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Experimental testing and development of improved modelling for multi-strand resistive SFCL

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***Abstract*—Magnesium Diboride (MgB_2) in simple round wire form has been tested and shown to be suitable as a low-cost resistive superconducting fault current limiter (SFCL). The commercial exploitation of MgB_2 SFCLs requires a considerable scale-up of the current-carrying capability of the MgB_2 wire. Multi-strand MgB_2 wire was developed for an SFCL coil to increase the current capacity. The paper will briefly report on the experimental results on a three-strand MgB_2 coil used as a resistive SFCL.**

An improved analytical model that predicts the behavior of the three-strand SFCL coil was developed taking the temperature and critical current variation along the wire into consideration. Variations in the critical current along the wire are to be expected as a consequence of normal manufacturing tolerances. The predicted current using the improved analytical model showed good correlation with experimental test result at different fault current levels. The improved analytical model is a useful tool for the practical design of commercial SFCLs.

***Index Terms*—Analytical model, MgB_2, Multi-strand superconductors, SFCL.**

I. Introduction

GLOBAL electricity demands are increasing with networks interconnected to improve the power quality and reliability as more distributed renewable energy generation is connected into the networks. This leads to increasing fault current levels in the electrical networks. Superconducting fault current limiters (SFCL) are a technology that can reduce the peak fault current levels and facilitate grid expansion [1-3]. Bismuth strontium calcium copper oxide (BSCCO), yttrium barium copper oxide (YBCO), and magnesium diboride (MgB_2) have all been widely researched for SFCL applications [4]. MgB_2 can be manufactured in simple round wire and tape form with different sheath materials and has been tested and proved to be suitable as a resistive SFCL [5, 6]. MgB_2 is also regarded as a cost-effective and economic material for SFCL applications because the raw materials are cheaper than BSCCO and the manufacturing process is simpler than YBCO coated conductors [4, 7, 8, 9]. State-of-the-art refrigerator systems have been discussed in [10]. Cryocooling systems for 4 K to 80 K temperature ranges include the recuperative types (steady flow) and the regenerative types. The Gifford-McMahon (G-M) and Stirling cryocooler are the most popular type for cooling superconductors in power applications [4, 10]. A 500 kVA SFCL using MgB_2 tape was designed and tested and this system used a Stirling cryocooler. [11]. The design feasibility of a dc resistive SFCL for 20 KV distribution system using cryogen free cooling has also been confirmed [12].

The commercial exploitation of MgB_2 SFCLs requires a considerable scale-up of the current-carrying capability of the MgB_2 wire. Multi-strand MgB_2 wire was developed for an SFCL coil to increase the current capacity [6, 13]. This paper will report the results of testing on a three-strand MgB_2 coil used as a resistive SFCL. A high-current line-frequency (50 Hz) supply was used to test the current-limiting properties in quench mode from 32 K to 23 K. The results demonstrate repeatable and reliable current-limiting properties and no detectable degradation of the wire performance during the quench process.

An analytical model that predicts the behavior of the SFCL coil using single MgB_2 wire has been developed previously [5]. The predicted fault current using the analytical model showed very good correlation with the experimental test results when the fault current level was much higher than the quench current. The predicted fault current however from the analytical model did not correlate as closely with the experimental results when the fault current just exceeded the quench current.

Variations in the critical current level along the wire would be expected as a consequence of normal manufacturing tolerances. An improved analytical model has been developed taking the temperature and critical current variation along the wire into consideration. The predicted fault current using the improved analytical model showed good correlation at different current levels. This paper describes the development of the improved analytical model under different simulation assumptions in detail and also the correlation with experimental test results.

