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Current overshoot operation of a REBCO magnet to mitigate SCF

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Abstract

Due to large in-field current carrying capacity and strong mechanical strength, a REBCO wire has been regarded as a viable high temperature superconductor (HTS) option for high field MRI and > 1 GHz (>23.5 T) NMR magnets. However, a REBCO magnet is well known to have an inherent problem of field inhomogeneity, so-called 'Screening Current induced magnetic Field (SCF)'. Recently, 'field shaking' and 'current overshoot operation' techniques have been successfully demonstrated to mitigate the SCF and enhance the field homogeneity by experiments. To investigate the effectiveness of current overshooting operation technique, a numerical simulation is conducted for a test REBCO magnet composed of a stack of double pancake coils using '2D edge-element magnetic field formulation' combined with 'domain homogenization' scheme. The simulation result demonstrates that an appropriate amount of current overshoot can negate the SCF. To verify the simulation results, current overshoot experiments are conducted for the REBCO magnet in liquid nitrogen. Experimental results also demonstrate the possible application of current overshoot technique to mitigate the SCF and enhance the field homogeneity.

Keywords: REBCO magnet, field homogeneity, screening current induced field, current overshoot, field shaking

1. INTRODUCTION

Due to continuous improvement of mechanical and electromagnetic performance of REBCO HTS (High Temperature Superconductor) wire [1], there have been research efforts to develop high field magnets over 20 T using these HTS wires combined NI (no insulation) winding scheme [2-8]. Several REBCO magnets have been fabricated and successfully demonstrated their magnetic field performance. Also, the REBCO wires has been considered as a feasible option for high field MRI (Magnetic Resonance Imaging) and NMR (Nuclear Magnetic Resonance) magnets over 1 GHz due to their large in-field current carrying capacity and excellent mechanical property [4-8]. However, the REBCO magnets are known to have an inherent problem of field homogeneity called as 'Screening Current induced magnetic Field (SCF)' [9-12] and it is regarded as a major hurdle for the development of the magnet that requires highly homogeneous magnetic field.

The SCF is known as the distortion of magnetic field caused by induced screening current as shown in Fig. 1. The screening current is generated by perpendicular magnetic field to the wire surface. To mitigate the SCF, the non-uniform current distribution should be manipulated to be uniform and several approaches have been suggested and demonstrated. The two well-known methods are (1) 'field shaking' using an external magnet' [13, 14] and (2) 'current overshoot' operations [15, 16]. Field shaking method uses an external AC magnet to apply parallel magnetic field to REBCO layers so as to reduce the current non-uniformity. For the current overshoot method, a magnet current is raised over a target current and return back to the target current as shown in Fig. 2. During this process, a reversed screening current is generated and the SCF is reduced effectively. Regarding the current overshoot method, authors presented a numerical simulation and experimental results of a NI REBCO magnet demonstrating an enhanced spatial homogeneity and temporal stability [16]. Yet, charging delay is also involved with temporal stability of the magnetic field in the NI REBCO magnet and it is required to decouple the charging delay effect from the measured field stability.

This paper describes the 'current overshoot' method using a REBCO magnet composed of a stack of three double pancake coils (DPCs), where a polyimide film is co-wound for turn-to-turn insulation to eliminate the charging delay from NI winding. To simulate the variation of the SCF of the magnet, '2D axisymmetric edge element

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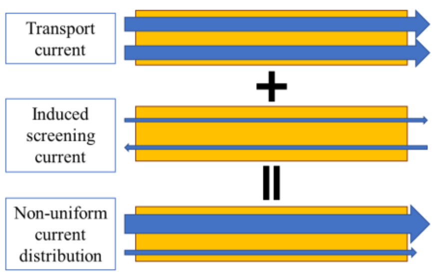

Fig. 1. Generation of non-uniform current distribution by induced screening current in a REBCO tape.

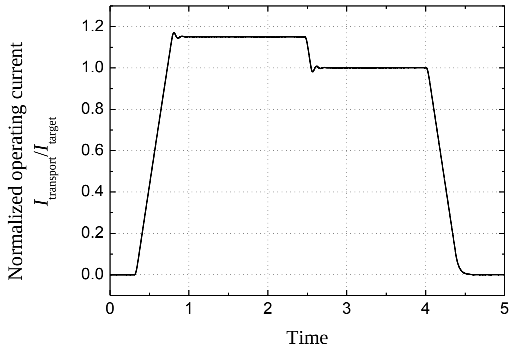

Fig. 2. Example of current overshoot operation.

