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Experimental study on an SFCL using series-connected YBCO thin films

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Abstract. Superconducting Fault Current Limiters (SFCLs) are able to reduce fault currents to an acceptable value, reducing potential mechanical and thermal damage and allowing more flexibility in an electric power system's design. Due to limitations in current YBCO thin film manufacturing techniques, it is necessary to connect a number of thin films in different series and parallel configurations in order to realise a practical SFCL for electric power system applications. The amount of resistance generated (i.e. the degree of current limitation), the characteristics of the S-N transition, and the time at which they operate is different depending on their comparative characteristics. However, it is desirable for series-connected thin films to have an operating time difference as small as possible to avoid placing an excess burden on certain thin films. The role of a parallel resistance, along with the influence of thin film characteristics, such as critical current ($I_c$), are discussed in regards to the design of SFCLs using YBCO thin films.

1. Introduction
Fault currents due to short circuit conditions that can develop in electric power systems continue to increase due to growing power demands and the introduction of distributed generation (DG) systems, which increases the complexity of electric power system design. In order to reduce the mechanical and thermal damage that can be caused by these currents, various superconducting fault current limiters (SFCLs) have been researched. The SFCL is expected to be an important part of future electric power systems, particularly in developing countries, where superconducting devices are expect to make the largest impact [1].

SFCLs are able to reduce fault currents to an acceptable value to reduce potential damage, while allowing more flexibility in a power system's design and improving its stability. The device can also help avoid replacing circuit breakers whose capacity has been exceeded due changes in its associated network, or in some cases, actually reduce the required capacity.

Resistive type SFCLs with YBCO thin film have been studied previously. It is self-triggered and limits fault current by a rapidly generated resistance at the superconducting-normal (S-N) transition (otherwise known as quenching) [2]. They show a number of desirable characteristics, such as low impedance during normal power system conditions, high impedance during abnormal (fault) conditions, and rapid operation only at the rated fault current and not for switching surges [3].
Due to limitations in current YBCO thin film manufacturing processes, and the brittle, crystalline nature of the YBCO superconductor, it is not easy to obtain one large thin film that satisfies the specifications for high voltage/current applications. From an industrial point of view, the combination of standardised thin films has merit to reduce costs and maintain device quality. It is necessary to connect these thin films in different series (to decrease voltage drops across the thin films) and parallel (to increase the operating current of the SFCL) configurations in order to produce an SFCL for a particular specification of a commercial device for electric power systems. However, because the connections between the thin films possess resistance and one of the merits of using an SFCL is its small impedance (i.e. loss) during normal power system conditions, the number of thin film interconnections should be minimised.

In this paper, the series connection of two or more YBCO thin films of different superconductivity characteristics is discussed. When a number of thin films are connected together in series, the amount of resistance generated (i.e. the amount of current limiting), the characteristics of the S/N transition, and the time at which they operate is different. The role of a parallel resistance, along with the influence of thin film characteristics, such as critical current ($I_c$), are discussed in regards to the design of SFCLs using YBCO thin films.

2. Experiment Details
The structure of the thin films used in the experiments is shown in Figure 1, and their characteristics are shown in Table 1.

### Table 1. Characteristics of thin films for experiment

| Thin Film Name | Symbol | $I_c$ | $R_{\text{normal}}$ |
|----------------|--------|------|-------------------|
| #1 FB12        | $I_{c \text{ low}}$ | 40 A | 9.2 Ω            |
| #2 FB10        | $I_{c \text{ high}}$ | 70 A | 9.0 Ω            |

* the ‘$I_c$’ in these experiments is defined as the magnitude of the AC current that causes a significant superconducting-normal (S-N) transition, not the standard definition of 1 µV/cm for DC current.

** $R_{\text{normal}}$ is the resistance present in the superconductor just above its critical temperature ($T_c \approx 90$ K).

The thin films were connected in series, using the experiment setup shown in Figure 2, and a resistance connected in parallel to each, denoted as $R_{10}$ and $R_{12}$, respectively, was varied. A variable AC voltage source was used, which was connected in series with $R_{\text{shunt}}$, a very small shunt resistance (0.5 mΩ) used for measuring circuit current without a significant voltage drop, and $R_p$, a 0.2 Ω resistor used to ensure exceedingly large currents do not flow in the circuit when the superconductors are in their superconducting state. The sum of $R_{\text{shunt}}$ and $R_p$ represents a fictive transmission network’s impedance in short circuit conditions (hereafter referred to as $R_s$). Resistors, $R_{10}$ and $R_{12}$, are connected in parallel with the thin films, FB10 and FB12, respectively.

