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A New Cable-in-conduit Conductor Magnet with Insulated Strands

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Abstract

Many studies have used cable-in-conduit conductor (CICC) coils in trying to develop an AC superconducting magnet because of its enormous potential if AC losses were low and insulation voltage was high. The strands in the most recent CICC magnets are coated with chromium or another metal with high electrical resistance to order to induce current re-distribution among the strands and to avoid a quench caused by a current imbalance. Current re-distribution is highly complex and very difficult to analyze because the conditions of the strand surfaces and the contact areas vary greatly with the operation of the conductor. If, however, the cable currents were well-balanced, insulating the strands would be the best way to reduce AC losses. We propose a new CICC magnet structure featuring a current lead that balances the strand currents via its resistance. Having calculated current balances, we find that strand currents are well within the present parameters for nuclear fusion experiments and superconducting magnet energy storages.

Keywords: superconducting magnet, quench, stability, current imbalance, CICC magnet, current lead

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I. INTRODUCTION

Cable-in-conduit conductor (CICC) magnets are used in nuclear fusion experiments [1]-[2], and superconducting magnet energy storages (SMESs) [3] because AC losses are iower and insulation voltage higher than in other types of magnets. CICCs are called bundle conductors and are composed of a great number of strands. The best way to minimize inter-strand coupling and AC loss is to insulate the strands individually.

However, current imbalance problems were first observed in a small-scale experiment [4], while Faivre and Turck [5] showed that the presence of resistance in the strand circuit alleviates the current imbalance problem; but the presence of resistance in the low temperature region of a superconducting magnet with its near-zero resistance is not at all desirable from the standpoint of the engineer. Faivre and Turck [5] also pointed out that a normal zone in the strands causes current re-distribution between them, which should improve the imbalance of the current and the performance of the superconducting magnet. A medium-scale superconducting magnet was built that used completely insulated strands [6], but the magnet was quenched at a current much lower than its design value. Analysis of this quench showed the current imbalance to have been its main cause [7]. The current imbalance is also created by an external field as a circulation current is induced. Koizumi et al. [8] introduced a new stable operation using a heater that creates a normal zone, improving the current imbalance and the performance of the magnet system. However, when the cable insulation breaks, a short circuit is created, and the current imbalance increases [9]. In recent CICC magnets, the strands are therefore not completely insulated, but their surfaces are coated by highly resistive material such as chromium [10].

We shall examine the principle of the current imbalance before proposing a new method to avoid the current imbalance without creating any extra heat in the superconducting magnet system. We then assess its performance and discuss its future applications.

II. PRINCIPLE OF CURRENT IMBALANCE

Since multistrand CICCs are bundled, thus constitute a parallel circuit, and we studied the two-wire model shown in Fig. 1. If the power supply voltage changes sinusoidally, the current ratio of these two wires is given by

$$\frac{I_1}{I_2}=\frac{R+i\omega(L_2-M)}{R+i\omega(L_1-M)} \tag{1}$$

$$k^2=\frac{M^2}{L_1L_2} \tag{2}$$

$$L_1=L \quad \& \quad L_2=L(1+\beta) \tag{3}$$

$$\gamma=\frac{\omega L}{R} \tag{4}$$

where I_1 and I_2 are the currents of the two wires, ω is the frequency, i the imaginary unit, R, the resistance, L_1 and L_2 are the self-inductances, and M is the mutual inductance.

Since the self-inductances are almost the same, we used the coupling factor k and introduced the parameters β and γ to analyze the circuit. Because of the structure of the circuit, the value of β is small and the value of k is close to unity, and the value of mutual inductance is therefore close to the value of self-inductance. The parameter γ is the impedance ratio. The absolute values of the current ratios are plotted in Fig. 2. Self-inductances differ by only 1 %, but when the coupling factor is between 0.96 to 0.99, the current ratio is over 1.5. Variation of self-inductance will depend on the manufacture and size of the conductor. If the magnet is large, the variation will be smaller than in a small-scale magnet of identical strand diameter. This means that the current imbalance problem is less severe in a large-scale magnet. Also, when the impedance ratio is low, the current ratio is low. This means that the current imbalance improves with higher resistance. When the impedance ratio is 400, the corresponding resistance will dissipate 1 % of the magnetic energy of the magnet in one AC cycle.

III. PROPOSAL

Superconducting magnet system consists of a superconducting magnet, power supply and current leads, as shown in Fig. 3. With the temperature of the current lead ranging from room temperature to a low temperature of 4 K, the conductors of the current lead are either in a normal or superconducting state. Heat flow through thermal conduction from the room temperature side of the current lead to the low temperature side and Joule loss created by the resistance of the strands should be kept as low as possible to realize a stable superconducting magnet system. The current lead should therefore consist of many strands and allow the low temperature gas flow to reduce the heat on the surfaces of the strands. The strands of the current lead should be insulated from each other and connected with the strands of the superconducting magnet, as shown in Fig. 4. This design allows the necessary resistance to be introduced to the strand circuits in series, which leads to a current balance.