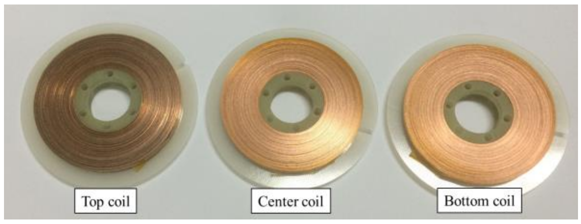

Fig. 3. Double pancake REBCO coils by co-winding of polyimide film.

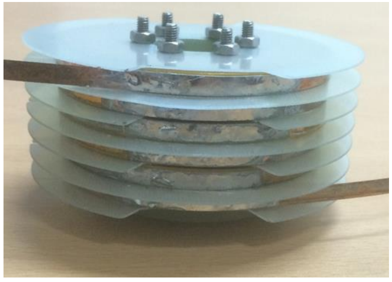

Fig. 4. Fabricated REBCO magnet by stacking 3 DPCs and external joints.

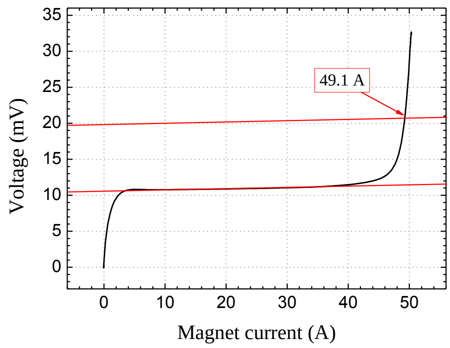

Fig. 5. Critical current measurement of the REBCO magnet.

magnetic field formulation' combined with 'domain homogenization method', which is known as the most efficient numerical simulation method for the stacked REBCO wires, was adapted [16-18]. For the verification of the effectiveness of the current overshoot method, experiments were conducted under same operating conditions in the simulation.

2. REBCO MAGNET

2.1. Fabrication of the magnet

The REBCO magnet consisted of stacked three DPCs and each DPC was fabricated by winding a REBCO wire of 4 mm width, 0.15 mm thickness on a 20 mm diameter GFRP winding form shown as Fig. 3. To eliminate charging delay in NI coil, a polyimide film was co-wound for the turn-to-turn insulation. The detail specifications of the REBCO wire and key parameters of the REBCO magnet are described in Table I. Fig. 4 shows the fabricated REBCO magnet.

2.2. Critical current measurement

The critical current of REBCO magnet was measured in a bath of liquid nitrogen to ensure that there was no defect in the winding process. Based on 1 μV/cm, the critical current of REBCO magnet was measured as 49.1 A while ramping up the magnet current by 1 A/s as shown in Fig. 5.

In our numerical analysis model, the measured critical currents of each DPC were used instead of field-angle dependency of the critical current for calculation simplicity.

TABLE I
SPECIFICATIONS OF REBCO WIRE AND KEY PARAMETERS OF REBCO MAGNET.

Parameter	Value
REBCO wire	
HTS material	(Gd)BCO
Substrate and stabilizer	Stainless steel/ electroplated copper
Width and thickness	4.1 (±0.1) mm / 150(±10) μm
Critical current	240 A @ 77 K, self-field
REBCO magnet	
Inner/Outer diameter	30 mm / 65 (±0.2) mm
Coil spacer	0.5 (±0.05) mm
Overall Height	28.1 mm
Conductor length per DPC	33 m
Turns per pancake	100
Operating temperature	77 K (liquid nitrogen)
Magnet constant, α	144.6 G/A
Total inductance	11.2 mH

3. NUMERICAL ANALYSIS OF SCF

3.1. Numerical analysis model

There have been many kinds of FEA (Finite Element Analysis) models to simulate the current distribution and AC loss of HTS magnets or HTS power cables in consideration of non-linear *E-J* correlations of HTS wires. Among them, 'edge-element magnetic field formulation' is known as an efficient model to obtain current distribution inside each HTS wire and resultant AC loss. However, this model also requires large computational resource for multiply stacked HTS wires such as REBCO magnets since the same number of additional constraints as the number of REBCO wires are required to impose the transport current in the REBCO wire. To dramatically reduce the computational resource while keeping accuracy, a more efficient analysis model has been proposed called as '2D edge-element magnetic field formulation with domain homogenization method', where single integral constraint is used for a stacked domain instead of individual constraints for each REBCO wire.

