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To cite this article: J I Lee *et al* 2018 *J. Phys.: Conf. Ser.* **1054** 012079

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Design and performance analysis of a 1500 A, 400 mH superconducting DC reactor coil using 2G multi-ply HTS wire

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Abstract. This paper deals with the design and performance analysis of a superconducting DC reactor using multi-ply high temperature superconducting (HTS) wire for a high-current DC reactor. To design the high-current DC reactor, 2G multi-ply HTS wire (SuNAM Co., Ltd.) was used to achieve a high ampacity. The critical current was measured according to the bending diameter in order to confirm the bending characteristics of the 2-ply and 3-ply wires. The HTS coils for a 1500 A, 400 mH HTS DC reactor were designed based on the characteristics of multi-ply HTS wire. Electromagnetic analysis of the toroid-type DC reactor was performed with the finite element method. HTS coils were wound with a D-shaped double pancake type bobbin. The critical current of the double pancake coil (DPC) modules was measured in a liquid nitrogen vessel. The performance test results were compared with the analysis results. Based on the critical current of DPC measured at 77 K, it was confirmed that 1500 A could be flowed at the operating temperature of 20 K. These results will be effectively utilized for the design and fabrication of an HTS DC reactor that can be used in real power systems.

1. Introduction

A DC reactor is a power system application device that reduces the current ripple and harmonics generated by thyristors during AC-DC conversion. It is usually used in high-voltage direct current (HVDC) systems. Conventional DC reactors are manufactured with metal conductors. However, there are some disadvantages to using metal conductors. First, a metal conductor has resistance, which inevitably causes electrical loss. As the current increases, the power loss also increases. Second, when DC reactors are made with metal conductors, the volume and weight become very large, which limits the installation space and insulation structure. These disadvantages can be overcome by using a superconducting wire that has zero resistance and a high current density [1]-[2]. However, a high temperature superconducting (HTS) DC reactor cannot be used in real kA-class systems. This is because the HVDC system current is higher than the critical current of commercial HTS wires. In addition, when HTS coils are manufactured, the critical current is decreased due to the magnetic field, and it is impossible to use in real HVDC systems with operating currents that exceed 1000 A. The authors propose an HTS coil-based DC reactor that can be applied to actual systems. The design target is based on high inductance compared to copper-conductor DC reactors used in conventional HVDC systems with a current capacity of 1500 A.

In this paper, a toroid-type HTS magnet for a DC reactor system was designed using 2G multi-ply HTS wires, which were made by soldering two or three overlapping HTS wires. The toroid-type magnet is suitable for a DC reactor, which should be compact with a large energy capacity because the



inductance has been increased. As the inductance increases, the magnetic flux density per current also increases. However, in the toroid-type coil, the perpendicular magnetic field that has a greater influence on the critical current of the HTS coil is reduced. The toroid-type coil can make a high operating current and low magnetization loss [3]-[9]. The target inductance and current level of the toroid-type HTS DC reactor were 400 mH and 1500 A, respectively. Compared to the characteristics of commercial copper reactors, the target capacity is set to a similar capacity and the inductance value is doubled. The magnetic fields and the inductances of the magnet using 2-ply and 3-ply HTS wires were analysed by the finite element method (FEM) program. Two types of double pancake coil (DPC) were fabricated using 2-ply and 3-ply HTS wires and experimented to obtain practical data. These fundamental data will be usefully applied to fabricate the entire system of a toroid-type HTS DC reactor.

2. Characteristics of multi-ply HTS wires

2.1. Specifications of multi-ply HTS wires

Multi-ply HTS wire is suggested to increase the critical current of conventional single-ply HTS wire. Multi-ply HTS wire could increase the critical current by stacking single-ply HTS wires several times. Thus, multi-ply HTS wires were fabricated from 12 mm 600 A at 77 K wire from SuNAM Co., Ltd. Figures 1 and 2 show the critical currents of single-ply HTS wire at 77 K and 20 K, respectively. The maximum output current of the power supply used for the measurement was 2000 A, so we could not measure the higher critical current.