II. Experimental setup

A monocore MgB_2 wire with a diameter of 0.36 mm was manufactured by Hyper Tech Research, Inc. Stainless steel was deliberately chosen as the sheath material for the wire to meet the high resistance per unit length requirement for application as a resistive SFCL. The average MgB_2 fill factor was 28.4% and had a manufacturing tolerance of ±12%. The

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lowest measured fill factor was 25.1% and highest was 30.6% in a population of 9 different wire batches [14]. Three wires were braided evenly together into one individual braid: a section of the braid is shown in Fig. 1. The critical current of the 3-strand wire was approximately 100 A at 25 K. Two braids were wound onto a ceramic coil former using an interleaved series connected coil design. The current flow direction is highlighted in Fig. 2. It is clear that the main solenoidal magnetic field is cancelled by the alternate current flow direction in adjacent slots, which minimizes the coil inductance. The SFCL coil was manufactured using a 'wind and react' method [7] and then tested in a commercial cryostat which could operate from 20 K to 80 K. The SFCL coil was placed in the copper containment vessel inside the cryostat, and then the cryostat was filled with liquid nitrogen. Conduction cooling using a commercial G-M cryocooler and an internal heater with a PI controller set the temperature on the SFCL coil. Assuming an operating current margin of typically 50%, the prototype SFCL coil had a nominal rating of 50 A/240 V at 25 K.

Fig. 3 shows the controllable high current supply circuit, which was used to test the quench behavior of the SFCL coil [5]. The variable transformer was manually adjusted to supply different voltage levels, which then provided different potential peak fault currents. A voltage step-down transformer with a turn ratio of 4:1 was used to increase the current level for the test coil. Voltage and current signals were monitored and recorded by a PC based LabVIEW system. The LabVIEW system also sent a signal to the switch so that the number of current cycles could be controlled.

Fig. 1. Three-strand MgB_2 wire braid

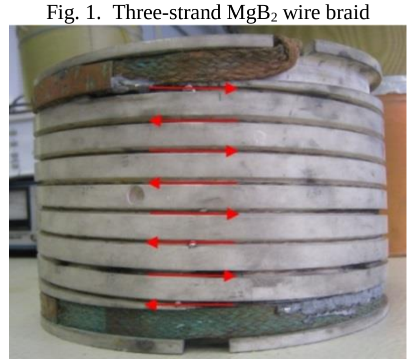

Fig. 2. Three-strand SFCL coil

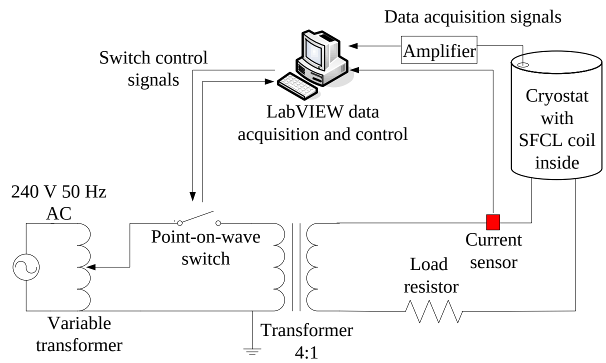

Fig. 3. High current test circuit schematic

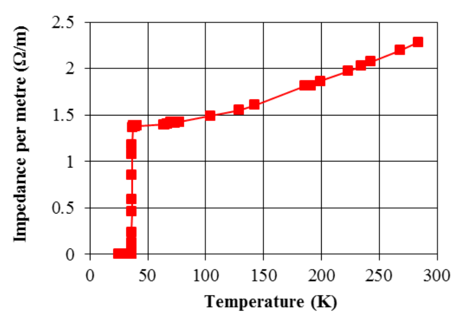

Fig. 4. Temperature-impedance variation

III. Experimental Results and Discussion

A. Temperature profile

The objective of the temperature profile test was to obtain the impedance of the coil at different temperatures and to determine if the coil was superconducting below the critical temperature. This temperature profile also could be used to model superconductor resistance when the coil is in the normal conduction state.

The impedance of the SFCL coil was measured from room temperature of 293 K down to 23 K. A low constant AC current was supplied to the coil and the instantaneous current and voltage were recorded. The impedance was calculated using the RMS voltage over RMS current. Fig. 4 shows the coil impedance variation with temperature. The resistance is 2.3 Ω/m at room temperature, reducing gradually as the temperature reduces. The resistance drops close to zero as it changes into the superconducting state. The critical temperature was found to be around 38 K.