In our analysis model, '2D edge-element magnetic field formulation with domain homogenization method' was adapted to calculate the current distribution and variation of the SCF in accordance with current overshoot sequences.

3.2. Numerical analysis results

Fig. 6 compares the calculated normalized current distribution at the target current of 40 A: (a) uniform current distribution where the induced screening current is not exists; (b) after simple linear ramp up to 40 A; (c) after 10 % current overshot; (d) after 20 % current overshoot. For simple ramp up in fig. 7 (b), current density is concentrated at the upper edge of stacked REBCO wire while negative current density appears at the low edge due to the induced screening current by increasing radial magnetic field and it results in the decreased magnetic field at the magnet center. In contrast, reversal screening current is generated during the decreasing radial magnetic field after the current overshoot and the non-uniform current densities are averaged out as in fig. 6 (c) and (d). Consequently, the SCF decreases after the current overshoot and the increased magnetic field depends on the amount of current overshoot.

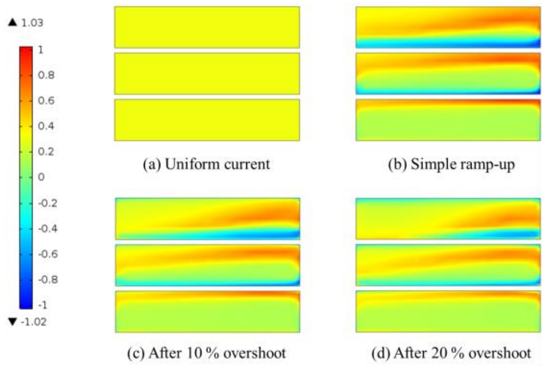

Fig. 6. Equivalent current distributions at transport current of 40 A: (a) uniform current distribution; (b) after simple ramp up; (c) after 10 % current overshoot; (d) after 20 % current overshoot.

In the same way, numerical analyses were conducted for various overshoot amounts and two target currents of 40.0 and 37.7 A which corresponds 30 and 17 % operation margins based on the measured critical current of 49.1 A in fig. 5. Fig. 7 describes the resultant SCF, B_{SCF}, at the center of the magnet in accordance with the different amount of overshoot current. The SCF is the difference between the magnetic field by our model, B_{model}, and that calculated with the uniform current distribution at the target currents, I_{target}, using the magnet constant, α, as in (1).

$$B_{SCF} = B_{model} - \alpha I_{target} \quad (1)$$

As the normalized overshoot amount increased, B_{SCF} decreased from negative to positive value. Therefore, it is expected that B_{SCF} can be minimized at the overshoot amount of 21 and 17 % for the target current of 37.7 and 40.0 A, respectively.

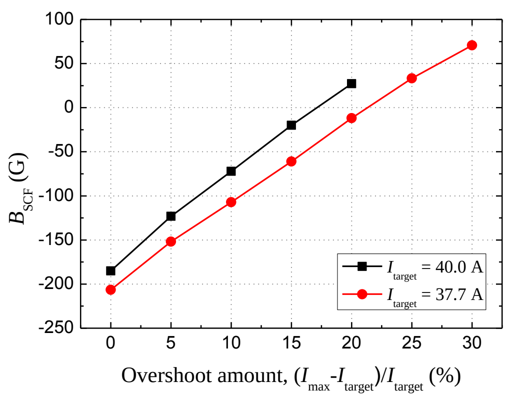

Fig. 7. Calculated SCF at the magnet center for different current overshoots and target currents.

4. EXPERIMENT

4.1. Experimental set up

To verify the effectiveness of the current overshoot technique, the fabricated REBCO magnet was cooled in a bath of liquid nitrogen and the axial magnetic field was measured at the magnet center using a cryogenic hall sensor (HGCA-3020, Lakeshore) while transporting the magnet current using a DC power supply.

4.2. Experimental results

Fig. 8 shows the variation of magnetic field during the simple ramp up and ramp down of the magnet current. In fig. 8, it was possible to observe the residual magnetic field of 297 G even though the magnet current returned to 0 A, which was commonly observed in other experiments and this is also caused by the SCF generated by decreasing magnetic field [10].