IV. PERFORMANCE OF PROPOSAL

Table 1 gives the parameters of CICC magnets for SMES and nuclear fusion experiments, and Table 2 gives the parameters of current leads.

The current of strands in superconducting magnets ranges from 30 to 120 A and the voltage differential in current leads from 35 to 155 mV. The diameter of a current lead strand is around 1 mm and its current around 100 A. Since the current of the strands in both the current lead and the superconducting magnet are of the same order of magnitude, it will be easy to connect them directly in series. The standard deviation of self-inductance was found to be 1.4 % , while the coupling factor was found to have a minimum value of 0.956 and a maximum value of 0.994 [9]. Current rise and fall times in nuclear fusion experiments and SMES are designed to be 1 to 100 seconds. Since we can gather the variations of the self-inductances and mutual inductances from an analytical model and experiments [4, 9], we can calculate the current of each superconducting magnet strand: Here, the current balance is estimated by Eqs. (1) to (4). The variation magnitude of (L-M) is order of 10^{-6} to 10^{-5} even in a large magnet [4, 10] because the coupling factor in the large magnet is high and the variations of self-inductance and mutual-inductance decrease. The magnitude of frequency ω is 10^{-1} to 10^{0}, on the other hand the resistance of current lead is the order of 10^{-3} to 10^{-4}, so the resistance part is at least 10^{2} to 10^{1} times larger than the inductance part in Eq. (1). This means that the currents are balanced even with a 2 to 20 mV voltage drop in the above-mentioned parameters. Since these voltage drops are lower than the voltage drops of the current leads (see Tables 1 and 2), our proposal solves the current imbalance problem.

V. DISCUSSION AND CONCLUSION

Present CICC strands are coated by highly resistive layers and are not completely insulated from each other. This means that normal zones and current re-distribution occur during the rise and fall in the current, which makes it impossible to establish a stable magnet system. When we apply our proposal, the current imbalance, induced by itself or an external field, will disappear, creating a more stable superconducting magnet.

If the current of one strand increases, the Joule loss increases raising the temperature and with it the resistance of the strand, which automatically decreases the current again bringing the current back into balance and making the system essentially stable. However, we have to consider the possibility that external factors lead to normal zones. A strong magnetic field, for example, would create strong magnetic forces, and the friction would generate heat. A time variable magnetic field would create an eddy current, and this would also generate heat in the structure of the superconducting magnet. With heat flowing into the magnet, normal zones would occur in the strands. When the strands are completely insulated from each other, the end of the strands in the room temperature connection terminals of the current leads facilitate current re-distribution. This re-distribution process is of great importance to the recovery of the superconducting state and depends on the parameters of both magnet and current leads.

The number of strands in Table 1 is over 200, and connecting each pancake of the superconducting magnet and the current leads separately will require a new connection method. However, it will not be difficult to build this connection because whatever its resistance, it will be smaller than that of the current lead. In present CICC magnets, it is very difficult to build the connections because their resistances should be identical to avoid current imbalances. High temperature superconducting material (HTSC) has recently been developed and is being used in current leads because thermal conductivity is lower than in the usual metallic materials (see Table 2). This high temperature superconducting material current lead (HTSCCL) has a reduced heat flow to the low temperature side and lower operation costs. HTSCCLs currently have a capacity of several hundred amperes, and many efforts are being made to develop a high current capacity HTSCCL. HTSC is very well suited for our proposal because current lead resistance occurs mainly on the room temperature side, while HTSC is used on low temperature side. If we apply our proposal, many low current capacity HTSCCLs could be used separately to form one high current capacity HTSCCL system. This part of our proposal is just entering the experimental phase. While our proposal complies with the parameters in Tables 1 and 2, the commercially available frequency does not support a current lead voltage differential great enough to bring the current back into balance. A high voltage differential would not be a suitable solution in a superconducting magnet system, and we are currently investigating other approaches to this problem.

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Figure Captions

Fig. 1. Circuit of a two-wire model. R is the resistance of the wires, L1 and L2 the self-inductances of the two wires, and M their mutual inductance.

Fig. 2. The vertical axis shows the current ratio and the horizontal axis the coupling factor. Impedance ratios were 100, 200, 400.

Fig. 3. Schematic drawing of superconducting magnet system.

Fig. 4. Connection of current lead strands with superconducting magnet strands.

Table 1. Parameters of CICC magnets for SMES and nuclear fusion studies.

Table 2. Parameters of various current leads.