B. Quench tests

Quench behavior is one of the most important features for an SFCL coil. A quench test was used to determine the quench current which is defined here as the current at which current limiting behavior is observed through the appearance of a resistive voltage across the superconducting coil. The quench test also determined if the SFCL coil would limit a fault current and if it did, whether it would recover to the superconducting state afterwards. Quench tests at different temperatures were also undertaken to determine the effect of the operating temperature on the quench current levels.

The high current test circuit was used to supply one cycle (50 Hz) to the SFCL coil. The prospective fault current level was gradually increased by manually adjusting the voltage set point of the variable transformer until the coil quenched before or at the first peak of the current. The prospective fault current is defined as the estimated fault current if the superconductor does not quench and is calculated based on the coil remaining in the superconducting state with negligible impedance. The quench tests performed at 25 K was taken as an example here because the MgB_2 coil was designed to operate at this temperature.

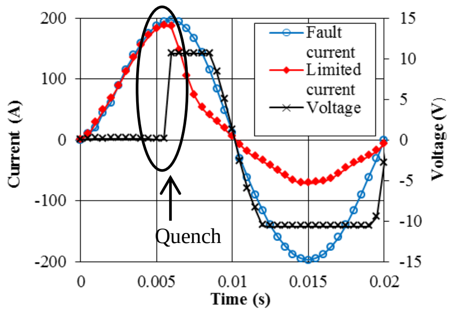

Fig. 5. Quench response at 25 K with a prospective fault current of 197 A

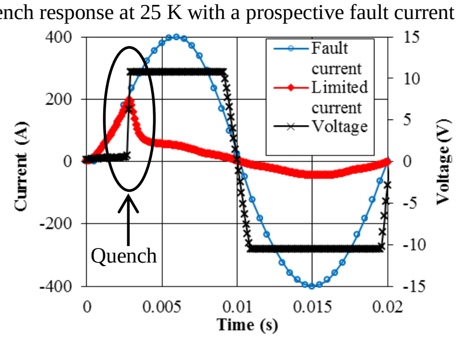

Fig. 6. Quench response at 25 K with a prospective fault current of 400 A

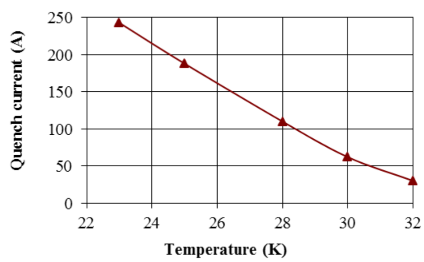

Fig. 7. Variation of quench current with temperature

Fig. 5 shows the fault current, measured coil current and voltage waveform with a prospective fault current of 197 A. It is clear that the voltage across the coil starts to increase when the current reaches 188 A and this current level is taken as the quench current for the 3-strand coil at 25 K. It should be pointed out that the LabVIEW card had a maximum input voltage of 10.5 V and the voltage signal above this level was clipped by the voltage amplifier to 10.5 V.

The prospective fault current was then increased to 400 A and the quench behavior shown in Fig. 6. The sampling rate of the LaBVIEW was increased from 2000 sample/sec to 10000 sample/sec to capture the rapid current change. Fig. 6 shows that the peak current was reduced effectively from 400 A to 193 A by the SFCL coil. The coil demonstrated consistent and reliable current-limiting properties as an SFCL.

Quench tests were then carried out from 32 K to 23 K. Fig. 7 presents the variation of the quench current level with temperature. It clearly shows that the quench current increases close to linearly from 32 K to 23 K. A linear variation of quench current from 23 K and above therefore was assumed in the analytical modeling.

