Design and Demonstration of a Double-pancake Coil for SMES using MgB$_2$ Multi-strand cable

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Abstract. MgB$_2$ round wires are now commercially available with applicable critical current density in magnetic fields up to 5 T. One of the promising applications using MgB$_2$ is a superconducting magnetic energy storage (SMES) coil. In our project, multi-strand cables with 600 A nominal current are designed for double-pancake (DP) coils with 400 mm inner diameter. The coil production processes in our project are wind-and-react (W&R) and react-and-wind (R&W) methods, in which a Rutherford-type cable consisting of eight (W&R) or ten wires (R&W) with specific twist pitch is reacted and then used to wind the DP coils, to investigate the suitable manufacturing process for MgB$_2$ coils. The final goal is to fabricate five-stacked DP coils, made up of four DP coils by the R&W method and one DP by the W&R method with a total number of 512 turns, forming a 30 kJ SMES coil and to demonstrate compensation of voltage fluctuation on the BUS line of 48 V DC in a micro grid consisting of renewable energy source and liquid hydrogen supply system in our project. The first DP coils made by the two manufacturing processes are constructed and tested with regard to their properties such as critical current density in liquid helium to keep uniform temperature distribution throughout the coils.

1. Introduction
MgB$_2$ round wires attract the interests of researchers from the point of view of applying them to large-scale power devices like superconducting magnetic energy storage (SMES). For compensation of power variations produced by photovoltaic cells and wind turbines, our group has developed a new DC-microgrid system (48 V), in which the voltage variations due to fluctuating weather conditions would
be well controlled by using a combination of a small SMES magnet made of Bi2223, a fuel cell, and a water electrolysis device [1][2]. The system has worked successfully, however, manufacturing process of SMES coils consisting of cost-effective wire should be pursued for installation in the real power grid system.

The MgB₂ production process resembles Nb₃Sn production, which needs heat treatment, and the strain sensitive characteristics of superconducting properties. Unlike the Nb₃Sn strand, MgB₂ wire has bending strain sensitivity even before the heat treatment. This might cause unexpected deterioration during conductor and coil fabrication process in any production method. Although the W&R process seems reasonable for the construction of these coils, the R&W process deserves our attention in terms of simple and easy fabricating features and turn-to-turn insulation, where applied strain to the wires is acceptable. Although many research groups have started the investigation of characteristics of cable using MgB₂ wires, the current capacities are not suitable for large-scale application or coil winding [3-7]. Our aim in this study is to design double-pancake (DP) coils for the SMES using a conductor with large current capacity by twisting the MgB₂ wires with allowable strain level. First, we performed a design study of a Rutherford-type cable for fabricating large-scale DP coils based on the differential geometry and space curve theory to optimize the cable parameters such as twist pitch and cable toughness. Second, the DP coils were produced by introducing both R&W and W&R methods to investigate the feasibility of the processes for large-scale coil production. Finally, we will present the first demonstration results of large-scale DPs using multi-stranded conductors which satisfy the applied bending strain criterion of strain-sensitive MgB₂ strands, at liquid Helium temperature.

2. Specifications of MgB₂ conductors and coils

2.1. Conductor specifications

Schematics of strand and conductor designed for DP coil is the Rutherford-type cable, as shown in figure 1, and their specifications are shown in table 1. The strands selected for making DPs are provided by Hyper Tech Inc., named NM strand. The diameter of the strand is almost identical 0.83 mm for 30-NM and 0.84 mm for 24-NM. The number in the strand name represents the number of filaments. The Cu ratio of strands are 12 % and 20 % for 30-NM and 24-NM, respectively. The permissible bending strain which is specified by the manufacturer, is 4 % and 0.23 %, before and after heat treatment, respectively.

| Items                      | Conductor for DP-1 (W&R) | Conductor for DP-2 (R&W) |
|----------------------------|--------------------------|--------------------------|
| Strand                     |                          |                          |
| Type                       | 30-NM                    | 24-NM                    |
| Diameter [mm]              | 0.83                     | 0.84                     |
| Heat Treatment Status      | Un react                 | Unreact                  |
| Num. of filaments          | 30                       | 24                       |
| Jc [A/mm²] @20K, 2T        | 1780                     |                          |
| Fill Factor                | 0.2                      | 0.11                     |
| Cu ratio [%]               | 12                       | 20                       |
| Permissible strain (before / after heat treatment) | 4 / 0.23 % |                          |
| Conductor                  |                          |                          |
| Num. of Strands            | 8+4CuZn                 | 10                       |
| Former                     | Cu                       | NA                       |
| Dimension [mm]             | 5.06×2.86                | 4.35×1.43                |
| Insulation                 | S-glass                  | kapton                   |
In this research, we introduced a Rutherford-type, rectangular cross-section conductor for fabricating the DP coils. The rated current is determined to be 600 A for development of large-scale MgB\(_2\) conductor for actual coil winding. To realize the current capacity, we considered not only the number of strands but also the thermal stability in case of quench event. The conductor using 30-NM, which has low Cu ratio, has Cu mandrel and four CuZn strands in it. On the other hand, the conductor using 24-NM has no metals in the conductor design with enough stability using 10 strands. The rated transport current is 600 A, which is almost half of the maximum current capacity estimated by the temperature limitation under perfect adiabatic conditions and yields 1.76 T maximum magnetic flux density for a net stored energy of 30 kJ by stacking two types of MgB\(_2\) coils.

