Theoretical and experimental investigation of R&W and W&R SMES coils wound with large-scale MgB2 Rutherford cables operated around liquid hydrogen temperature

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Abstract. We have developed the system called Advanced Superconducting Power Conditioning System (ASPCS) composed of a Superconducting Magnetic Energy Storage (SMES), a fuel cell and a water electrolyzer for effective use of renewable energy such as wind and solar power generation. We have been investigating about the SMES coil using the large-scale Rutherford-type conductors made of commercially-available MgB2 wires. Due to strain sensitivity even before heat treatment for MgB2 production, the design for large-scale Rutherford cables both in the wind and react (W&R) method, and the react and wind (R&W) method applied to coil fabrication has to be done cautiously to prevent the degradation of the Ic by the optimizing design parameters such as the twist pitch and the cable compaction. Especially for the R&W method using heat-treated wires, other factors like handling during the coil production process which affect the conductor and coil Ic should be also considered. To evaluate the applied strains during the manufacturing process, we conducted theoretical investigation on the strains applied to individual filaments caused by wire-bending. We developed a test coil designed for the R&W method based on analyzing those factors. Furthermore, we measured the coil Ic-B-T characteristics and compared to those of other test coils made by the W&R method.

1. Introduction
MgB2 round wires attract the interests of researchers from the point of view of applying them to the large-scale power devices like the superconducting magnetic energy storage (SMES). For compensation
of power fluctuations produced by the photovoltaic cells and the wind turbines, our group had developed new DC-microgrid system (48 V) in which the voltage fluctuations due to unsettled weather would be well controlled by using the combinations of the small SMES magnet made of Bi2223, fuel cell and water electrolysis device[1][2]. The system worked successfully, however, the manufacturing process of SMES coils consisting of cost-effective wires should be pursued the economical manufacturing process for installation in the real power grid system.

The MgB2 production process resembles the Nb3Sn production which needs heat treatment, and also resembles to the strain sensitive characteristics of superconducting properties. As for the MgB2 wires, the 4% permissible strain is designated by a supplier before the heat treatment of the MgB2, and 0.2% strain after the heat treatment. When we construct a large-scale coil for energy storage device, three ways for the coil fabrication are available in terms of the heat treatment process. One is to use heat-treated wires. In this process, owing to the tight permissible strain, a conductor and coil fabrication might be extremely tough work. Another is to use non heat-treated wire, and the coil winding after heat treatment of a “conductor”. In this case, the twisting process is easier than that using heat-treated wires due to larger permissible strain. The coil-winding process is simple because inter-turn insulation and terminals for the current feed is not exposed at high temperature. The other is also to use unreacted wires, then the whole coil including the insulation and the attached terminal are heat-treated together. The advantage of the final case is to have the large strain margin throughout the whole process, while the exposure at the very high temperature would be inevitable. The first and second cases are called as react-and-wind (R&W), the last one is called as wind-and-react (W&R) method, respectively. The W&R process seems reasonable for the construction of those coils, while R&W process deserves our attention in terms of simple and easy fabricating feature, turn-to-turn insulation, if applied strain to the wires is acceptable. Although many research groups started to investigate characteristics of the round cable using MgB2 wires, the current capacities are not suitable for large-scale applications due to adopting fine wires [3-7]. As for the coil fabrication, several groups have carried out fabricating the test coils consist of single tapes with large aspect ratios, not using the conductors made of several tapes or wires [8][9].

Our aim in this study is to design and demonstrate pancake coils for the SMES by two construction methods. One is to use the conventional W&R method mentioned above. The other is to use the R&W method by which the reacted MgB2 wires are wound with acceptable strain. Our group has constructed small test coil with 200 mm in inner diameter by the W&R method and has evaluated test result of the coil Ic-B-T characteristic, using the non-react strands supplied by Hyper Tech Research, Inc. [10]. Furthermore, we have developed the other test coil having the coil dimension identical to the W&R test coil made by the R&W method, using Columbus strands (Columbus Superconductors S.P.A). This paper presents the performance of the test coil designed by the R&W method with the reacted strand based on analysis and experimental result of the coil Ic-B-T characteristic.

