CONTROL SYSTEM FOR SMES COIL WINDING MACHINE

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Abstract

The coil winding machine for SMES (Superconducting Magnetic Energy Storage) coil has been constructed in NIFS (National Institute for Fusion Science). We employed the control system which consists of eight pulse motors and a PLC (Programmable Logic Controller). The main role of personal computer is to measure and control the twisting angle of the superconductor within the error range of plus or minus five degrees in order to reduce the AC loss, which is sensitive to the magnetic direction.

Last year 100 kJ prototype SMES coil was constructed and the performance test has finished successfully. In the next step, 1 MJ class SMES coil is scheduled.

INTRODUCTION

Although a momentary voltage drop or instant power failure causes serious damage to the experimental facilities like a nuclear fusion device or the production lines of the industrial plants, effective countermeasures have not been considered because of its large electric power capacity. We are developing a 1 MW, 1sec SMES to protect the facilities from this kind of failure [1].

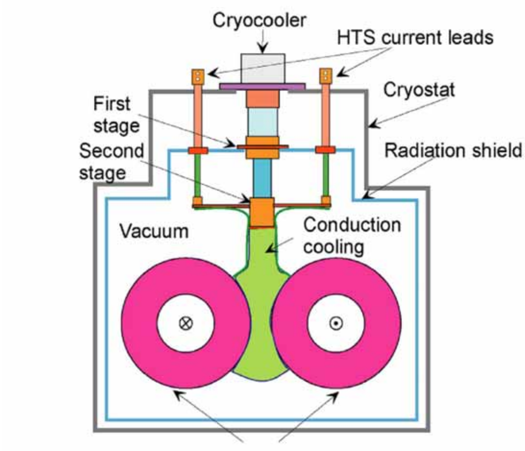

Figure 1: Conduction-cooled LTS pulse coil.

The SMES stores magnetic energy by energizing superconducting (SC) coil. We determined to utilize a conduction cooled low temperature superconducting (LTS) pulse coil for SMES because of its high reliability and easier operation than conventional cooling schemes such as a pool boiling or forced cooling as shown in Fig. 1. The reduction of AC loss and the increase of heat capacity are required for a SC conductor because the conduction-cooled coil connot rely on the high specific heat of helium. The SC conductor of a NbTi/Cu compacted strand cable extruded with aluminium is designed to have the anisotropic properties to minimize the coupling loss under the specified orientation of the time varying magnetic field (Fig. 2) [2].

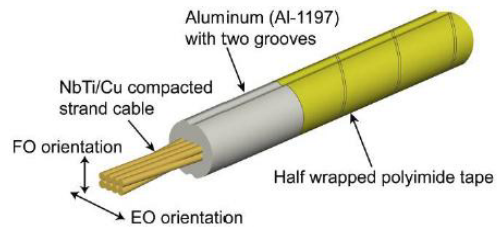

Figure 2: SC conductor for the LTS pulse coil.

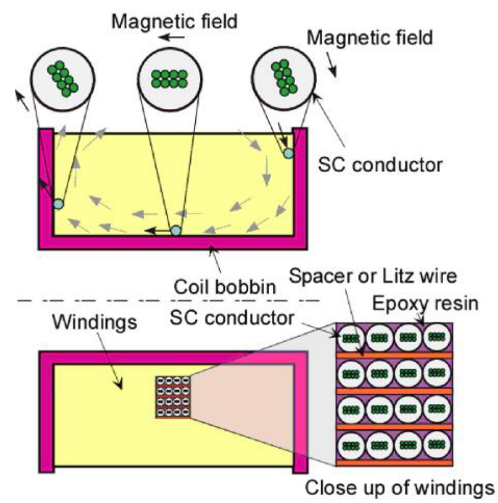

Figure 3: Twisting the conductor in the coil.

In order to reduce the AC loss, the twisting angle around the axis of the conductor should be always controlled to adjust the direction of edge-on orientation of the compacted cables in the conductor to the direction of local magnetic field (Fig. 3). The conductor has two grooves on the surface to detect the conductor angle. In the winding process, the error between the measured conductor angle and its reference should be controlled within 5 degree by personal computer (PC). At the same time it is necessary to control the conductor tension at 1000 N to support the strong electromagnetic force generated in the energizing process.