IV. Modelling and Simulation

A. Analytical model

An analytical model is very useful in assessing the impact of an SFCL in modern power networks. In this analytical model, the SFCL coil was assumed to be a solid conductor with an outer surface adiabatic boundary condition. The SFCL coil was divided into a large number of sections of equal length so that the model allowed different initial conditions and wire parameters to be defined in each section. The modeling of the superconductor MgB_2 wire was divided into three operating states: superconducting state, flux flow state and normal conducting state.

The superconducting state of the MgB_2 wire was represented by *E-J* power law as follows:

$$E = E_c \left(\frac{J}{J_c} \right)^n \tag{1}$$

where J_c is the critical current density defined at the critical electrical field E_c of 1 μV/cm. J_c was taken to be 50% of quench current density as suggested in [15]. The *n*-value defines the steepness of the transition curve. An *n*-value of 13.8 was used for MgB_2 [7].

In the flux flow state, the following equation has been suggested and is commonly used [16]:

$$E = E_0 \left(\frac{E_c}{E_0} \right)^{\beta/n} \frac{J_c(25K)}{J_c(T)} \left(\frac{J}{J_c} \right)^{\beta} \tag{2}$$

where E_0 is 1 mV/cm and $\beta = 3$ are used in this model. *T* is the temperature the of MgB_2 wire.

The resistivity for the superconducting and flux flow states was developed from Ohm's law, which relates the current density to the electric field.

$$\rho = \frac{E}{J} \tag{3}$$

The resistance of the SFCL coil was determined as:

$$Rfcl = \sum_{m=1}^{ns} \frac{\rho_m l}{A} \tag{4}$$

where $Rfcl$ is the total resistance of the SFCL coil. *ns* is the total number of sections in the wire and *m* is the individual section number. The SFCL coil was separated into 100 sections for example in the model presented here. *l* is the length of each section and *A* is the total cross-sectional area of MgB_2 in the 3 strands of wire.

In the normal conducting state with the temperature above 38 K, a curve-fitting approximation to the resistance-temperature profile shown in Fig. 4 was used to model the resistance of the SFCL. This expression is given below:

$$Rfcl = \sum_{m=1}^{ns} (10^{-7} T_m^{\ 2} + 5.7 \times 10^{-6} T_m + 1.33 \times 10^{-2}) \tag{5}$$

where T_m is the wire temperature of section number *m*.

Circuit equation (6) was used to simulate the coil current in the high current test circuit.

$$\frac{di}{dt} = \frac{V - I(Rl + Rfcl)}{L} \tag{6}$$

where *V* is the sinusoidal source voltage, *Rl* is the circuit resistance including the load, transformer and lead resistances, and *L* is the coil or circuit inductance.

B. Modelling assumptions

An analytical model that predicts the behavior of the SFCL coil using single MgB_2 wire has been developed and presented in [5]. The predicted fault current from the analytical model showed very good correlation with the experimental test results when the fault current level was much higher than the quench current. The predicted fault current however did not correlate so accurately with the experimental results when the fault current was just greater than the quench current.

This improved analytical model that predicts the behavior of the three-strand SFCL coil has been developed including the temperature and critical current variation along the wire. Three modelling assumptions were studied:

(a) The first simulation investigated the temperature variation along the wire. Both ends of the coil were connected to copper braids and then to the copper terminals. The ends of the coil in practice therefore are usually slightly warmer than the middle of the coil during the tests. The two end sections of the coil therefore were defined to be 0.1 K higher than the mid-point section. The temperature therefore was assumed to vary linearly along the sections from each end to the mid-point on the coil [5].

(b) The second simulation considered the critical current variation along the wire. Variations in the critical current along the wire are to be expected as a consequence of normal manufacturing tolerances. As mentioned in section II, the wire sample had a manufacturing tolerance of ±12%. A random function was used to generate the critical current for each section of the coil within ±12%.

(c) The third simulation included both the temperature and critical current variations along the wire. The results from the above three simulations were compared to the experimental test results and discussed in the next section.