![Figure 1. Schematic view of conductor cross sections both for W&R and R&W coils](image)

2.2. Specification of double-pancake coils
The schematic view of the cross section of the stacked DP coils is shown in figure 2. The items listed in table 2 are the specifications of the DP-1, DP-2, and SMES coil. In figure 2, there are two types of coils, using different types of conductors. One is a DP by the conductor with NM30 while the other is DP coils by the conductor using NM24. The difference between the two DP coils is not only in the conductors used but also the production method. The DP-1 coil using NM30 conductor is fabricated by using the W&R method, while DP-2 is by using the R&W method. The reason for introducing two different methods is to demonstrate which one is the best as a production method for large-scale coil fabrication of future SMES coils using MgB\(_2\). At this moment, the R&W method has some advantages against the W&R method with regard to forming inter-turn insulation, impregnation, preventing heat treatment of terminal and easier dimension control. Therefore, we determined the ratio of number of DPs, one W&R coil (DP-1) and four R&W coils (DP-2,3,4,5). The whole coil would have an inner diameter of 400 mm and an outer diameter of 606 mm, with the height at around 55 mm.

| Items (DP)                  | DP-1 | DP-2 | SMES Coil (5-DP coils) |
|-----------------------------|------|------|------------------------|
| Inner diameter[mm]          |      |      |                        |
| Outer diameter[mm]          |      |      |                        |
| Height[mm]                  | 11.1 | 11   | 55                     |
| Inductance[mH]              | 3.9  | 9.1  | 170                    |
| Rated current[A]            |      |      |                        |
| Num. of turns               | 72   | 110  | 512                    |
| Maximum B field[T]          | 0.4  | 0.61 | 1.76                   |
| B field at the center[T]    | 0.11 | 0.17 | 0.77                   |
| Stored energy [kJ]          | 0.7  | 1.6  | 30                     |
3. Theoretical Background

3.1. Governing equations of space curve
Because the conductors are fabricated by twisting and assembling the strands, resultant strand traces in the coil form complex space curves. To calculate the traces, we introduce the governing equations of the space curve. First, the given position on a strand section is expressed as the following vector, as shown in figure 3, that is,

\[ r(t) = x(t)i + y(t)j + z(t)k \]  \hspace{1cm} (1)

where \( t \) is a parameter, \( i, j, k \) are unit vectors in the \( x, y, z \) directions, respectively. The tangent vector \( t \) is obtained by differentiating the equation (1) with respect to parameter \( t \),

\[ t = \frac{dr}{dt} = \frac{dx}{dt}i + \frac{dy}{dt}j + \frac{dz}{dt}k \]  \hspace{1cm} (2)

The curvature vector \( R \), which is a key parameter for estimating bending strain, will be obtained by differentiating the tangent vector in equation (2) with respect to the arc length in equation (3), resulting in,

\[ R = \frac{(t + dt) - t}{ds} = \frac{d^2x}{ds^2}i + \frac{d^2y}{ds^2}j + \frac{d^2z}{ds^2}k \]  \hspace{1cm} (4)

To evaluate the bending strain, we need the curvature radius, which will be calculated by taking the absolute value of the curvature vector \( R \) in equation (4). The inverse of the radius is expressed as follows [8],

Figure 2. Schematic of cross section of 30 kJ SMES coil. Two types of DPs will be used to confirm the feasibility of both R&W and W&R production methods.
By using these equations, the bending strain \( \varepsilon \) applied to the strands in conductor and coil windings is represented as

\[
\varepsilon = \frac{r_{fil}}{\rho} \times 100 \text{ [%]}
\]

where \( r_{fil} \) is the radius of filament region. Once the strand traces are calculated, the strain distributions along strand lengths are obtained.

### Figure 3. Definition of three-dimensional vectors for deriving space curve equations

#### 4. Analysis of strain dependence on the twist pitch

When we take a twist pitch, the strand traces are obtained. The differential geometry gives us the local bending radius distribution along strand axis, then the strain distribution is estimated. By taking maximum value of the strand, one twist pitch design gives one representative strain value.