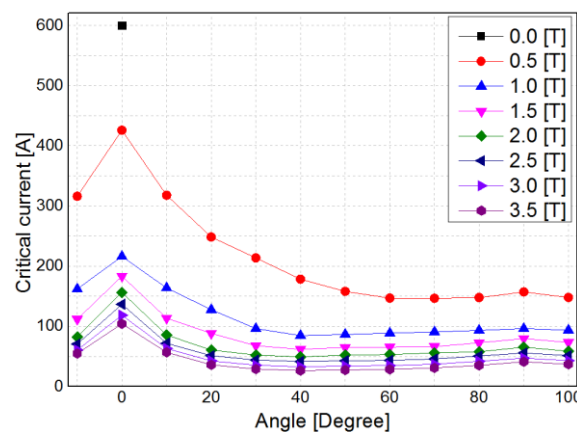


Figure 1. Critical current of single-ply HTS wire at 77 K

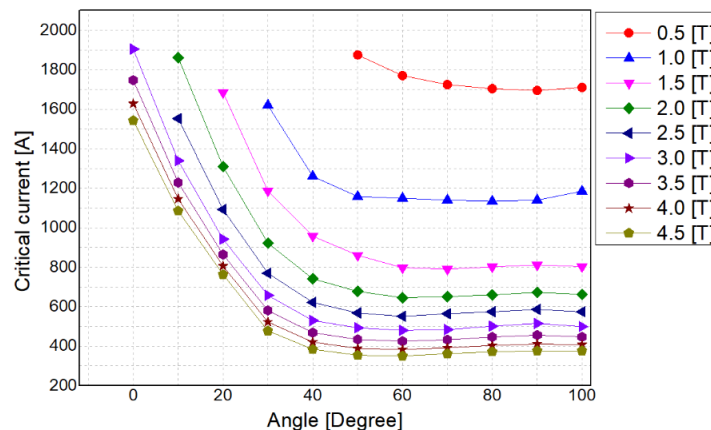


Figure 2. Critical current of single-ply HTS wire at 20 K

The HTS wire was stacked to 2-ply or 3-ply and then soldered using In-Sn. The average thicknesses of the fabricated 2-ply and 3-ply HTS wires were 0.34 mm and 0.48 mm, respectively. These thicknesses include stacked HTS wire, kapton tape for insulation, and solder for the HTS wire stacking. Figure 3 shows the critical current of 2-ply, 3-ply, and single-ply HTS wires at 77 K. The reference voltage for the critical current is 1 $\mu\text{V} / \text{cm}$. The critical currents of single-ply, 2-ply, and 3-ply were measured as 614 A, 1166 A, and 1713 A, respectively. The 2-ply wire has a 95% critical current of twice the critical current of a single-ply wire, and the 3-ply wire has a 93% critical current of three times the critical current of a single-ply wire.

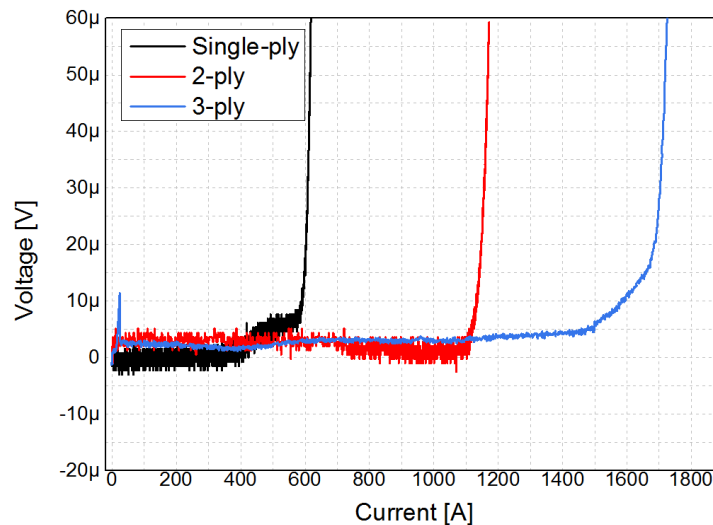


Figure 3. Critical currents of single-ply, 2-ply and 3-ply HTS wires at 77 K

2.2. Bending test of multi-ply HTS wires

2G HTS wire is fabricated in tape form according to the characteristics of the material. Therefore, the degradation of critical current due to bending occurs. The manufacturer of the HTS wire provides the information for the minimum double bending diameter of a single-ply HTS wire. The minimum double bending diameter of the single-ply HTS wire must be greater than 30 mm. However, in the case of the multi-ply HTS wire, it is necessary to measure the critical current according to the bending diameter because the ampacity characteristics of 2-ply or 3-ply wires were changed. Diameters from 70 mm to 40 mm were measured every 10 mm in a liquid nitrogen temperature. The HTS wire was bent using a constant weight as shown in figure 4.



