Book Chapter

Experiment and numerical analysis on temporal stability of a bitter-like HTS magnet excited by MPFM

Xi Yuan*, Yinshun Wang, Yueyin Wang, Yukai Qiao, Changtao Kan and Wei Pi

State Key Laboratory for Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, China

*Corresponding Author: Xi Yuan, State Key Laboratory for Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China

Published May 25, 2020

This Book Chapter is a republication of an article published by Xi Yuan, et al. at AIP Advances in September 2019. (Xi Yuan, Yinshun Wang, Yueyin Wang, Yukai Qiao, Changtao Kan, Wei Pi. Experiment and numerical analysis on temporal stability of a bitter-like HTS magnet excited by MPFM. AIP Advances. 9, 095004 (2019); https://doi.org/10.1063/1.5112148.)

How to cite this book chapter: Xi Yuan, Yinshun Wang, Yueyin Wang, Yukai Qiao, Changtao Kan, Wei Pi. Experiment and numerical analysis on temporal stability of a bitter-like HTS magnet excited by MPFM. In: Prime Archives in Physical Sciences. Hyderabad, India: Vide Leaf. 2020.

© The Author(s) 2020. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License(http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
Acknowledgments: The authors would like to thank the Shanghai Creative Superconductor Technologies Co., Ltd. for providing help in processing REBCO annular plates. This work is supported in part by the National Natural Science Foundation of China under Grant No. 51877083.

Abstract

A full high temperature superconducting (HTS) magnet can operate in persistent current mode (PCM), which has promising application in high magnetic field. A laboratory scale Bitter-like HTS magnet stacked by REBaCuO (RE: rare earth element) annular plates was proposed and it can operate in PCM without current lead and joint resistance. This study focuses on the temporal stability of the magnetic field generated by the magnet, which was energized by the multi-pulsed field magnetization (MPFM) method composed of a solenoid coil and pulsed triangular waveform current source and tested at 77 K (LN$_2$ bath). The characteristics of the magnetic field in the magnet with various pulsed current amplitudes, durations and reversal excitation experiments were systematically researched. Moreover, the numerical simulation of the magnet energized with the pulsed current amplitude 3A was performed and the attenuation of the magnetic field in the magnet was discussed and analyzed.

Introduction

The Bitter magnet was a solution created by Francis Bitter in the 1930s to solve the thermal heating problem with metal conductors in resistive magnets [1]. The Bitter magnet has been reported to achieve 41 T ultra-high magnetic field [2]. Currently, the structure of the Florida-Bitter is often adopted in bitter disk [3–5]. However, the Bitter magnet requires a huge power supply and water-cooling system. The typical applications of the high temperature superconducting (HTS) coated conductors was promising in application high field magnet because of its superior mechanical characteristics and high current density in high field comparing with the low temperature superconducting...
(LTS) conductors [6]. The REBaCuO (RE: rare earth element) coated tape was investigated intensively for using in HTS magnets/coils with the structure of the double-pancake or layer-wound coil [7–9]. However, the HTS coated conductors joint of sufficient technological quality have not been achieved to date, a series of research work have been developed to achieve the true persistent current mode (PCM). Flux pump technique is an excellent substitute for large power supply to magnetize the HTS coil because it can inject the flux into the REBCO coated conductors incrementally and has inexpensive experimental setup [10–14]. However, the joint between the HTS coils still remains in the excitation system. Once the flux pump is turned off, the magnetic field generated by the HTS coils decayed rapidly over time.

Furthermore, the REBCO coated conductors can be cut into pieces and stacked to a composite and compact magnet, which can generate high magnetic fields by field cooled magnetization (FCM) or pulsed-field cooled magnetization (PFM) technique [15–17]. The geometry structure of this HTS magnet is flexible and it can be easily machined allowing shapes without limiting and this superior property offered by stacks of the REBCO coated conductors make it attractive application for permanent magnets. Since 2010, trapped field in the various stacking REBCO tapes were performed. S. Hahn et al. constructed 40 mm × 40 mm with 26 mm bore YBCO thin plates to trap field as compact NMR magnet in Refs. 18 and 19. Then, a stack of YBCO annuli achieved high field 0.65 T at 77 K and 3.53 T at 4.2 K [20]. A. Petel et al. also stacked 240 REBCO tapes trapped field 7.34 T at 4.2 K. Moreover, a hybrid stack of REBCO tapes has trapped highest field 17.7 at 8 K [21,22]. However, excitation methods of these magnets most focus on the FCM, which needs high field of background magnet and it is inconvenience for the magnets to practical application. At present, the PCM operation of the HTS magnet is not commercial on account of the immature joint technique in HTS coils. In order to realize the PCM operation of the HTS magnet, the REBCO annular plates was proposed and fabricated based on the structure of the bitter disk. The Bitter-like HTS magnet stacked by REBCO annular plates can work in PCM without
joint resistance and current lead. Furthermore, the current in each REBCO annular plate can work independently and there is also no joint resistance between adjacent REBCO annular plates. Additionally, the Bitter-like HTS magnet was magnetized by flux pump, which injects flux into the magnet to generate magnetic field without heat leak of the current lead.