Using the same operating sequences in the analysis, experiments were conducted by controlling the magnet power supply. Fig. 9 shows the measured SCFs at the center

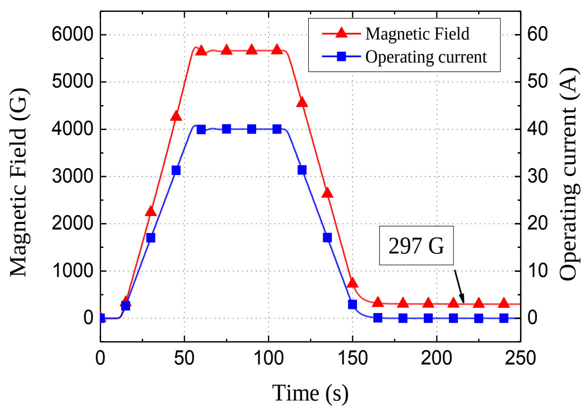

Fig. 8. Experimental results of simple linear ramp up and down.

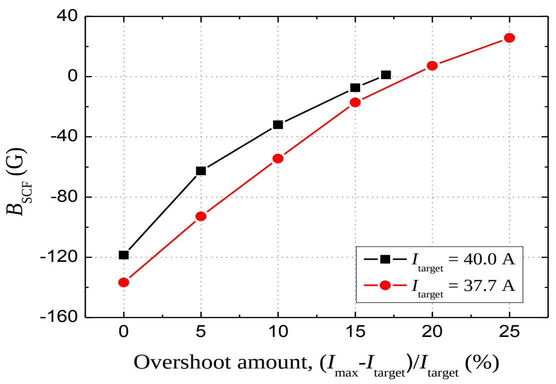

Fig. 9. Measured SCF at the magnet center for different current overshoots and target currents.

TABLE II
COMPARISON OF ANALYSIS AND EXPERIMENTAL RESULTS.

Target current	Overshoot amount	B_{SCF}	
		Analysis	Experimental
37.7 A	0 %	-207 G	-137 G
	5 %	-152 G	-92.8 G
	10 %	-107 G	-54.4 G
	15 %	-61.0 G	-17.2 G
	20 %	-11.8 G	7.2 G
	25 %	33.3 G	25.7 G
40.0 A	0 %	-185 G	-119 G
	5 %	-123 G	-62.6 G
	10 %	-72.1 G	-32.1 G
	15 %	-19.9 G	-7.4 G
	17 %	0 G	1.2 G

of the magnet in accordance with the different amount of overshoot current. The experimental results showed that the SCF was -137 and -119 G after simple ramp up for the respective target current of 37.7 and 40 A, while they were decreased to 7.2 G and 1.2 G after overshoot amount of 20 and 17%, respectively.

5. DISCUSSION

Through numerical analysis and the experiment, the mitigation of SCF was investigated for the various amounts of current overshoot and two target currents. Although the magnitude of SCF in Table II shows some discrepancies between the analysis and the experiment, decrease of the SCF was verified as the overshoot amount increased. Especially, the SCF of analysis was larger than that from experiment and this is thought to be caused by inexact modeling of the magnet and REBCO wire. Generally, the critical current depends on the magnetic field and its angle to wire surface. The analysis model, however, used a constant critical current. This makes larger induced screening current at a low magnetic field region of the magnet and it is believed to result in the over estimation on the SCF in the analysis. Hence, it was possible to verify the discrepancy decreased as the overshoot amount increased, where the assumed critical current approached the actual value.

6. CONCLUTION

In this paper, a REBCO magnet, where polyimide films were co-wound using a REBCO wire, was fabricated to investigate the effectiveness of current overshoot operation to mitigate the SCF excluding charging delay in NI magnets. The analysis model adapted '2D axisymmetric edge element magnetic field formulation' combined with "domain homogenization method" to calculate current distribution and the SCF for the various overshoot amounts. Through the analysis, the relation between the current distribution and the SCF was investigated and it was confirmed that the manipulation of current distribution by current overshoot could mitigate of SCF.

For the verification of the analysis model, experiments were conducted under same operating conditions of the analysis and the results showed the same tendency of the analysis. Although there was some discrepancy between the analysis and the experiment, it was possible to determine the optimized overshoot amount to minimize the SCF. The discrepancy might be reduced using an exact field-angle dependency data of critical current in the REBCO wire.

With this study, it is expected that a proper amount can be determined to mitigate the SCF of actual high-resolution NMR/MRI magnets.

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