Figure 4. Jig for the HTS wire bending

The bent wire was straightened again, and then the critical current was measured in liquid nitrogen. Figure 5 shows the experimental results at the point of degradation of the critical current. The critical currents of the 2-ply and 3-ply HTS wires were decreased in the bending diameter ranges of 50 ~ 60 mm and 60 ~ 70 mm, respectively. In the figure, the voltage of 10 μ V is due to the high current ramp rate of the power supply and is not a factor in the results.

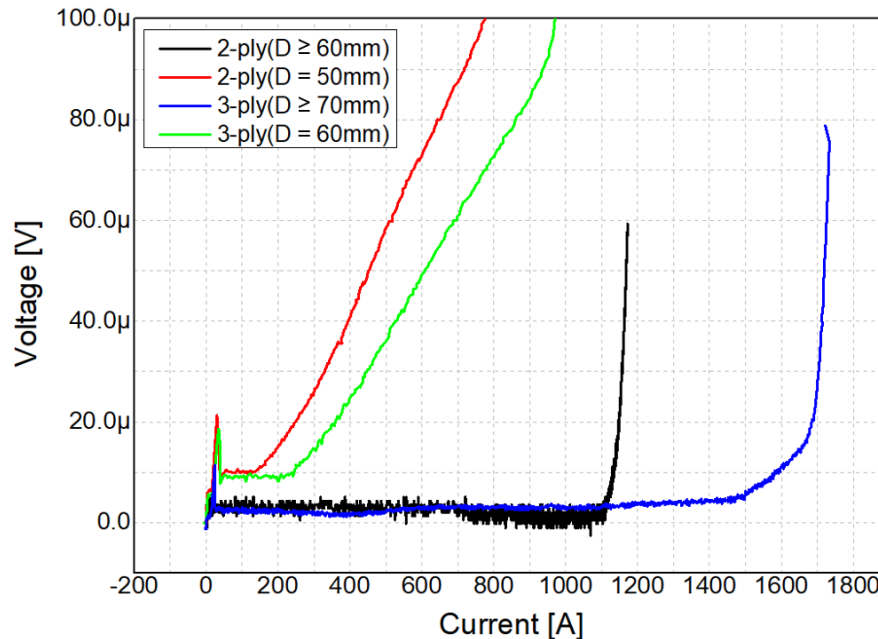


Figure 5. Measurement of the critical current while considering bending diameter

3. Design of the 1500 A, 400 mH superconducting toroid-type DC reactor coil

3.1. Design of the toroid-type DC reactor coil

Figure 6 shows the detailed structure of a D-shaped HTS coil and a toroid-type DC reactor magnet. The DPC was joined at the inner straight portion of the D-shaped coil with a 5 mm gap between the two single pancake coils. The distance from the center of the DPC to the center of the reactor was 295 mm, and each DPC was arranged at an angle of 12 degrees. In figure 6, the parameter “N” is the thickness of the HTS wire multiplied by the number of turns. N was determined through analysis by the design goals of the 1500 A and 400 mH.