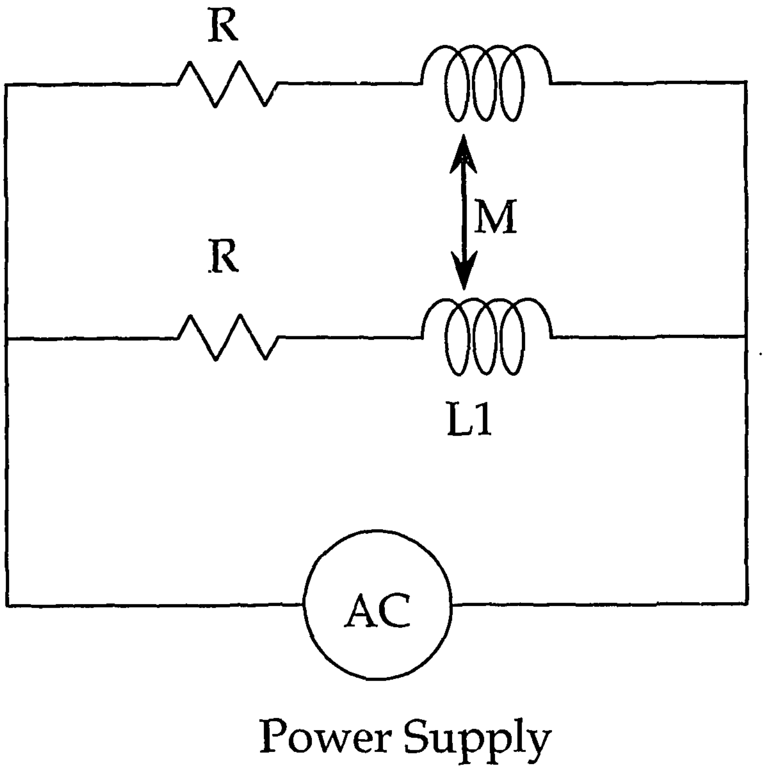

Fig. 1

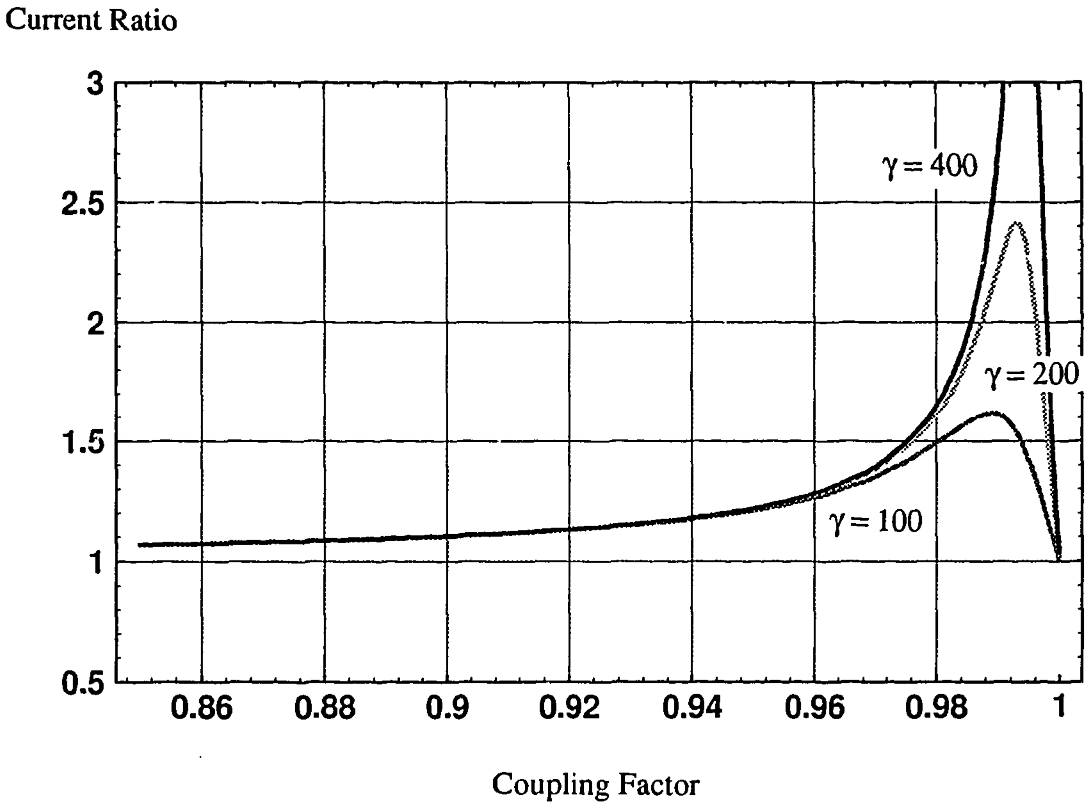
Current Ratio
3
2.5
2
1.5
1
0.5
0.86
0.88
0.9
0.92
0.94
0.96
0.98
1
γ = 400
γ = 200
γ = 100
Coupling Factor