2. Conductor and coil Design and Specifications

2.1. Strand Curvature Calculation in a Pancake Coil

To consider the double pancake (DP) coil for SMES, the number of strand should be larger than 8 according to its current density Jc = 5300 A/mm² around 20 K. In order to simplify the calculation, we primary introduced the round cable geometry with round core to ensure the 600 A operation and enough thermal stability. Parameters for calculating strand trace in a pancake coil are shown in figure 1. The major and minor radius is expressed by using R and r, respectively. To determine the strand position on the trace, we need angles as a function of parameter t from original axes, which are $\Phi t$ and $\theta t$, where $\Phi$ and $\theta$ indicate toroidal and poloidal pitch, respectively. By using these parameters, the given position on the trace $(x,y,z)$ is expressed as follows,
\[ x = (R + r \cos(\theta t)) \cos(\phi t) \]
\[ y = (R + r \cos(\theta t)) \sin(\phi t) \]
\[ z = r \sin(\theta t) \]  

Equation (1) enables us to express the second derivatives in the equation (10) in ref. [10] as a function of line element vector along a given curve \( ds \).

\[
\begin{align*}
\frac{d^2x}{ds^2} &= \frac{d}{ds} \left( \frac{dx}{ds} \right) = \frac{d^2x ds - d^2s dx}{ds^3} \\
\frac{d^2y}{ds^2} &= \frac{d}{ds} \left( \frac{dy}{ds} \right) = \frac{d^2y ds - d^2s dy}{ds^3} \\
\frac{d^2z}{ds^2} &= \frac{d}{ds} \left( \frac{dz}{ds} \right) = \frac{d^2z ds - d^2s dz}{ds^3}
\end{align*}
\]

Equation (2)

\[ ds^2 = dx^2 + dy^2 + dz^2 = [\theta^2 r^2 + \phi^2 (R + r \cos(\theta t))^2] dt^2 \]  

Equation (3)

\[ \frac{d^2x}{ds^2} = [-\theta^2 \cos(\theta t) \cos(\phi t) + 2\phi r \sin(\theta t) \sin(\phi t) - \phi^2 (R + r \cos(\theta t)) \cos(\phi t)] dt^2 \]
\[ \frac{d^2y}{ds^2} = [-\theta^2 \cos(\theta t) \sin(\phi t) + 2\phi r \sin(\theta t) \cos(\phi t) - \phi^2 (R + r \cos(\theta t)) \sin(\phi t)] dt^2 \]
\[ \frac{d^2z}{ds^2} = [-\theta^2 r \sin(\theta t)] dt^2 \]

\[ \frac{d^2s}{ds^2} = -\frac{\phi r^2 (R + r \cos(\theta t)) \sin(\theta t)}{\sqrt{\theta^2 r^2 + \phi^2 (R + r \cos(\theta t))^2}} \]  

Equation (4)

According to the vector calculus, a unit tangential vector \( \mathbf{T} \) on a curve is expressed by using differentiation of position vector \( \mathbf{dr} = (dx, dy, dz) \) and a line element vector \( ds \).

\[ \mathbf{T}(s) = \frac{\mathbf{dr}}{ds} \]

Equation (5)
The equations (2)-(5) result in the final expression of the curvature radius $\rho$ which is described as an inverse of a differentiation of tangential unit vector $T$ along a curve.

$$\rho = \left| \frac{dT}{ds} \right|^{-1}$$

(6)

as functions of toroidal angle, poroidal angle, major radius $R$ and minor radius $r$.

$$\frac{1}{\rho^2} = \frac{1}{\left[ \theta^2 r^2 + \phi^2 (R + r \cos(\theta t))^2 \right]^3} \left( \theta^6 r^4 + \theta^4 \phi^2 \left[ r^4 (3 + \sin^2(\theta t)) + 4r^3 R \cos(\theta t) + r^2 R^2 \right] + \theta^2 \phi^4 r (R + r \cos(\theta t)) \left( 3r + r \sin^2(\theta t) + 2R \cos(\theta t) \right) + \phi^6 (R + r \cos(\theta t))^4 \right)$$

(7)

Because the toroidal and poroidal pitch determine the coil radius and the conductor twist pitch, the curvature in equation (10) in ref. [10] is successfully expressed as a function of the parameter $t$.