In our previous studies, a Bitter-like HTS magnet has been experimented the dynamics behavior of the magnetic field [23–25]. It is clearly illustrated that the attenuation of magnetic field in the magnet occurs after stopping the magnetization process. In this paper, we present systematically experimental and simulation results of the induced magnetic field in the Bitter-like HTS magnet. The magnetic field generated by the HTS magnet excited with different pulsed current amplitudes and falling periods are measured at 77 K. And, reversible experiments of the magnet magnetized with various pulsed current amplitudes are also measured. Additionally, comparison between measured and simulated results of the magnet was also performed for the purpose of analysis the characteristic of the induced magnetic field in the magnet. The attenuation characteristic of the induced magnetic field and numerical simulation concerning with the current density distribution in the REBCO annular plates are also discussed and analyzed.

**Experimental Procedure**

**MPFM Procedure**

Multi-pulsed field magnetization (MPFM) consists of a copper solenoid coil and a pulsed triangular waveform current source. The Bitter-like HTS magnet was magnetized by the magnetic field provide by the solenoid coil, which was controlled by pulsed triangular waveform current source. The solenoid coil with 600 turns was wound by the copper wire with the diameter 0.1 mm on an insulated former, its inner and outer diameters as well as height are 2 mm, 4 mm and 200 mm, respectively. And, the solenoid coil was charged by continuous pulsed current controlled by pulsed triangular waveform current source with adjustable amplitudes and periods. The pulsed currents have adjustable amplitudes 0∼10 A, rising period of 1ms and different
falling periods of 1 s~100 s in one cycle. The magnetic field waveform generated by the solenoid coil is consistent with the applied pulsed current waveform. The magnetic field values of the solenoid coil provided to the magnet are 0~50 mT corresponds to applied current of 0~10 A.

Figure 1 indicates the pulsed currents with different amplitudes and cycles. In this work, pulsed currents are carried out in various pulsed current amplitudes 2 A, 3 A, 5 A, 8 A with the same cycle, that is, it has rising period of 1 ms and falling period of 10 s, as shown in Figure 1(a). The central magnetic field values of the solenoidal coil excited with different pulsed current amplitudes 2 A, 3 A, 5 A, 8 A are 10 mT, 15 mT, 25 mT and 40 mT, respectively. Additionally, the pulsed currents with different falling periods are in rising period of 1 ms and different falling periods of 30 s, 60 s, 90 s also performed under same pulsed current of amplitude 5 A, as indicated in Figure 1(b). Figure 1(c) shows the pulsed current with amplitude 5 A in rising period of 1 ms and different falling periods of 1 s, 4 s, 7 s, respectively.

**Figure 1**: Diagram of the pulsed triangular waveform current with different amplitudes and durations. (a) A series of pulsed current amplitudes in once cycle, (b) pulsed currents with different durations (increasing) and (c) pulsed currents with different durations (decreasing).

**Bitter-like Magnet Magnetization System**

The Bitter-like HTS magnet is constructed by stacking REBCO annular plates and polypropylene laminated paper (PPLP). 60 REBCO annular plates were stacked in a construction sequence that REBCO annular plates and PPLP insulation paper were stacked one by one. After that, the REBCO annular plates were reinforced by two epoxy resin flanges. The inner and outer
diameters of the magnet are 7 mm and 12 mm, and the stack height is 10 mm. Table I lists the main specifications of the REBCO annular plate.

