of Power System Transient Stability Using Inductive Superconducting Fault Current Limiter with YBCO and Bi-2212

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Abstract—This paper presents the results of analysis about transient stability enhancement using inductive superconducting fault current limiter (Inductive-SFCL) with different superconducting materials as YBCO and Bi-2212. Transient stability investigations concern in studying the rotor oscillation of synchronous generators after the occurrence of large disturbance, e.g. short circuit. The goal is to indicate if the generators remain in synchronism after the short circuit. The fault duration, the output electrical power during the fault and the auto-reclosing of the circuit breaker are the most important factors to be considered. In fact, the shorter the fault and the larger the output electrical power during the fault, the more the maintaining of synchronization can be guaranteed.

Superconducting fault current limiter (SFCL) has an extremely fast current limitation and consequently a better ability to maintain the synchronization of the system. The nature of the SFCL helps in increasing the output electrical power during the fault and hence enhances the stability of the generators. Simulation studies are performed using one machine connected to an infinite bus by two parallel lines. The study covers simulations of the inductive at different superconducting materials like YBCO and Bi-2212, different fault duration the auto-reclosing of the circuit breaker.

Keywords—Fault current limiter, superconductor, power system stability, auto-reclosing

Nomenclature

\begin{align*}
R_{sc} & \quad \text{resistance of SFCL film} \\
R_1 & \quad \text{the primary winding resistance} \\
L_m & \quad \text{the magnetizing inductance of the iron core} \\
L_1, L_2 & \quad \text{the leakage inductance in the primary and secondary} \\
a & \quad \text{the turns ratio between the primary and the secondary} \\
E_v & \quad \text{the voltage per turns} \\
L & \quad \text{the height of the window} \\
D & \quad \text{the centre to centre distance of the cores} \\
f & \quad \text{the frequency} \\
B_m & \quad \text{the flux density} \\
A_r & \quad \text{the core cross-section area} \\
A_w & \quad \text{the window cross-sectional area} \\
D & \quad \text{the core circumscribing diameter} \\
\delta & \quad \text{the current density} \\
W & \quad \text{the overall length of the yoke} \\
\rho_{sc} & \quad \text{resistivity of the superconducting (SFCL)} \\
\rho_{sc} & \quad \text{resistivity of the superconducting film} \\
I_c(T) & \quad \text{critical current density at temperature T} \\
I_c(77) & \quad \text{critical current density at 77 K} \\
T_c & \quad \text{critical temperature} \\
E_c & \quad \text{critical Electric field value at critical current density} \\
E_0 & \quad \text{depend on material processing conditions} \\
P_m & \quad \text{mechanical output power of the turbine} \\
G_0 & \quad \text{the transfer conductance between generator’s bus ij} \\
B_0 & \quad \text{the transfer susceptance between generator’s bus ij} \\
\delta_{ij} & \quad \text{angle between } E_i \text{ and } E_j \Rightarrow \delta_i - \delta_j \\
V' & \quad \text{system voltage} \\
E' & \quad \text{generator voltage (emf)} \\
X_{ij} & \quad \text{transfer reactance between generator and system} \\
H & \quad \text{the inertia constant} \\
\omega_s & \quad \text{the rated synchronous speed} \\
\end{align*}

I. Introduction

Increasing power demands are leading to power transmission systems which cover large distances and carry high power at high stability. This expansion in power system capacities led to development of larger-scale generating units and interconnection between networks. Therefore, a fault on the power system may abnormally induce large fault current and cause over-stress problems on generators, transformers, circuit breakers, and transmission lines etc. On the other hand, the power systems are exploited to the limits of stability maintained by the generators [1, 2].

The majority of faults on transmission lines are intermittent so that, after clearing the fault by opening the necessary circuit breakers, the faulty line can be switched on...
again after allowing sufficient time for the arc across the breaker points to extinguish. This process may adversely affect the system stability as the rotor may still have some kinetic energy that increases the accelerating area and makes the available decelerating area too small to absorb this energy and stop the rotor [3].

In the electric power system, the system stability is essential to be improved, and at the same time, the fault current should be suppressed by the current limiter. Power system stabilizing apparatus such as power system stabilizer (PSS), static var compensator (SVC) [3] and so on have been developed. Superconducting magnetic energy storage (SMES) has been applied to the stabilization of power swing, frequency control, voltage control and power quality control [4]. However, these apparatus do not have the ability to limit the fault current. SFCLs are expected to be ultimate automatic protection systems against short circuit faults and a powerful controller for transient stability enhancement [5-7].

In this paper, a number of computer simulations using MAT LAB were developed to examine the transient stability of an electric power system using the inductive-SFCL with different superconducting materials as YBCO and Bi-2212. A single machine infinite bus circuit with parallel circuit transmission line was used. The effects of introducing the SFCL on limiting fault currents and enhancing the transient stability of the system are discussed. The effect of autoreclosing of the circuit breaker on the system stability is also examined.