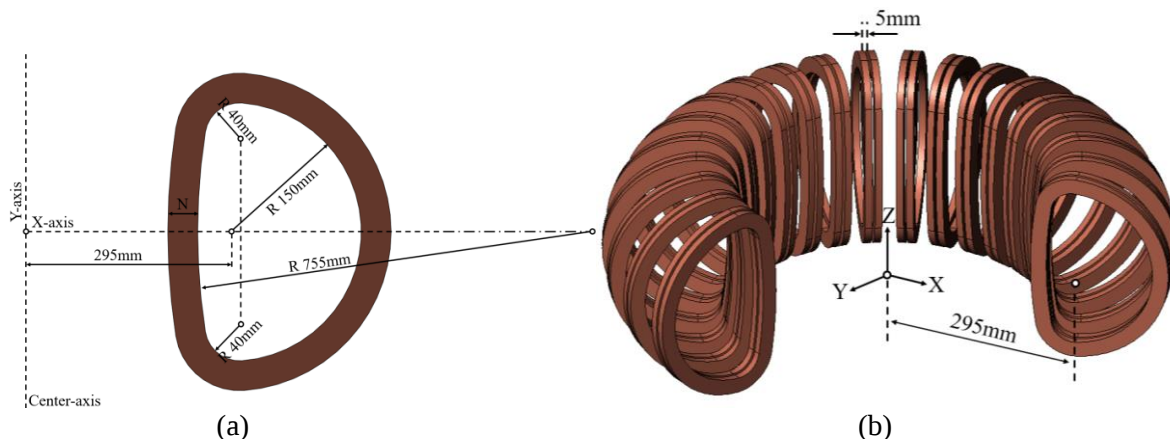


Figure 6. Detailed structure of the HTS DC reactor magnet: (a) a D-shaped HTS coil, (b) a toroid-type DC reactor magnet.

3.2. FEM simulation results of the DC reactor coil

Figure 7 shows the results of the magnetic field distribution analysis, which was conducted on one-half of the DPC with a selected boundary condition [10].

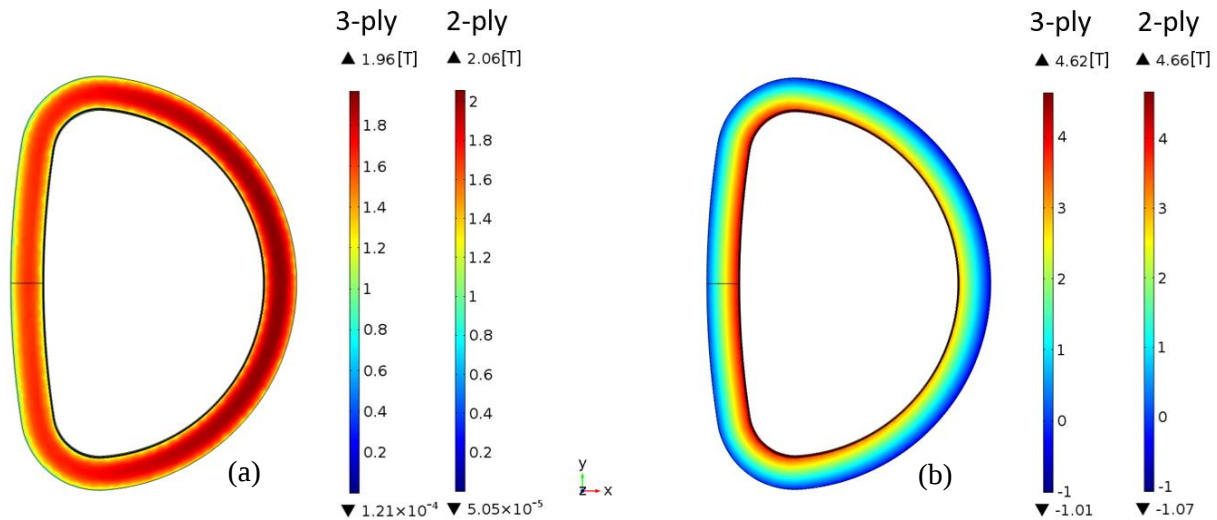


Figure 7. Electromagnetic analysis of the DC reactor coil: (a) the perpendicular magnetic field, (b) the parallel magnetic field

The values were applied to all of the DPCs in order to determine the overall parameters of the magnets. When the operating current was assumed to be 1500 A, the maximum perpendicular flux density and the maximum parallel flux density of the 2-ply HTS DC reactor magnet were 2.06 T and 4.66 T, respectively; in the case of the 3-ply DC reactor magnet, they were 1.96 T and 4.62 T, respectively. The calculation results of 2-ply and 3-ply inductances were 401.66 mH and 405.85 mH, respectively. The detailed specifications of the 1500 A, 400 mH toroid-type HTS DC reactor magnets are shown in Table 1.

Table 1. Specifications of the toroid-type multi-ply HTS DC reactor magnet.