Table I: Main specifications of the REBCO annular plate.

| Quantity                      | Values       |
|-------------------------------|--------------|
| I.D                           | 7 mm         |
| O.D                           | 12 mm        |
| $J_{c0}$ of REBCO tape in self-field and 77 K | 2 MA/cm$^2$ |
| Hastelloy layer               | 50 μm        |
| YBCO layer                    | 1 μm         |
| Ag layer                      | 2 μm         |
| Cu layer                      | 5 μm         |
| Buffer layer                  | 100 nm       |

The magnet was magnetized by the MPFM through the inner excitation method, as shown in Figure 2. The solenoid coil was located at the central of the magnet and powered by the continuous pulsed current so that the magnet can induce magnetic field through the MPFM excitation, as shown in Figure 3(a). According to Faraday’s law, the magnetic field generated by the solenoid coil can drive the flux into the magnet at its each cycle and the induced magnetic field of the magnet was enhanced with the increasing of the number of pulse magnetization cycles until the magnetic field achieves the saturated value. It should be noted that the magnet was only excited by the internal magnetic flux of a solenoid coil because the magnetic flux generated by the solenoid coil in the external of the HTS magnet is approximately zero, as a result of the height of the solenoid coil much higher than the height of the magnet [25].
Figure 2: (a) Cross-sectional view of the model of the magnet magnetized using a solenoid coil and (b) photo of the magnet and a solenoid coil.

Figure 3: (a) Photo of the magnet magnetized by the MPFM with the solenoid coil. (b) Photo of measuring magnetic field in the magnet with Hall probe.

The measurement system of the magnet was operated as follow. The Bitter-like HTS magnet was magnetized by a continuous pulsed magnetic field provided by the solenoid coil. At recording date, the pulsed current was switched off in falling edge and the solenoid coil was pulled from the magnet. Meanwhile, a Hall probe was located at the top center surface of the magnet to keep a record of the axial magnetic field generated in the magnet, as shown in Figure 3(b). After recording date of the axial magnetic field values in the magnet for each cycle, the solenoid coil was reinserted in the magnet again to magnetize the magnet continuously. Therefore, the measured data was discontinuous and have short intervals because the magnet was magnetized and measured by the same circular hole. Aforementioned measurement steps were repeated until the axial magnetic field value in the magnet reached a saturated value without increasing.
The solenoid coil was moved from magnet stopping excitation and a Hall probe kept recording the axial magnetic field with the time evolution.

**Experimental Results**

Figure 4 indicates experimental results of the magnetic field in the magnet with various pulsed current amplitudes under same cycle rising period of 1 ms and falling period of 10 s. The axial saturated magnetic field excited with different pulsed current amplitudes 2 A, 3 A, 8 A are 1.23 mT, 1.48 mT, 1.48 mT, respectively. It can be clearly seen that the magnetic field component $B_z$ increases rapidly at beginning and reaches a saturated value in short time during the MPFM magnetization process. Furthermore, the rising slope and the saturated value of the magnetic field $B_z$ does not significantly increase with the pulsed current amplitude increasing, especially the pulsed current amplitude exceeding 3 A. Consequently, it can be concluded that pulsed current amplitude 3 A is the appropriate for this magnet excited by MPFM because it has the same excitation speed and magnetic field saturated value compared to pulsed current amplitudes 5 A and 8 A.

![Figure 4: Experimental results of the magnetic field $B_z$ in the HTS magnet excited by the pulsed current with various amplitudes.](image)

Furthermore, the magnetic field $B_z$ attenuates to a constant value and then maintains constant after stopping MPFM magnetization.
in three cases. As the pulsed current amplitude is 2 A, the magnetic field $B_z$ initially decreases and then reaches a stable value 1.11 mT and the attenuation ratio of the saturation value is 9% compared to the saturation value 1.23 mT. Whilst the pulsed current amplitude is 3 A, the magnetic field $B_z$ declines and then reaches a constant value 1.34 mT and the attenuation ratio is 9% compared to the saturation value 1.48 mT. For the magnet energized with pulsed current amplitude 8 A, the magnetic field $B_z$ has same magnetic characteristic that with the 3 A, that is, it attenuates to a constant value 1.35 mT and keeps in constant with the temporal evolution. The attenuation ratio of the saturated magnetic field is 9% compared to the saturated value 1.48 mT. It can be observed that the attenuation ratio of the saturated magnetic field is 9% in three cases and it less affected once the pulsed current amplitude exceeds 2 A.