We have newly developed the special winding machine to wind a 100 kJ prototype coil as the first step of the 1 MW, 1 sec SMES.

WINDING MACHINE

The whole view of the winding machine is shown in Fig. 4. The winding machine is classified into three parts i.e., 'conductor supply part', 'middle part' and 'winding part'. The conductor is supplied from the dram in the ‘conductor supply part’ and is lead to the ‘middle part’ then is wound at winding bobbin in the ‘winding part’. There is a tension detector in the ‘middle part’ and the conductor tension is controlled at 1000 N by PLC.

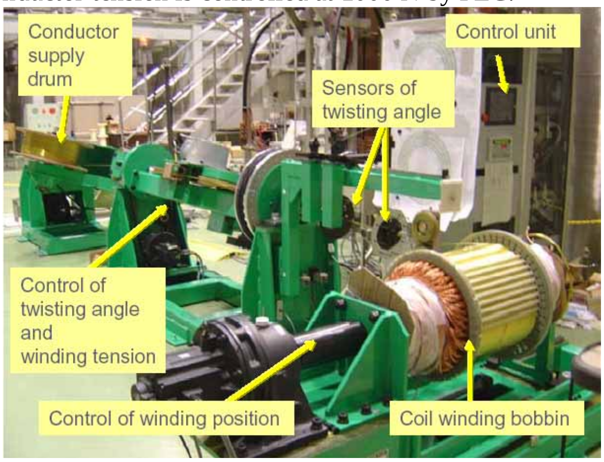

Figure 4: The whole view of the winding machine.

There are two proximity sensors just behind the winding bobbin. They rotate around the conductor to detect the groove positions on the conductor (Fig. 5).

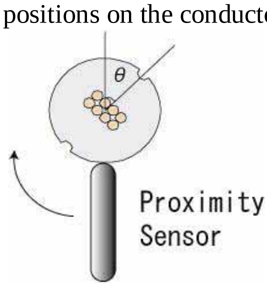

Figure 5: The groove detection technique with proximity sensor.

100 KJ PROTOTYPE COIL

The 100 kJ prototype coil wound with this machine is shown in Fig. 6 and its specifications are listed in table.1.

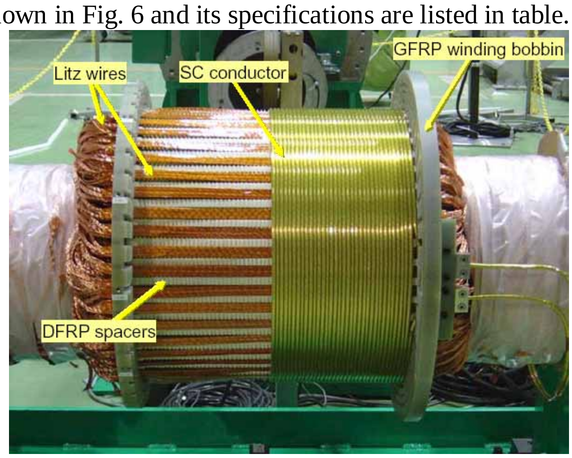

Figure 6: The 100 kJ prototype coil.

The coil forms a single solenoid of 67 turns x 14 layers wound on the GFRP bobbin. The Dyneema FRP (DFRP) spacers and the Litz wires (braided wires of insulated copper stands) are inserted between layers. The DFRP spacers have a good thermal conductivity along with Dyneema filaments, which enhance the heat transfer from layer to layer in the windings. On the other hand, the Litz wires increase the heat transfer from turn to turn in the windings and enable conduction cooling of the coil by attaching the end of the Litz wires directly to the cold heads of the cryo-coolers.