II. STRUCTURE OF SFCL

A. Fundamental properties of HTS

In superconducting materials, there are three parameters: critical temperature (Tc), critical magnetic field (Bc), and critical current density (Jc) form a parameter space within which the material remains in the superconducting state, as shown in Fig. 1 and becomes a normal conductor everywhere outside [9]. In this work, no externally magnetic field was applied. The effect of the self-magnetic flux from the current in the SC film was neglected, because it is too small to have any effect on Jc [10]. Also, Jc in Table I is measured at self-flux.
Figure (2): (a) HTS tube inserted between the primary coil and the iron core. (b) Approximate equivalent circuit for the Inductive SFCL in fault condition.

C. Design of Iron Core in Inductive-SFCL

In this section we preview the design of the iron core Fig. 2(a) and the secondary superconducting tube[12]. The voltage per turns is determined by (1).

\[ E_t = K_f \sqrt{\frac{KVA}{3}} \]  

(1)

The cross-sectional area of the core is determined by (2). The flux density is assumed a value so that the core is not saturated during normal and fault conditions.

\[ E_t = 4.44f B_m A_k \]  

(2)

The core circumscribing diameter \( d \) is calculated by (3).

\[ A_k = K_f \times d^2 \]  

(3)

The window area is determined by using (4).

\[ Q = 3.33 f B_m A_k A_w K_w \delta \]  

(4)

Window height and width are calculated by (5) and (6).

\[ A_w = L(D - d) \]  

(5)

\[ L/((D - d)) = 2.5 \text{ to } 4 \]  

(6)

III. Modeling for Simulations

A. Material Modeling

The limiting resistance of the superconductor depends on the material length and cross-sectional area. It also depends on the resistivity of the material during the fault condition as given by (7).

\[ R_{sc} = \rho_{sc} \frac{L_{sc}}{A_{sc}} \]  

(7)

The resistivity of the superconducting materials depends on the current, the magnitude and direction of any externally applied magnetic field directed at the material and the temperature of the material. \( \rho_{sc} \) varies over a three operating regions to be considered as in (8–10) for YBCO [13] and (8.11 – 13) for Bi-2212 [14].

\[ \rho_{sc} = \begin{cases} 
0 & \text{For } T < T_c \text{ and } J < J_c \\
\rho k \left(1 - \frac{T}{(T_c - J_c)}\right) & \text{For } T < T_c \text{ and } J > J_c \\
10^6 + 10^8 (T - 90) & \text{For } T > T_c 
\end{cases} \]  

(8)

\[ \rho_{sc} = \rho_k \left(1 - \frac{T}{(T_c - J_c)}\right) \]  

(9)

\[ \rho_{sc} = 10^6 + 10^8 (T - 90) \]  

(10)

B. Power System Model

A simplified power transmission model was used in this study as shown in Fig. 3. The system is composed of a synchronous generator (40MVA, 13.8kV), SFCL, step-up transformer (13.8/220kV), 220kV transmission lines and an infinite bus. A three-phase fault is assumed to occur at the sending end of a single circuit of the transmission line. The fault is assumed to occur at 0.02s and clear at 0.14s by opening the circuit breaker. The simulation is done on the unsymmetrical fault which is the worst case.

![Figure 3: System model](image)

**TABLE I**

<table>
<thead>
<tr>
<th>PARAMETERS OF THE SFCL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SFCL</strong></td>
</tr>
<tr>
<td>( J_c = 3 \times 10^7 ) A/cm²</td>
</tr>
<tr>
<td>( T_c = 90K )</td>
</tr>
<tr>
<td>Thickness=20mm</td>
</tr>
<tr>
<td>Height=2 m</td>
</tr>
<tr>
<td>Number of turns =184</td>
</tr>
<tr>
<td>Material (Copper)</td>
</tr>
</tbody>
</table>

C. Theoretical Analysis of Improving Power System Transient Stability Using SFCL

The studies performed on the system in Fig. 3, the synchronous generator is represented by a voltage source,
behind a transient reactance $x'_t$. During transient conditions the generator internal voltage remains constant in magnitude but changes its angle ($\delta_i$). This angle corresponds to the angle between the generator internal voltage and the infinite bus voltage. The mechanical power, supplied by the turbine remains also constant. The transformer is represented by reactance $x_t$. The two lines are equal and characterized by reactance $x_k$.

When the system is operating in normal conditions the SFCL presents zero impedance, during fault conditions the SFCL is represented by its resistance $R_{sc}$ value.