Figure 5 shows measurement results of the magnetic field with diverse pulsed current falling periods. The magnetic field $B_z$ under the same pulsed current amplitude 5 A with rising period of 1 ms and different falling periods of 30 s, 60 s, 90 s are 0.54 mT, 0.52 mT, 0.48 mT, respectively. It can be clearly seen that the magnetic field $B_z$ under three cases does not reach the saturation value of 1.48 mT. Moreover, as the falling period of the pulsed current increasing, the magnet need longer time to reach the saturation value. Therefore, the increase of pulsed current falling period results in a decrease of the excitation speed. It is also indicated that the magnetic field $B_z$ has no attenuation over time and the saturated value decreases with the pulsed current falling periods increasing. Consequently, the amplitude and attenuation characteristics of the magnetic field $B_z$ is relevant to the pulsed current falling periods, that is, the $B_z$ is influenced by the rate of excitation magnetic field falling periods.
Figure 5: Measured results of the magnetic field $B_z$ in the magnet magnetized by the pulsed current with different falling periods.

Figure 6 indicates the magnetic field $B_z$ in the magnet under the pulsed current amplitude 5 A with rising period of 1 ms and various falling periods of 1 s, 4 s, 7 s, respectively. The saturated $B_z$ are 1.48 mT, 1.48 mT, 1.48 mT in three cases. It can be clearly seen that the magnetic field $B_z$ reach the saturation value of 1.48 mT sharply and keeps in constant with the temporal evolution. After MPFM was carried out termination of excitation, the magnetic field $B_z$ initially decreases and then reaches a stable value 1.23 mT in three cases. It can be seen that the saturated value was not influenced by the pulsed current falling periods increasing. Furthermore, as the falling period of the pulsed current decreasing, the magnet takes short time to reach the saturation value compared to falling period of 10 s, as shown in Figure 5. However, a decreasing in the pulsed current falling period causes an increasing attenuation value in the magnet. It can be observed that the attenuation ratio of the saturated magnetic field is 17% by comparing the saturated value 1.48 mT with the stable value 1.23 mT, that is large than the attenuation ratio 9% in Figure 4. Consequently, it can be believed that the attenuation characteristics of magnetic field $B_z$ is still related to the change of excitation magnetic field falling periods.
Figure 6: Experimental results of the magnetic field $B_z$ in the magnet magnetized by the pulsed current with various falling periods.

Figure 7 shows the magnetic field $B_z$ in the magnet with different pulsed currents reversible experiments. The magnetic field $B_z$ under various pulsed current values of 2 A, 3 A, 5 A with rising period of 1 ms and falling period of 10 s were measured. Firstly, the magnet was separately magnetized by the solenoid coil with various pulsed current values. As the magnetic field $B_z$ of the magnet saturated, the pulsed current was pumped down to zero and then the magnet experienced the attenuation process and reached a stable value. Then, the solenoid coil started to magnetize the magnet in the opposite direction so that the magnetic field $B_z$ of the magnet increased and achieved saturated value again in the reverse direction. At last, the solenoid coil stops excitation and the magnet experiences an attenuation period and remains constant.

Figure 7: Measured results of the magnetic field $B_z$ in the magnet with different pulsed currents reversible experiments.
It is revealed that the saturated magnetic field $B_z$ are 1.23 mT, 1.48 mT, 1.48 mT, respectively. During the MPFM excitation process with same amplitudes and periods of the pulsed current, the saturated value of magnetic field $B_z$ is approximately consistent with pulsed current reversal process. Moreover, the upward slope and the attenuation slope of the magnetic field in the magnet are almost same in both MPFM excitation and reversal processes. Consequently, it can be considered that the characteristic of the magnetic field $B_z$ is less affected by the reversal process under same pulsed currents amplitudes and periods excitation process.

**Numerical Analysis**

The magnetic field $B_z$ of the magnet was computed by means of A-formulation and transient finite element modeling was also performed [26–29]. Experimental equipment including the magnet and the solenoid coil was immersed at 77 K. The temperature is assumed to be constant in whole system because the magnet is small and the heat generated by the magnet would diffuses into the liquid nitrogen bath during the MPFM magnetization process. The magnetic vector pote general expression

$$\frac{1}{\mu_0} (\nabla \times \nabla \times A) + \sigma \frac{\partial A}{\partial t} = J_s \quad (1)$$

where $J_s$ is the current density flowing through the solenoid coil and $\mu_0$ is the permeability of vacuum. The expression of the electrical conductivity of the REBCO annular plates $\sigma$ is given by the E-J power law expression

$$\sigma = J_c E_c \left( \frac{\partial A}{\partial t} \right)^{\frac{1-n}{n}} \quad (2)$$

where $J_c$, $E_c$, and $n$ are the critical current density, the critical electrical field (equal to 1 $\mu$V/cm), the n-value of the REBCO...
annular plate, respectively. The \( n = 30 \) was adopted in the simulation of the magnet at 77 K [30,31].