Table 1: Coil Specification

Cooling method	Conduction cooling with Litz wires
Coil shape	Solenoid
Inner diameter	0.305 m
Outer diameter	0.509 m
Length	0.402 m
Number of turns per layer	67
Number of layers	14
Total length of conductor	1.20 km
Maximum magnetic field	2.2 T
Magnetic stored energy	100 kJ
Total weight	400 kg

CONTROL SYSTEM

Concept

While the DFRP spacer and the Litz wire are inserted by hand, the conductor tension should be kept at 1000 N and each motor has high capability of maximum torque of 15-50 Nm. Therefore, we have carefully designed the safety interlock logic e.g., emergency stop, limitation of motor torque and rotation speed on PLC [3].

We have developed the control software on the PC because it is necessary to collect the historical control parameter as much as possible to research the control algorism that includes complicated calculation of the twisting angle.

We are also planning a perfect automation in the future and it is an important subject how to secure the enough reliability and precision by introducing a PC.

Hardware

The eight servo motors, eight rotary encoders, one tension detector and two proximity sensors are connected to the PLC (Fig. 7). The hardwares usually are operated at control terminal automatically. In debugging, maintenance or trial operation, they are operated manually from touch panel.

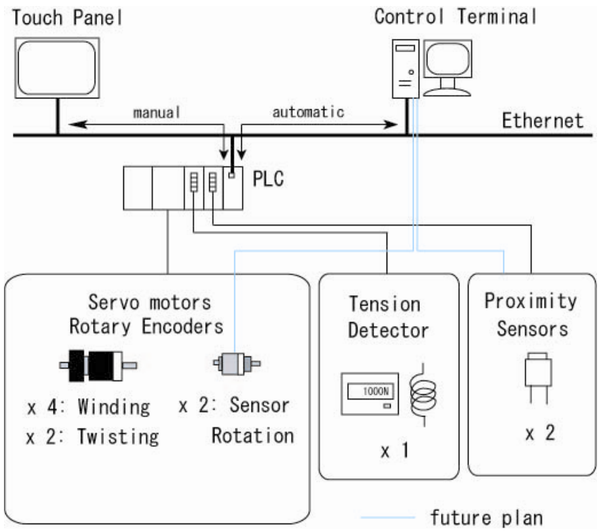

Figure 7: Control system.

Software

The control application in the PC consists of 'winding process' and 'twisting process'. The winding process sends START/STOP command and parameters e.g., rotation angle and rotation speed to the PLC by UDP/IP socket.

There are three steps in the twisting process.

1) The twist angle is calculated from the conductor angles measured by proximity sensors.
2) The conductor supply drum and the middle part are turned together (Fig. 8).
3) The conductor is wound to the coil bobbin by 1/12 turn.

This procedure is repeated every 1/12 turn till 14 layers x 67 turns.

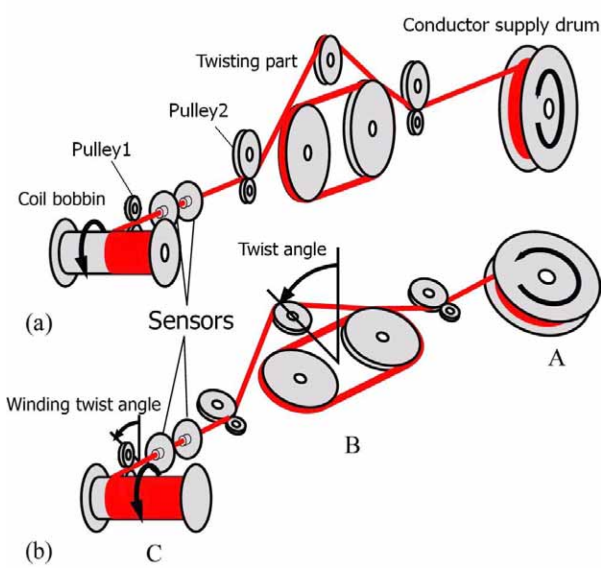

Figure 8: The principle operation of the twist-winding machine.

The calculation method of twisting angle is explained in detail.

The function of conductor angle between the two pulleys is calculated by linear approximation (Fig. 9).