Items	2-ply	3-ply
Wire width	12.2 mm	12.2 mm
Wire thickness	0.34 mm	0.48 mm
Co-winding SUS-tape thickness	0.1 mm	-
Number of turns	58 turns	58 turns
Reactor inductance	401.66 mH	405.85 mH
Perpendicular magnetic field at 1500 A	2.06 T	1.96 T
Parallel magnetic field at 1500 A	4.66 T	4.62 T
Calculated HTS DC reactor critical current at 20 K	2280 A	3380 A

4. Fabrication and performance test of a DPC module

DPC module bobbins for the critical current measurement of multi-ply HTS coils were produced. Figure 8 shows the detailed structure of a DPC module coil in a multi-ply HTS DC reactor. The 2-ply and 3-ply HTS wires were wound into the DPC modules for 58 turns.

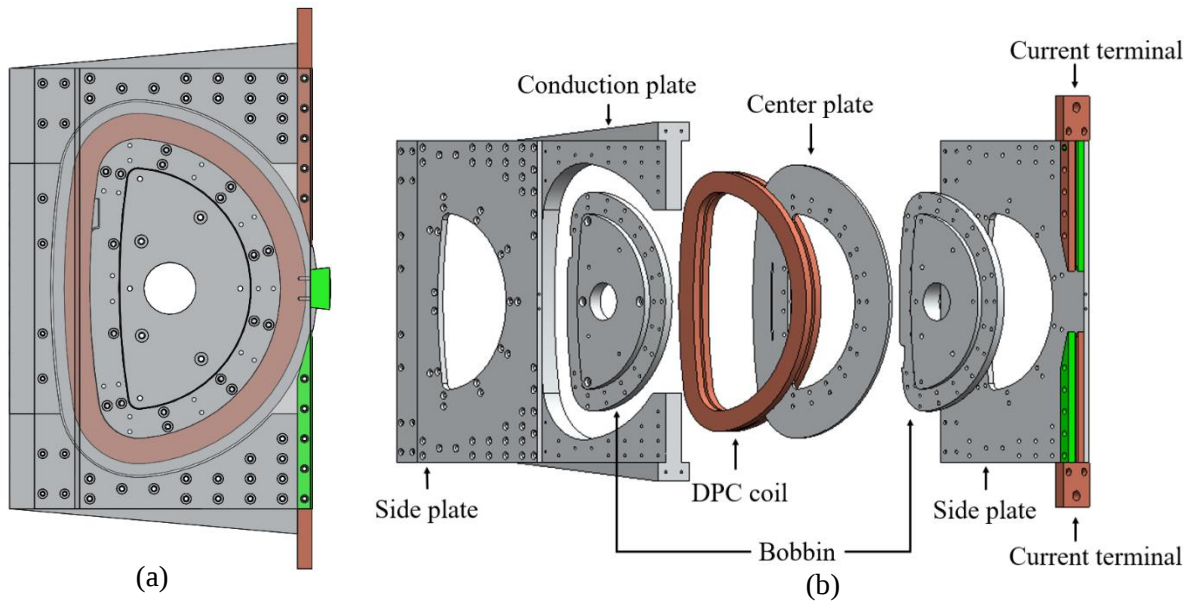


Figure 8. 3D modeling of a fabricated DPC: (a) the assembled DPC module, (b) the parts of the DPC module

The calculated critical current of the 2-ply DPC module was 315 A, and the inductance was 5.62 mH. In the case of the 3-ply DPC module, the critical current was 420 A, and the inductance was 5.59 mH. The critical current was calculated by considering the intensity of the magnetic field and the angle dependency [11]. The critical currents of the 2-ply and 3-ply DPC modules were measured at 77 K. Figure 9 shows the actual DPC using 2-ply and 3-ply HTS wires. Voltage signal lines for the critical current measurement were attached near the current terminals.