The critical current density \( J_c \) related to the magnetic field can be described by the empirical formula

\[
J_c = J_{c0} \left( 1 + \frac{1}{B_0} \sqrt{\left( \frac{1}{\gamma} \right)^2 B_\parallel^2 + B_\perp^2} \right)^{-\alpha}
\]

where \( J_{c0} \) is critical current density at \( B = 0 \) and \( B_0 \) is constant, \( B_0 = 20 \) mT, \( \gamma = 5 \) and \( \alpha = 0.65 \). \( B_\parallel \) and \( B_\perp \) are separately parallel and perpendicular to the surface of the REBCO annular plate [23]. The axisymmetric model is applied in the magnet model, as illustrated in the Figure 2(a). In the previous measured results, it can be observed that the pulsed current amplitude \( 3 \) A with rising period of \( 1 \) ms and falling period of \( 10 \) s were the optimal parameters for MPFM excitation model, so that we apply it into the simulated model.

In order to compare to experimental results more clearly, the excitation period of MPFM used in the simulated model was \( 240 \) minutes in consistent with the experimental MPFM excitation period.

**Simulation Results**

Figure 8 indicates the simulated and measured results of the magnetic field \( B_z \) in the magnet. The solid square and solid lines correspond to the time evolution of the simulated magnetic field \( B_z \) and the measured magnetic field \( B_z \) at top location of the magnet, respectively. The magnet achieves the saturated magnetic field \( B_z \) \( 1.60 \) mT energized with the pulsed current amplitude \( 3 \) A with rising and falling periods of \( 1 \) ms and \( 10 \) s in the simulation process. The error between the saturated experiment value \( 1.48 \) mT and the saturated simulation value \( 1.60 \) mT is \( 0.12 \) mT accounting for \( 7.5\% \) of the simulation value \( 1.60 \) mT. The simulation and measurement results can be considered consistent quantitatively and a little difference between them can be considered simulated or measured error.
There is a decline in the magnetic field $B_z$ during both measurement and simulation process. It can be seen that the magnetic field $B_z$ decreases from 1.60 mT to 1.34 mT and the decreased value 0.26 mT amounts to 16.3% of the simulated value (1.60 mT). Comparatively, the attenuation ratio of the saturated magnetic field is 9% compared the saturated value 1.48 mT with the stable value 1.35 mT in the measurement process. The difference between two attenuation ratios is considered to be the difference in saturation values. In the simulation process, the magnet takes 15 minutes to obtain the saturated value and experiences 20 minutes attenuation process and then keeps a stable value again. Comparatively, the magnet experiences 10 minutes to achieve the saturated value and also has 20 minutes attenuation process then keeps a stable value again in the measurement process.

Figure 9 indicates the magnetic field distribution of the magnet magnetized by MPFM under one cycle. After one cycle of MPFM excitation process, the net magnetic field of the magnet was generated. The net magnetic field in one cycle is that the magnetic field generated during rising period (1 ms) minus that generated during falling period (10 s). Figure 9(a), Figure 9(b), Figure 9(c) and Figure 9(d) indicate rising period 1 ms, falling period 4 s, falling period 7 s and falling period 10 s of the magnetic field distribution in the solenoid coil and the magnet in one cycle, respectively. It can be seen that the magnetic field $B_z$
of the magnet was attenuated as the falling time of the solenoid coil increasing. Then, the net magnetic field was generated in the magnet after one cycle termination. The net magnetic field will be accumulated in the magnet each cycle with continuous pulsed current number increasing until the magnetic field reaches saturation. Then, the MPFM put an end to excitation and the change of the magnetic field of the magnet would be observed in the attenuation process.