Fig. 2

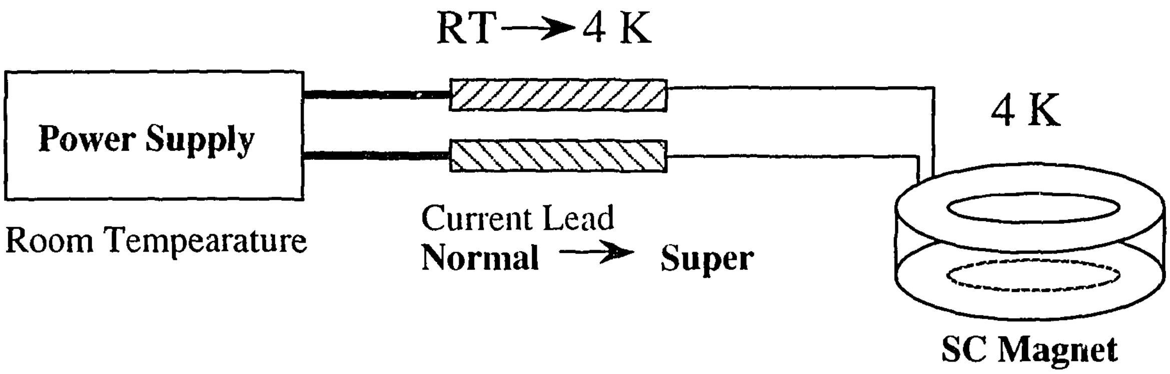
RT → 4 K
Power Supply
Room Tempearature
Current Lead
Normal → Super
4 K
SC Magnet

Fig. 3

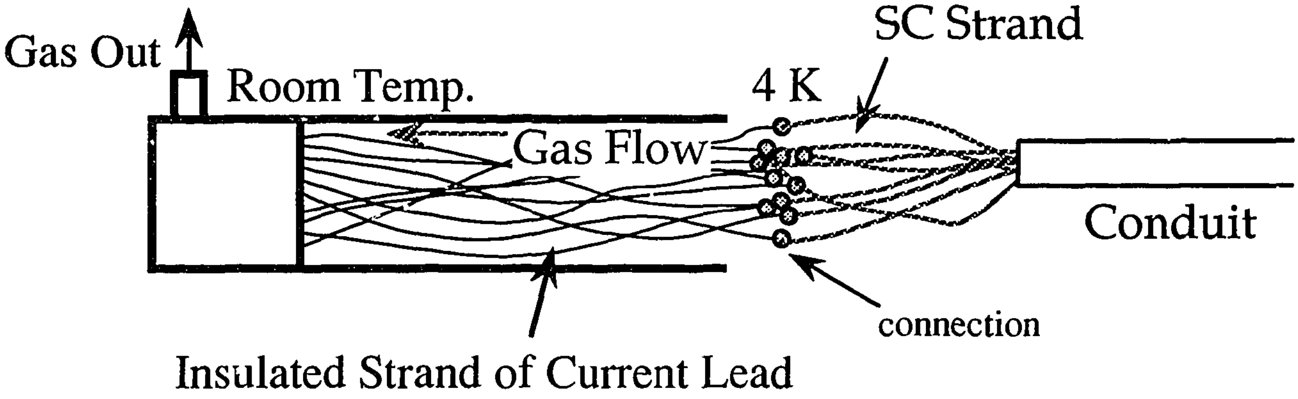
Gas Out
Room Temp.
4 K
SC Strand
Gas Flow
Conduit
connection
Insulated Strand of Current Lead

Fig. 4

Table 1

	Temp. (K)	Field(T)	Current(kA)	Number of Strand	Current of Strand (A)	Material	Comment
SMES	4.5	6.2	40.0	324	123.46	Nb3Sn	Ref. [18]
SMES	4.5	5.6	60.0	972	61.73	Nb3Sn	Ref. [17]
NIFS	4.5	3.0	21.0	486	43.21	NbTi	Ref. [16]
JAERI	4.2	10.0	10.0	153	65.36	Nb3Sn	Ref. [15]
ITER-TF	4.5	12.5	46.6	1152	40.45	Nb3Sn	Ref. [9]
ITER-CS	4.5	13.0	39.0	1152	33.85	Nb3Sn	Ref. [9]

Table 2

	Ideal Gas Cool CL	Commercial-1 (Gas Cool CL)	Commercial-2 (Gas Cool CL)	Direct Cool Bi-oxide CL
Voltage Drop (single)	80 mV	50 mV	35 - 55 mV	61 mV
Current	50 A	5.0 kA	30 kA	31.1 A
Comment	Ref. [11]	Ref. [12]	Ref. [13]	Ref. [14]

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