2.2. Evaluation of Filament Strain Applied After Straighten and Acceptable Strain

To evaluate the initial strain, we used the equation (5) for calculating curvature of filaments in a strand. Figure 3 shows the three-dimensional strain distributions of the filaments estimated based on the space curve theory detailed in [10] when a strand is straightened for the length of one filament twist pitch, 300 mm. The bending center is located on the horizontal surface, which is perpendicular to the strand axis. The maximum strains appear on the right surface of the strand, while minimum on the left surface. The value is estimated around 0.11 % by using the bending radius (i.e. curve radius) calculated by the equation in [10] and the filament radius ($r_{\text{filament}}$), such as,

$$\varepsilon = \frac{r_{\text{filament}}}{\rho}$$

(8)

Next, we evaluate the acceptable strain considering the initial strain and the minimum bending strain assigned by the supplier, which is 100 mm. The calculated strain distributions of the filaments are shown in figure 4. The maximum strain 0.24 % is generated on the outer surface of the bending curve. Since
the strand characteristics, i.e. critical current is affected only by the maximum strain of the filaments, we regard the strand strain as the maximum value of filament strain.

2.3. Filament Strain Evaluation during Twisting Process

When we will fabricate the conductor, we will use the twisting machine with the twist back function. The strands are cabled and twisted simultaneously in the opposite direction with respect to the cable axis at the ratio of one twist pitch for one turn of the cable, which is so called “planetary motion”. This mechanism prevents the shear stress application to the strand during the twisting process.

Figure 6 shows the calculation concept of filament strain during twisting process with the above mentioning twist back function. The strain calculation needs not only the filament traces but also the distance between the filament position and the neutral axis of the strand bending curve, \( d \) in figure 4. The distance \( d \) is expressed by using position vector of strand axis \( P \) and bending radius vector \( R \), that is,

\[
d = P \frac{R}{|R|}
\]  

(9)

Because the bending radius vector is second derivatives of filament position vector \( r \) and a unit tangential vector \( T \).

\[
R = \frac{\partial T}{\partial s} = \frac{\partial^2 r}{\partial s^2} = \frac{\partial^2 x}{\partial s^2} i + \frac{\partial^2 y}{\partial s^2} j + \frac{\partial^2 z}{\partial s^2} k
\]  

(10)

Where \( i, j, k \) are unit vector in \( x, y, z \) direction. Clearly, the \( |R| \) is identical to an inverse of curvature radius \( \rho \). Lastly, we get the expression of filament strain as follows,

\[
\varepsilon(P) = \frac{d}{\rho} = P \cdot \frac{R}{\rho|R|} = P \cdot R
\]  

(11)

Figure 4. Schematic drawing of the concept of calculating filament strain with twist back function

Figure 5. Example of filament strain distribution on the strand cross section. Both neutral line and normal vector are shown here. The maximum strain appears when the vectors heat treatment and bending manufacturing are parallel to each other (bottom strand). We define the maximum strain as maximum filament strain in a strand.

Figure 7 shows the filament strain distribution evaluated by equation (11) on the conductor cross section. In this case, the bending strains are applied only by the twisting process, which means that this cross section does not experience the bending strains by the winding process. In the figure, there are two vectors described in each strand, which are curvature vector (pink-coloured) and the heat treatment axis vector (green-coloured). The bending curve vector for cabling is along the direction from circumference to the strand center. The maximum strain of the filament appears when the two vectors are completely
parallel to each other, the bottom strand in this case. When we wind the coil with the round conductor, we have to consider additional bending vector of bending the conductor.

\[ \varepsilon = \frac{r_{\text{filament}}}{\rho} = r_{\text{filament}} \sqrt{\left(\frac{d^2x}{ds^2}\right)^2 + \left(\frac{d^2y}{ds^2}\right)^2 + \left(\frac{d^2z}{ds^2}\right)^2}, \]  

where \( r_{\text{filament}} \) indicates the radius of the filament region of the MgB\(_2\) strand. The equation enables us to evaluate local bending strain of strand traces calculated in the manner mentioned above.

According to the equation (12), we found the coil with 450 mm inner diameter and 100 mm strand twist pitch became more than the acceptable strain. Therefore, we determined to introduce the rectangular-shaped, and 9-stranded conductors with the Cu mandrel twisted with pitch of 450 mm through several design activities.