![Figure 9: Magnetic field $B_z$ distribution of the magnet in one cycle. (a) Magnetic field $B_z$ in the magnet with saturation $t=1$ ms, (b) magnetic field $B_z$ in the magnet with attenuation $t=4$ s, (c) attenuation $t=7$ s and (d) attenuation $t=10$ s.](image)

Figure 10 indicates the magnetic field $B_z$ of the magnet in the saturated period and different attenuation periods. Figure 10(a) shows the distribution of the saturated magnetic field $B_z$ in the magnet that is the attenuation period is zero ($t=0$ min.). In addition, Figure 10(b), Figure 10(c) and Figure 10(d) indicate the magnetic field $B_z$ in the magnet under various attenuation periods corresponding to the attenuation period of $t=5$ min., $t=10$ min., $t=20$ min., respectively. It can be observed that the magnet has attenuated sharply at beginning and the slope slows down as time evolution. Then, the magnetic field has no longer attenuation and remains constant eventually.

![Figure 10: Magnetic field $B_z$ distribution of the magnet in the saturated period and different attenuation periods.](image)
Figure 10: Magnetic field $B_z$ distribution of the magnet under saturation and various attenuation periods. (a) Magnetic field $B_z$ in the magnet with saturation $t=0$ min., (b) magnetic field $B_z$ in the magnet with attenuation $t=5$ min., (c) $t=10$ min. attenuation period, and (d) $t=20$ min. attenuation period.

The attenuation process of the magnetic field $B_z$ in the magnet under both measurement and simulation are begin from 240 minutes. And, both of them experience 20 minutes attenuation period. In order to analyze the attenuation tendency of the magnetic field $B_z$ more clearly, the attenuation period from 240 minutes to 260 minutes is scheduled to the period from zero to 20 minutes.

Figure 11 indicates the measurement and fitting results of the magnetic field $B_z$ in the magnet. Data fitting is carried out for the magnetic field $B_z$ within 20 minutes and the corresponds to the exponential function

$$B(t) = 0.16e^{-t/\tau} + B_0$$

where $\tau=8.84$ minutes, $B_0=1.32$ mT refers to the characteristic time and magnetic field constant. It can be observed that the attenuation of the magnetic field $B_z$ is one exponential function attenuation. And, the attenuation of magnetic field $B_z$ in the magnet decreases exponentially at first and then keeps a constant.

Figure 11: Measured and fitting attenuation curve of the magnetic field $B_z$ in the magnet.
The axisymmetric model was adopted in the simulation process, so that the cross section of REBCO annular plates can be observed. Therefore, the current density distribution along the radial direction of the REBCO annular plates can be achieved in the simulated model. Because the critical current density of the middle REBCO annular plate of the magnet is more influenced by the axial magnetic field, the current density distribution of the 30th REBCO annular plate at the central of the magnet along with the radius was indicated. The current density of the magnet can be computed by vector potential A.

Figure 12 shows distribution of current density of the 30th REBCO annular plate along the radius under the saturation and various attenuation periods. In order to keep consistent with the magnetic field $B_z$ attenuation process, the current density distribution of the REBCO annular plate at 5 different periods is indicated. The results manifested that the current density is non-uniform distributed in the 30th REBCO annular plate during the MPFM excitation process. Furthermore, during the attenuation process, the current in the 30th REBCO annular plate flows along the radius from the inner to the outer along radius of the annular plate in the magnet and then keeps a relative stable distribution. Therefore, it can be considered that the redistribution of the current density with the time evolution causes the attenuation of magnetic field. Furthermore, other factors including flux creep possible causes the decay of magnetic field. This attenuation characteristics need to be analyzed and researched in detailed in near future.
Figure 12: Current density distribution in the 30th REBCO annular plate under saturation and various attenuation periods.

Conclusion

This study presents a Bitter-like HTS magnet that can be operated in the PCM without joint resistance and current lead. Furthermore, detailed experimental and simulation results of the magnetic field in the magnet were analyzed. It can be observed that the magnetic field characteristics of the magnet was influenced by the change of excitation magnetic field amplitudes and periods. And, the attenuation of the magnetic field $B_z$ is exponential. Although the magnetic field $B_z$ of the Bitter-like HTS magnet is small, this kind of the magnet provides a technical reference for applications of the superconducting magnets.