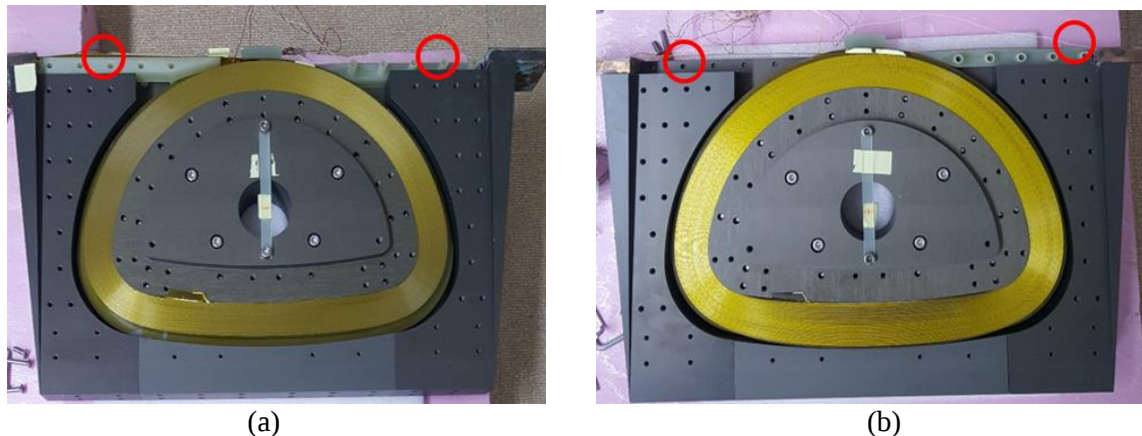


Figure 9. DPC module coil with signal line connection for voltage measurement (red circle): (a) 2-ply DPC, (b) 3-ply DPC

Figure 10 shows the critical current measurement results of DPC modules at 77 K. The experimental results show that the 2-ply and 3-ply DPC modules' critical currents were 322 A and 421 A, respectively. The experiment was performed at a current ramp rate of 1 A / s. As a result, as the voltage is biased to about 5.7 mV, the inductance is 5.7 mH due to $V = L (di / dt)$.

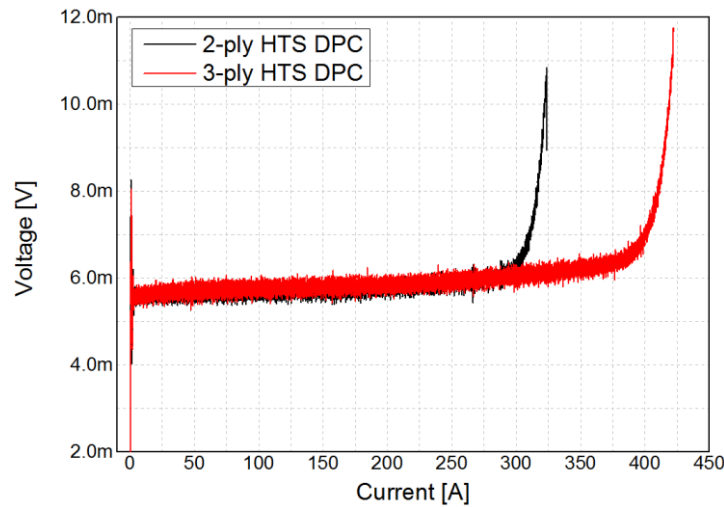


Figure 10. The critical current measurement results of DPC modules

5. Conclusions

In this study, a 1500 A, 400 mH D-shaped toroid-type HTS DC reactor magnet with multi-ply HTS wire was designed. The characteristics of the multi-ply HTS wire and the reduction of the critical current according to the bending diameter were presented. The multi-ply HTS wire included 2-ply and 3-ply HTS wires. The critical current degradation of the multi-ply HTS wire was less than 7%. The operating current and inductance of the designed DC reactor were concluded to be 1500 A, 401.66 mH (2-ply), and 405.85 mH (3-ply). The critical current of the 2-ply HTS DC reactor, when considering the intensity and angle of the magnetic field at 20 K, was 2280 A; it had a margin of about 34% at the operating current of 1500 A. In the case of the 3-ply HTS DC reactor, 3380 A had a margin of about 56%. Considering that the critical current margin of the superconducting applications is about 30% on average, it can be confirmed that the target value of this paper can be achieved sufficiently with the 2-ply HTS wire. In the case of an HVDC system, which needs a higher current capacity, 3-ply (or more) HTS wire can be used. Through the experiments, the performance characteristics (inductance and critical current) of a DPC module for the toroid-type HTS DC reactor magnet were tested in a liquid nitrogen temperature. The fundamental data will be applied to an actual-scale HTS DC reactor system on a real HVDC system.

Acknowledgment

This research was supported by Korea Electric Power corporation [grant number: R16XA01]

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