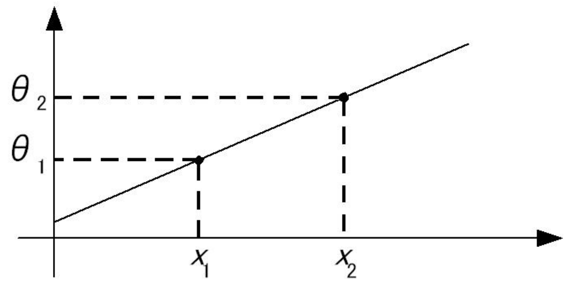

Figure 9: Linear approximation of conductor angle.

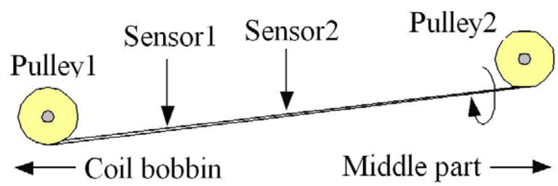

Figure 10: Arrangement of pulleys and sensors.

The pulleys are installed behind the coil bobbin and after middle part. There are two proximity sensors between the pulleys (Fig. 10).

The function of conductor angle before twisting is given by equation(1).

$$\theta_{bef}(x)=\frac{\theta_2-\theta_1}{x_2-x_1}(x-x_1)+\theta_1 \tag{1}$$

Sensor 1 position: x_1 measured angle: θ_1
Sensor 2 position: x_2 measured angle: θ_2

We can assume that the conductor angle at the pulley behind the coil bobbin will not change after twisting because the conductor angle is fixed at pulley (Fig. 11). Based on this assumption, the function of conductor angle after twisting is given by equation(2).

$$\theta_{aft}(x)=a_{aft}(x-x_0)+\theta_0 \tag{2}$$

Pulley1 position: x_0 , conductor angle: θ_0 , constant value: a_{aft}

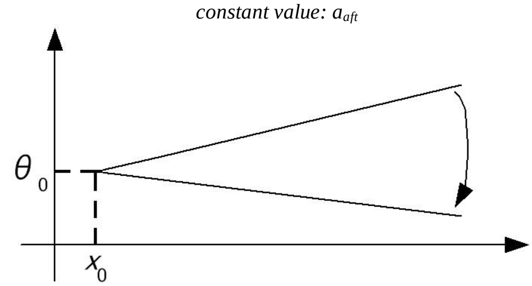

Figure 11: Fulcrum of the conductor in twisting.

The function of reference angle is given by equation(3).

$$\theta_{ref}(x)=a_{ref}x+b_{ref} \tag{3}$$

constant value: a_{ref}, b_{ref}

The suitable equation(2) is found by minimizing the integration of the error between equation(2) and equation(3) at arbitrary range.

$$\int_0^{L+x0} \left|\theta_{ref}(x) - \theta_{aft}(x)\right| dx$$

Constant value: L

This equation equals to calculate the cross point of equation(2) and equation(3) at $L+x_0$ as equation(4).

$$\theta_{ref}(L + x_0) = \theta_{aft}(L + x_0) \tag{4}$$

The θ_{aft} is given by equation(5) from equation(2) and equation(4).

$$\theta_{aft}(x) = \frac{(a_{ref}(L + x_0) + b_{ref} - \theta_0)}{L}(x - x_0) + \theta_0 \tag{5}$$

Finally, the twist angle is given by equation(6) (Fig. 12).

$$\Delta\theta = \theta_{aft}(x_{mid}) - \theta_{bef}(x_{mid}) \tag{6}$$

Pulley2 position: x_{mid}

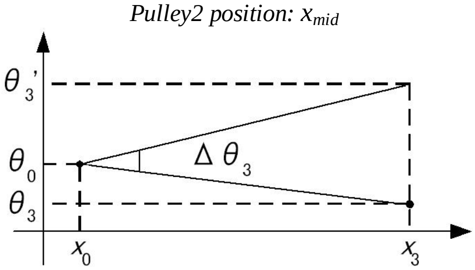

Figure 12: Machine twisting angle.