C. Simulation results

The analytical model using previous presented equations was implemented in MATLAB. The quench response with a prospective fault current of 197 A, which was just slightly in excess of the quench current of 188 A, was initially simulated. Fig. 8 presents the experimental test result and the analytical model simulation results with the above three modelling assumptions. Fig. 8 clearly shows the coil failed to quench in simulation (a), which only includes the temperature difference along the wire. This model is obviously not sufficient to predict the quench behavior for this specific SFCL coil when the current is just slightly higher than the quench current.

The simulation results however from both the second condition (b) and third condition (c) are similar and both show a good correlation with the experimental test results. The third simulation model considering both the temperature and critical current variation along the wire gives the best fit with the experimental test results.

Fig. 9 presents the comparison of the experimental test and analytical model results with a prospective fault current of 400 A. In this case all three simulation models show a good correlation with the experimental results. Overall the third wire model shows the best correlation with the experimental test result. It should be noted that the voltage spike highlighted in the circle is the inductive voltage due to the rapid decreasing current.

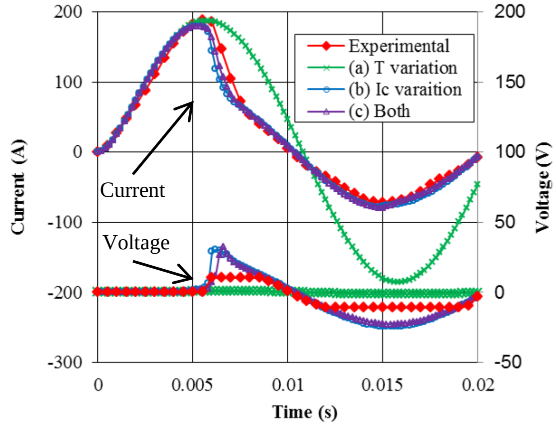

Fig. 8. Comparison of experimental test and analytical model results at 25 K with a prospective fault current of 197 A

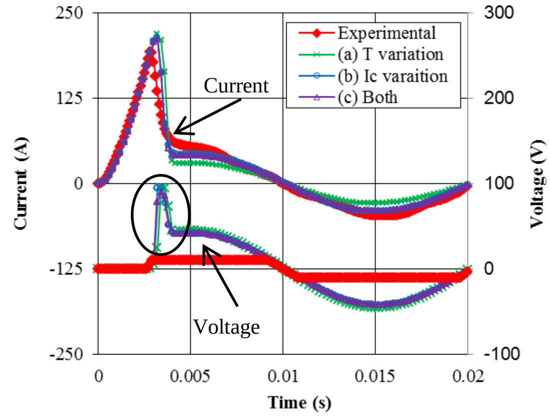

Fig. 9. Comparison of experimental test and analytical model results at 25 K with a prospective fault current of 400 A

The simulation with the high prospective fault current is less sensitive to the temperature and critical current variation along the wire because the coil will definitely quench due to the high current and following the quench the response is dominated by the increased wire temperature. The simulation with lower prospective fault current close to the quench current however tends to be more sensitive to the temperature and critical current variation along the wire, particularly to the critical current variation because the temperature variation is low.

In general all three simulation model conditions are suitable for modeling with prospective fault current much higher than the quench current. However only the simulation model considering both the temperature and critical current variation along the wire showed good correlation with experimental test results when the potential fault current just exceeded the quench current level and also when much higher than the quench current level. This improved model therefore is a useful design tool for practical SFCL coil simulation under different fault current levels.

V. Conclusion

Multi-strand MgB_2 wire was used to develop an SFCL coil with increased current capacity. A three-strand MgB_2 coil was tested experimentally as a resistive SFCL and has shown repeated and reliable fault current-liming properties.

An improved analytical model that predicts the fault current response of the three-strand SFCL coil has been developed, taking the critical current and temperature variations along the wire into consideration. The predicted fault current using the improved analytical model showed good correlation at different fault current levels. The improved analytical model is a useful tool in the practical design of commercial SFCLs.

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