References

1. F Bitter Rev. Sci. Instrum. 1936; 7: 479–482.
2. G Kuang, S Shao. Science & Technology Review. 2018; 36: 93–96.
3. BJ Gao, H Schneider-Muntau, YM Eyssa, MD Bird. IEEE Trans. Magn. 1996; 32: 2503–2506.
4. MD Bird, S Bole, YM Eyssa, BJ Gao, H Zhang, et al. IEEE Trans. Magn. 1994; 30: 2192–2195.
5. MD Bird, S Bole, YM Eyssa, BJ Gao, H Schneider-Muntau. IEEE Trans. Magn. 1996; 32: 2542–2545.
6. H Maeda, Y Yanagisawa. IEEE Trans. Appl. Supercond. 2014; 24: 4602412.
7. HW Weijers, WD Markiewicz, AV Gavrilin, AJ Voran, YL Viouchkov, et al. IEEE Trans. Appl. Supercond. 2016; 26: 4300807.
8. KL Kim, S Yoon, K Cheon, J Kim, H Lee, et al. IEEE Trans. Appl. Supercond. 2016; 26: 4302604.
9. D Park, J Bascuñán, PC Michael, J Lee, S Hahn, et al. IEEE Trans. Appl. Supercond. 2018; 28: 4300205.
10. C Hoffmann, D Pooke, AD Caplin. IEEE Trans. Appl. Supercond. 2011; 21: 1628–1631.
11. Coombs, J Geng, L Fu, K Matsuda. IEEE Trans. Appl. Supercond. 2017; 27: 4600806.
12. Z Jiang, CW Bumby, RA Badcock, NJ Long, HJ Sung, et al. J. Magn. 2016; 21: 239–243.
13. S Lee, W Kim, Y Kim, J Lee, S Park, et al. IEEE Trans. Appl. Supercond. 2016; 26: 0606104.
14. CW Bumby, AE Pantoja, H Sung, Z Jiang, R Kulkarni, et al. IEEE Trans. Appl. Supercond. 2016; 26: 0500505.
15. S Zou, VMR Zermeño, F Grilli. IEEE Trans. Appl. Supercond. 2016; 26: 8200705.
16. Y Zheng, Y Wang, J Li, Z Jin. AIP ADV. 2017; 7: 095218.
17. J Sheng, M Zhang, Y Wang, X Li, J Patel, et al. Supercond. Sci. Technol. 2017; 30: 094002.
18. S Hahn, S Kim, M Ahn, J Voccio, J Bascunan, et al. IEEE Trans. Appl. Supercond. 2010; 20: 1037–1040.
19. S Hahn, J Voccio, DK Park, KM Kim, M Tomita, et al. IEEE Trans. Appl. Supercond. 2012; 22: 4302204.
20. S Hahn, Y Kim, JP Voccio, J Song, J Bascuñán, et al. IEEE Trans. Appl. Supercond. 2014; 24: 4300805.
21. A Patel, K Filar, VI Nizhankovskii, SC Hopkins, BA Glowacki. Appl. Phys. Lett. 2013; 102: 102601.
22. A Patel, A Baskys, T Mitchell-Williams, A McCaul, W Coniglio, et al. Supercond. Sci. Technol. 2018; 31: 09LT01.
23. X Yuan, Y Wang, Y Hou, C Kan, C Cai, et al. IEEE Trans. Appl. Supercond. 2018; 28: 4603005.
24. X Yuan, Y Wang, Y Hu, H Chen, M Liu, et al. IEEE Trans. Appl. Supercond. 2019; 29: 4700405.
25. Y Hu, Y Wang, X Yuan, H Chen, M Liu, et al. IEEE Trans. Appl. Supercond. 2019; 29: 4900505.
26. E Vinot, G Meunier, P Tixador. IEEE. Trans. Magn. 2000; 36: 1226–1229.
27. N Nibbio, S Stavrev. IEEE Trans. Appl. Supercond. 2001; 11: 2627–2630.
28. F Trillaud, K Berger, B Douine, J Lévêque. IEEE Trans. Appl. Supercond. 2016; 26: 6800305.
29. F Trillaud, K Berger, B Douine, J Lévêque. IEEE Trans. Appl. Supercond. 2018; 28: 6800805.
30. F Grilli, S Stavrev, Y Le Floch, M Costa-Bouzo, E Vinot, et al. IEEE. Trans. Appl. Supercond. 2005; 15: 17–25.
31. F Grilli, E Pardo, A Stenvall, DN Nguyen, W Yuan, et al. IEEE. Trans. Appl. Supercond. 2014; 24: 8200433.