The non-linear differential equation (swing equation) that describe the motion of the synchronous machine rotor is

$$\frac{2H}{\omega_s} \frac{d^2 \delta}{dt^2} = P_m - P_e$$  \hspace{1cm} (14)

The electrical machine power is a function of angle $\delta_i$ and depends on the network topology [16]. Power systems are made up of many power plants, transmission lines and various kinds of loads. Given a system of generators, so the electromagnetic power of the generator can be formulated as in (15).

$$P_i = \text{Re}(E_i I_i^*) = \text{Re}\left(\sum_{j=1}^{n} E_j Y_{ij}^* I_j^*\right)$$ \hspace{1cm} (15)

$Y_{ij}$ is the complex network transfer admittance matrix, which can be expressed as shown in Equation (16).

$$Y_{ij} = G_{ij} + jB_{ij}$$ \hspace{1cm} (16)

Using equation (17), the electromagnetic power of the generator can be also expressed as a function of the power angle as shown in Equation (17).

$$P_i = E_i^2 G_{ii} + \sum_{j=1, j \neq i}^{n} E_j G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}$$ \hspace{1cm} (17)

Before the fault (Without SFCL) the generator’s power is deduced from Equation (18) and can be described by Equation (18).

$$P_1 = \frac{E V}{X_1} \sin\delta$$ \hspace{1cm} (18)

$$X_1 = X_d + X_f + X_L/2$$ \hspace{1cm} (19)

The three-phase short circuit is the worst case in a network, the electrical power from the generator to the system drops from its pre-fault value to zero ($P_1 \text{max} = 0$), when SFCL is not inserted in the network, because the transfer reactance in Equation (19) becomes infinite. The driving mechanical power becomes much greater than the opposing electrical power and the rotor begins to accelerate, and may lose synchronism.

Suppose an inductive -SFCL is inserted in the network as shown in Fig. 4. The generator’s output power is deduced from Equation (17) can be expressed by Equation (20).

$$P_2 = E^2 G_{11}$$ \hspace{1cm} (20)

where $G_{11}$ is represented by Equation (21).

$$G_{11} = \frac{a^2 R_{sc} X_{m}^2}{a^4 R_{sc}^2 (X_m + X_d + X_f)^2 + X_m^2 (X_d + X_f)^2}$$ \hspace{1cm} (21)

With inductive-SFCL, a resistance appears in the network which consumes the kinetic accelerating power. The decelerating torque will force the generator rotor back toward the equilibrium point or reach an acceptable steady state operating point following the fault.

![Figure 4: Equivalent circuit of a model power system with Inductive-SFCL](image)

**IV. RESULTS AND DISCUSSION**

During the fault, the electrical power from generator drops to zero. Therefore, the generator is accelerated due to the excessive mechanical input power. As a result, the power angle of the generator increased. The change of the internal angle will go to infinity with no SFCL used. This means that the generator starts to accelerate uncontrollably and the system becomes unstable. During an out-of-step condition, there are large cyclic variations in currents and voltages with the frequency being a function of the rate of slip of its poles which in turns causes high frequency oscillations in the output power.

**A. Results of Inductive-SFCL using YBCO and Bi-2212.**

The inserted resistance of the SFCL into the power system could not only limit the short circuit currents but also increase the electrical power. So the SFCL could reduce the excess power of the generator, damp the load angle oscillations. Fig. 5 shows the load angle versus time curve during the three-phase fault is assumed to occur at the sending end of a single circuit of the transmission line. The results show that, without SFCL the system lost its synchronism but when using the inductive-SFCL damps out the generator load angle nearly from the first cycle of oscillations and reached to the initial angle with a small time but when. This prove that the resistance appears in the network of inductive-SFCL can improve the system
stability as proving in the previous theoretical analysis equations(21).

Also, Fig. 6 shows that the generator speed deviation was damped with oscillations and could return to a new stable state.

**Figure (5): Generator load angle with and without Inductive-SFCL**

**Figure (6): Generator speed deviation with and without Inductive-SFCL**

### B. Autoreclosing

Fig. 7 shows the waveform of generator load angle when increasing the output power of the generator in which the power factor is assumed to be 0.9. The system is still stable. However, when the auto-reclosing of the circuit breakers is taken into account, the system lost its stability. The sequence of the fault is assumed as: fault occurs at 1/50s, circuit breakers opened at 7/50s, closed again at 19/50s and finally opened at 25/50s.

Fig. 8 shows the generator load angle for the rotor speed without and with YBCO SFCL. The system is unstable without SFCL. However the introduction of Inductive-SFCL brings the system back to stability that manifest the function of transient stability improvement in the system. The reason is that without SFCL, the output power is dropped when the fault occurs and not recovered after clearing the fault. On the other hand, with Inductive-SFCL, the generator output power is higher during the fault period because the fault current is limited immediately. Also, the output power is recovered back after clearing the fault.

**Figure (7): Generator load angle without Autoreclosing**

**Figure (8): Generator load angle with Autoreclosing**

**Figure (9): Generator speed deviation with Autoreclosing**

### V. CONCLUSION

The studies performed in this paper show the influence of superconducting devices on power transient stability. The inductive–SFCL was analyzed. Simulation studies are performed using one-machine connected to an infinite bus by transformer and two parallel lines.

It was shown that the system stability can be enhanced by the introduction of inductive-SFCL in the system due to its function of limiting the fault current immediately.
The problem of auto-reclosing, which makes the stable system unstable, was found to be solved by using inductive-SFCL in the system in case of YBCO material. When using Bi-2212 material, the resistive type makes the system stable, but the inductive type doesn't make the system stable. It is clearly from these figures that YBCO material make the stability is better than the Bi-2212 material, the reason of this is because the resistance of YBCO is greater than the Bi-2212 in this case.

References