### Figure 1. Structure of YBCO thin film for experiment.

### Figure 2. Circuit schematic for series-connected thin film tests.

3. Theoretical Analysis
The circuit can be divided into three separate conditions for circuit current in this experiment setup, for an input signal $v_0(t) = V_s \sin(\omega t)$:

1. Below $I_{c \text{ low}}$ ($I_{\text{all}} \leq I_{c \text{ low}}$): $i_{\text{all}}(t) = \frac{V_s(t)}{R_e}$.
2. Between thin film Ics (Ic high ≥ Iall ≥ Ic low):

\[ i_{\text{low}}(t) = \frac{V(t)}{R_c + r_{\text{low}}} \quad \text{where} \quad r_{\text{low}} = \frac{r_{FB12} \cdot R_{12}}{r_{FB10} + R_{10}} \]

3. Above Ic high (Iall ≥ Ic high):

\[ i_{\text{low}}(t) = \frac{V(t)}{R_c + r_{\text{low}} + R_{\text{high}}} \quad \text{where} \quad r_{\text{high}} = \frac{r_{FB10} \cdot R_{10}}{r_{FB10} + R_{10}} \]

\( r_{FB10} \) and \( r_{FB12} \) are the resistances generated in FB10 and FB12, respectively. 

The transition from condition 1 to condition 2 occurs when \( r_{FB10} + R_{10} \) and \( r_{FB12} \) are the resistances generated in FB10 and FB12, respectively.

Thus, \( t_{\text{low}} = \frac{1}{2\pi f} \arcsin \left( \frac{I_{\text{low}} \cdot R_c}{V_s} \right) \). Similarly, the transition from condition 2 to condition 3 occurs when \( i_{\text{low}}(t) = I_{\text{low}} = \frac{V_s \cdot \sin(\omega t)}{R_c} \).

However, because of the time dependence of the thin film’s resistance, this equation cannot be easily solved. To simplify the analysis, the extreme cases, where R12 is either small or large, are considered. However, an accurate model of the resistance generated in a thin film is required to present a more accurate circuit analysis.

For R12 small, \( t_{\text{high}} = \frac{1}{2\pi f} \arcsin \left( \frac{I_{\text{high}} \cdot R_c}{V_s} \right) \). For R12 large, and assuming, for simplification, no time dependence for the thin film resistance, \( t_{\text{high}} = \frac{1}{2\pi f} \arcsin \left( \frac{I_{\text{high}} \cdot (R_c + r_{FB12})}{V_s} \right) \).

The operating time difference between the thin films is given by \( \Delta t = t_d = t_{\text{high}} - t_{\text{low}} \) for \( |I_{\text{all,peak}}| \geq I_{c \text{ high}} \). Similar equations to those above can be derived for any number of thin films connected in series.

4. Experiment Results

4.1. R12 Alteration

In this experiment, the parallel resistance of FB12 (the thin film with a lower I_c), R12, was varied and its effect on the SFCL was analysed, for a fixed R10. The current and voltage waveforms are shown in Figures 5 and 6, for R12 = 10 Ω and 1 Ω, respectively, for a source voltage of 60 V and R10 = 1 Ω. The source voltage of 60 V corresponds to a circuit current in between the lower and higher I_c, meaning that only FB12 quenches (i.e. condition 2). For increasing R12 values, no extra current flows through the thin film, but increased equivalent resistance causes the current to be limited further. 60 V corresponds to an I_sc of approximately 300 A, where I_sc is the expected current flow in the circuit without the SFCL present. Thus, the current is around 90% limited for R12 = 10 Ω, and around 75% limited for R12 = 1 Ω. Therefore, the parallel resistance can be selected such that the current is limited to a particular level. In each case, the current flowing through the thin film is constant, so the maximum potential limitation occurs for no parallel resistance (i.e. infinite R12).

From the previous equation for \( t_{\text{low}} \), a solution exists for \( V_s > 8 \) V. The resistance \( r_{\text{low}} \) affects \( t_{\text{low}} \) and the source voltage at which the thin film of higher I_c starts quenching. Figure 7 shows the resistance generated in FB12 for a source voltage of 60 V, R10 = 1 Ω, and various values for R12, ranging from 1 Ω and 10 Ω. It can be deduced from these results that the resistance generated in the thin film is dependent on the current flowing through it and remains relatively constant for changes to its parallel resistor.

For R12 = 0.25 Ω, the second thin film operated for \( V_s \geq 34 \) V (I_sc ≈ 170 A); for R12 = 1 Ω, \( V_s \geq 70 \) V (I_sc ≈ 350 A); and for R12 ≥ 1.5 Ω, \( V_s \geq 85 \) V (I_sc ≈ 425 A). Thus, by selecting a lower parallel resistance for R12, the thin film FB10 will quench at a lower fault level (i.e. lower source voltage). It is possible to design the parallel resistor such that thin films could be used in a primary-secondary-like configuration for systems with multiple fault levels. In this case, one thin film would operate for 40 A to 425 A, and both thin films would operate for above 425 A.

The operating time differences for all experiments is shown in Figure 8 for R12 = 0.25, 0.5, 1 and 1.5 Ω, and various R10 values, ranging from 0.25 Ω to 14 Ω. Note that the value of R10 does not significantly affect the operating time difference.
4.2. $R_{10}$ Alteration
In this experiment, the parallel resistance of FB10 (the thin film with a higher $I_c$), $R_{10}$, was varied and its effect on the SFCL was analysed, for a fixed $R_{12}$. The current and voltage waveforms, as well as the resistance generated and instantaneous power in each thin film are shown in Figures 9 and 10, for $R_{10} = 0.25 \, \Omega$ and $3.1 \, \Omega$, respectively, for a source voltage of 75 V and $R_{12} = 0.5 \, \Omega$.