Figure 4 (a) shows the result of strain calculation for the Rutherford-type cable using the 30-NM strand.

#### Figure 4. (a) Strain Calculation vs. twist pitch for 30-NM Rutherford conductor and (b) strain distribution in DP-1 coil in case of 51 mm twist pitch.

The range of twist pitch for strain calculation is from 30 mm to 120 mm. As for the Rutherford-type cable for W&R DP-1 coil, the strain is well below the permissible strain 4 % which is specified by the
manufacturer. With regard to the twist pitch, any pitch is applicable for conductor and DP coil fabrication. However, the twisting machine is not able to select the continuous pitch length because the pitch is determined by the combination of gears in the machine. Besides, the conductor toughness is also an important parameter to make the winding process easier. Finally, the 51 mm twist pitch was selected for the DP-1 conductor.

Figure 4 (b) shows a part of the calculated strain distribution of DP-1. The maximum strain appears at the edge of the conductor, while the strain is still lower at flat surface of the conductor. The value is 1.38 %, slightly higher than the maximum strain in the straight conductor. Once the coil is wound, the strain remains constant because DP-1 introduces the W&R method. The rated current of 600 A is expected to be realized in DP-1 coil due to enough margin of bending strain.

Figure 5(a) shows the result of strain calculation in Rutherford-type cable without mandrel using 10-24-NM strands. The range of strain calculation is performed from 40 mm to 100 mm. Unlike the 30-NM Rutherford conductor using 30-NM with Cu mandrel, the thin dimension due to the mandrel-free design causes higher strain around the edge of the conductor. Therefore, a longer twist pitch should be selected for enough strain margin. Therefore, the 82 mm pitch was selected but with reduced thickness compared to the original thickness of 1.68 mm for getting better tightness.

Figure 5(b) shows a part of strain distribution in DP-2 R&W coil. After conductor fabrication, the Rutherford-type cable is wound on a specialized bobbin with 800 mm for heat treatment. In the treatment process, the strain in the conductor is initialized and the permissible strain becomes 0.23 %. After winding, the maximum strain appears at the outer flat side of the winding, which shows 0.17 % strain still below the permissible strain. As a brief summary of the design activity, the analysis ensures that the coils may be operated without any problem.

5. DP coil test at liquid helium temperature

Figure 6 shows the schematic diagram of settings of DP-1 and DP-2 tests. The inset is the picture after finishing the setup. The DPs are series-connected to feed the same transport current and intentionally exposed to a more severe magnetic field and electromagnetic force conditions. The power supply has enough capacity to feed larger current than the rated one, up to 700 A. The coil voltages are measured by a nano-volt meter, to prevent the quench event by sending a signal to the circuit breaker. To verify the field generation, we put the hole probes at the center of the coil and 165 mm radial position, which detects almost maximum field of the coil. The DPs are immersed into liquid helium at 4.2 K without any external field. The coil current shows that the DP coils are in good operation, without enormous
voltage occurrence. The maximum B field at the 165 mm in radial position is 0.54 T, which is identical to 0.53 T calculated by FEM using COMSOL Multiphysics software. This is the first demonstration of large-scale DP coil operation using conductors consisting of multi-stranded configuration. As the next step, we will prepare for the LH2 indirect cooling experiment in which the operating temperature is in the range of 20.2 K to 25 K, and also DP-3,4,5 coil production.

![Image of experimental setup](image)

**Figure 6.** Experimental setup of series-connected DP-1 and DP-2 at liquid helium temperature. The external field is not applied in this demonstration.

![Graph of current and field](image)

**Figure 7.** Experimental result of continuous current feed to the coils up to 700 A. The ramp up and down of the transport current was successfully performed without any fault.
6. Conclusion
We carried out the design study of the coil for large-scale, 30 kJ SMES for investigating the feasibility of commercially available MgB$_2$ strands. The conductors forming large-scale coils are designed based on the Rutherford-type cable geometry with specified twist pitches in which the applied strains are well below the permissible strains of strain-sensitive MgB$_2$ strands. The first DP coils fabricated by introducing both the R&W and W&R methods showed excellent performance at liquid helium temperature, proving the validity of the design parameters of the conductors. This is the first and only demonstration of a large-scale DP coil operation using multi-stranded MgB$_2$ conductors all over the world. In the next phase, the remaining three DP coils will be produced in the same way as the process used for DP-2 production and liquid hydrogen indirect-cooling operation to demonstrate the compensation of power fluctuation in a SMES device.

Acknowledgments
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