The operation window developed on the Visual Basic.NET is shown in Fig. 13. The grooves on the conductor are detected as ‘V shapes’ in the waveform.

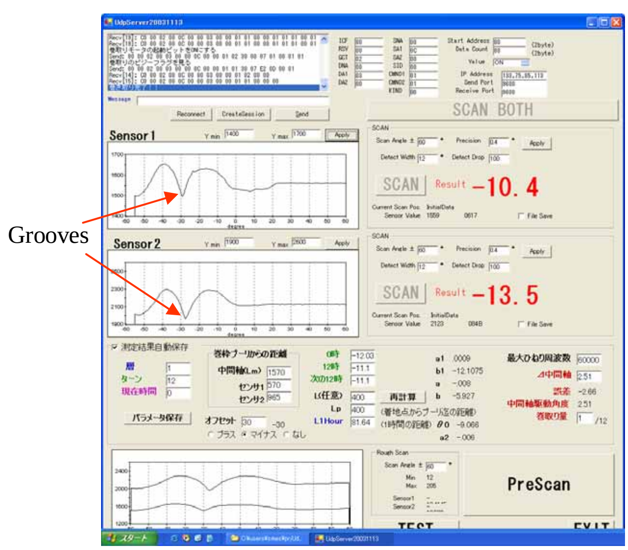

Figure 13: Operation window.

RESULTS OF WINDING

We have analysed the historical control parameters. The precision in a layer is shown in Fig. 14. The coil is wound within the error range of plus or minus 10 degree in this sample data.

The remaining subjects for the next step are listed below. We will continue to improve the winding machine and the control system.

- It is difficult to express the actual conductor angle by linear approximation because the conductor is twisted as the non-linear function (spiral-shaped). We will add the sensors to achieve the higher precision.
- The conductor angle at landing point on the coil surface is hard to measure by proximity sensor. We will solve this problem by image processing.
- Faster control speed is necessary for the 1 MJ coil winding. We are going to connect some of the servo motors and proximity sensors to the PC directly to improve the control speed.

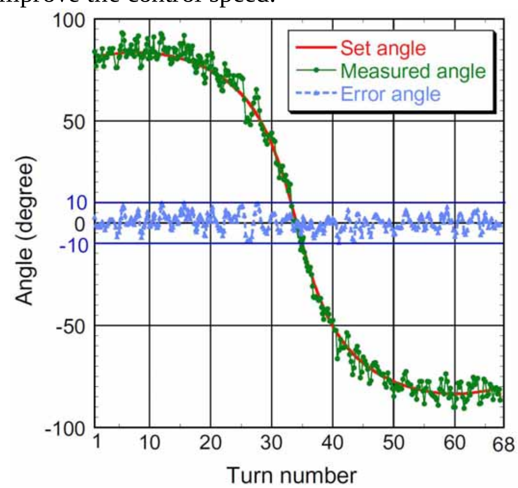

Figure 14: Precision in a layer.

CONCLUSION

We have been developing a conduction-cooled LTS pulse coil for 1 MW, 1 sec SMES. The construction of the 100 kJ prototype coil has been completed successfully by development of the special winding machine and the control system by try and error. Finally, the 100 kJ coil has achieved nominal performance in the qualitative examination. We will improve the winding machine and control system to increase the precision, the reliability and the winding speed toward the 1 MJ class coil winding.

REFERENCES

[1] T. Mito, et al., “Development of UPS-SMES as a protection from momentary voltage drop” IEEE Trans. Appl. Supercond., vol.14, no. 2, pp.721-726, 2004.

[2] A.Kawagoe, et al., “Winding Techniques for conduction cooled LTS pulse coils for 100 kJ class UPS-SMES as a protection from momentary voltage drops”, IEEE Trans. Appl. Supercond., vol.14, no. 2, pp. 727-730, 2004.

[3] M.Yokota, et al., "Production of the winding machine for the SMES coil" (in Japanese), Meeting on Engineering & Technology at KEK, February 2004, P-020