For increasing $R_{10}$ values, the equivalent resistance is greater for the thin film FB10, leading to a higher voltage across it; thus, larger generated resistance. There is less resistance generated in the other thin film (FB12), leading to a mismatch in instantaneous power in favour of FB10. The reverse occurs when $R_{10}$ is less than $R_{12}$.

Figures 11 and 12 show the resistance generated in thin films FB10 and FB12, respectively, for a source voltage of 75 V, $R_{12} = 0.5 \, \Omega$, and various values for $R_{10}$, ranging from 0.25 $\Omega$ to 10 $\Omega$. As can be expected, as the ratio of the two resistances change, there are changes observed in the resistance generated in each thin film.

It can be deduced from Figures 9 – 12 that there exists an optimal parallel resistance ratio ($R_{10} = R_{12}$ for identical thin films), such that the resistance or voltage generated, or the instantaneous power in each thin film, are equal. This is discussed further in Section 4.3.

4.3. Optimal Resistance Ratio
As mentioned in the previous section, there exists an optimum ratio between the two parallel resistances, dependent on their individual characteristics, such that the resistance generated, voltage sharing or instantaneous power are equal – there are merits for each situation. In this experiment, the ratio of the parallel resistors is adjusted in order to obtain the same generated resistance waveform in each thin film.

The optimum ratio was calculated using the generated resistance waveforms shown in Figures 11 and 12 (for a source voltage of 70 V and a fixed $R_{12}$ of 0.5 $\Omega$). This ratio was found to be $R_{12} = 1.2 \, R_{10}$. Figure 13 shows the results for a source voltage of 70 V, using the optimum ratio equation for $R_{12} = 0.5 \, \Omega$ (i.e. $R_{10} = 0.6 \, \Omega$), and this is compared with equal parallel resistances ($R_{12} = R_{10} = 0.5 \, \Omega$), shown in Figure 14. The resistance generated in each thin film is shown, along with the instantaneous power.

The resistance generated waveform increases in similarity using the ratio of resistances; however, the instantaneous power differs. For such low parallel resistances, most of the power is dissipated in these, rather than the thin film; thus, there is a significant effect on the power when the resistance ratio is changed.

For $R_{12} = 1 \, \Omega$, the same equation was used to select $R_{10}$; however, it was found that this ratio could not be directly applied to different resistance values – there was no significant change in the resistance generated or the instantaneous power in each thin film. An optimum ratio would need to be selected for different resistances based on graphs of the resistance generated, such as Figures 11 and 12, or similar figures for instantaneous power, for that particular experiment setup.

**Figure 5.** Current & voltage waveforms for $V_s = 60 \, V$, $R_{10} = 1 \, \Omega$, $R_{12} = 10 \, \Omega$ (condition 2).

**Figure 6.** Current & voltage waveforms for $V_s = 60 \, V$, $R_{10} = 1 \, \Omega$, $R_{12} = 1 \, \Omega$ (condition 2).
**Figure 7.** Resistance generated in FB12 for various R\textsubscript{12} (fixed R\textsubscript{10}) during condition 2.

**Figure 8.** Operating time differences between thin films for different parallel resistances & operating voltages.

**Figure 9.** $V_s = 75$ V, $R_{12} = 0.5$ $\Omega$, $R_{10} = 0.25$ $\Omega$.

**Figure 10.** $V_s = 75$ V, $R_{12} = 0.5$ $\Omega$, $R_{10} = 3.1$ $\Omega$.

**Figure 11.** Resistance generated in FB12 for $V_s = 75$ V, $R_{12} = 0.5$ $\Omega$, varied R\textsubscript{10}.

**Figure 12.** Resistance generated in FB10 for $V_s = 75$ V, $R_{12} = 0.5$ $\Omega$, varied R\textsubscript{10}. 

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5. Conclusion

The series connection of two or more YBCO thin films of different superconductivity characteristics in an SFCL was discussed, in particular with regard to the parallel resistance connected to each thin film. The value of the resistance parallel to each thin film affects the amount of current limited by the device, but more importantly, the resistance parallel to the thin film of lower \(I_c\) affects the source voltage (i.e. fault current level) at which the thin film of higher \(I_c\) also quenches.

The ratio of the resistances between the thin films affects the resistance generated, as well as the instantaneous power, in each thin film. For equal parallel resistances, these characteristics differ depending on the particular properties of the thin film, which become more apparent for higher parallel resistances.

Thus, for a practical SFCL design, a value for the resistance parallel to the thin film of lower \(I_c\) can be selected for a particular current limiting specification and for the fault current levels for a primary-secondary-type configuration. Using waveforms of the resistance generated (or instantaneous power) in each thin film, an optimum resistance ratio can be calculated to produce similar resistance, voltage or instantaneous power waveform characteristics in both thin films.

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