### 2.4. MgB\(_2\) Conductors and coils

A specification of the strands and the conductors designed for a small test coils is consequently shown in table 1. The cross sections of the conductors for both R&W and W&R methods are also shown in Figure 8. The strands selected for making several DP coils (DPs) with a nominal current 600 A and a stored energy of 30 kJ, made up with the SMES coil under the condition of liquid hydrogen temperature by conduction cooling between liquid hydrogen and the SMES coil to separate the hydrogen and electric current.

Two small test coils were fabricated using the Rutherford-type conductors made of these MgB\(_2\) wires. The Rutherford-type conductors was designed to carry 600 A under 1.5 T at 25 K keep thermal stability even when the conductors would be in fully normal state under various conditions (MgB\(_2\) wire, conductor and coiling method). In the small test coil by the W&R method, reference [10] gives more details on the analysis.

| Table 1. Specifications of MgB\(_2\) strand |
|-------------------------------------------|
| Number of filaments | Hyper Tech (30-NM) | 30 |
| Fill Factor | 0.2 |
| Twist Pitch of Filament [mm] | NA |
| Cu ratio | 0.12 |
| Diameter [mm] | 0.83 |
| Jc (20K, 0T) [A/mm\(^2\)] | 5350 |
| Heat Treatment Status | Un-react |
| Permissible strain [%] (before / after reaction) | 4 / 0.23 |

Concerning the small test coil fabrication by the R&W method, we should evaluate the acceptable strain of MgB\(_2\) filaments in the Columbus wire against the strand bending from 100 mm to the minimum bending radius instructed by Columbus [11], including draw and straighten process from the heat
treatment bobbin as mentioned previous section. Table 2 shows specifications of two test coils and conductors.

**Table 2. Specifications of conductors and coils**

| Items                        | W&R (30-NM)       | R&W (Columbus) |
|------------------------------|-------------------|----------------|
| Conductor                    |                   |                |
| Number of strands            | 8+4 CuZn         | 9 CuNi         |
| Former                       | CuNi              | Cu             |
| Insulation                   | S-glass           | S-glass        |
| Twist pitch (mm)             | 51                | 450            |
| Maximum bending strain (%)   | 1.25              | 0.17           |
| Coil                         |                   |                |
| Coil Type                    | Single Pancake    | Single Pancake |
| Inner diameter               | 200               | 250            |
| Number of turns              | 10                | 10             |
| Maximum bending strain (%)   | 1.54              | 0.19           |

2.5. Strain Trace and Bending Strain in Coil Configuration

Figure 9 is indicative of a part of the calculated strain distribution of small test coil by R&W method. The simulation result show that the maximum bending strain in coiling process can be kept within the permissive strain by setting the pitch range much longer than that of a conductor using 30-NM.

![Figure 7. Strain distribution in small test coil using Columbus strands](image)

2.6. Experimental procedure

The test to check the degradation by cabling and coiling in small test coil by R&W method was conducted in Railway Technical Research Institute. Figure 8 illustrates a schematic diagram of the system for measuring the Ic-B-T characteristic of test coil. To compare R&W coil with W&R coil, this experiment conducted has the same conditions as the previous test for measuring the performance of the
W&R test coil [10]. The test coils were cooled by refrigerators and an external field was applied using a 5.5 T magnet.

3. Experimental Results

Figure 9 (a) and (b) show the $I_c$-B-T characteristics of W&R test coil and R&W test coil, respectively. The operating temperatures are set from 20 K to 30K at 1 K intervals by the heater power input to the coil. Since the self-magnetic field is small and can be ignored, it is plotted with the value of the applied magnetic field. The results of two test coil demonstrations showed the R&W coil was more degraded than the W&R coil. The cause of the deterioration of this coil speculate that the distortion applied during the production process exceeded the theoretical value.

4. Conclusion

Our group have designed the conductors and coils for R&W and W&R SMES coils with 30 kJ stored energy designed by using commercially available MgB$_2$ strands. This report presents that conducting the Rutherford-type strands using reacted wires by R&W method prove a challenge. On the other hand, our group has developed and tested coils for SMES using un-reacted wires and has shown its practicality. Based on the experience, the application of reacted wire is open to further discussion.

Acknowledgments

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