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Design and performance analysis of a dynamo-type HTS flux pump for 10 kW superconducting generator

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1 Introduction

This paper presented the design and performance analysis of a dynamo-type HTS flux pump for a 10 kW superconducting generator. The HTS field coil of a 10 kW superconducting generator was designed and fabricated. The induced DC current, output voltage, and dynamic resistance of the flux pump connected to the HTS field coil were estimated using electric circuit equations. They were tested at various rotational speeds and air gaps, and the test results were compared with the estimated results. The performance was confirmed by applying a flux pump to the 10 kW superconducting generator. As a result, as the rotational speed of the flux pump increased, the induced DC current of the flux pump connected to the HTS field coil increased proportionally. As the air gap of the flux pump increased, the induced DC current decreased. A sufficient current was induced in the field coil to produce a 10 kW output.

2 Electrical circuit model

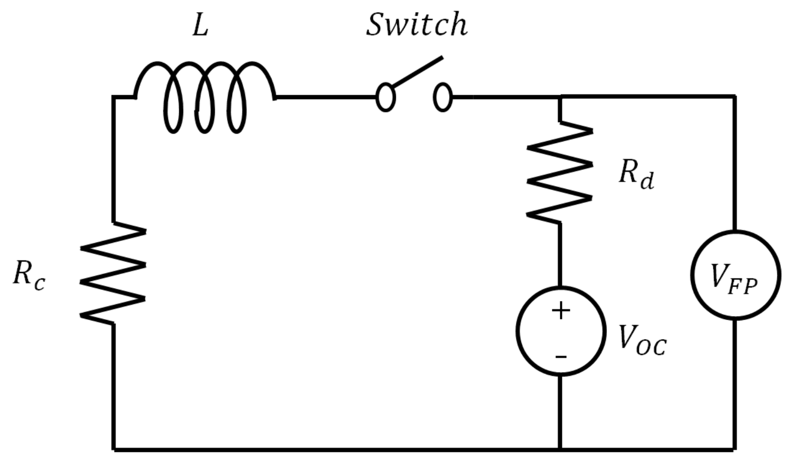

Fig. 1. Electrical circuit model for a flux pump connected in series to an HTS coil

The voltage generated by the flux pump V_{FP} can be represented by an open circuit voltage V_{OC} and a dynamic resistance R_d according to the relation:

$$V_{FP} = V_{OC} - IR_d \quad (1)$$

The current I delivered by the flux pump connected to the HTS coil of inductance L by soldered joints with resistance R_c is given by:

$$I = I_O\left[1 - e^{\left(-\frac{(R_d+R_c)t}{L}\right)}\right] \quad (2)$$

where t is the time since the dynamo started and I_O is the maximum current that can be delivered to the HTS coil and is given by:

$$I_O = \frac{V_{OC}}{R_d + R_c} \quad (I > I_c) \quad (3)$$

3 Experimental apparatus

A. Design of an HTS test coil

The HTS test coil was designed and fabricated to verify the electrical circuit model and the related equation. The HTS coil was a joint less type for minimizing the joint resistance.

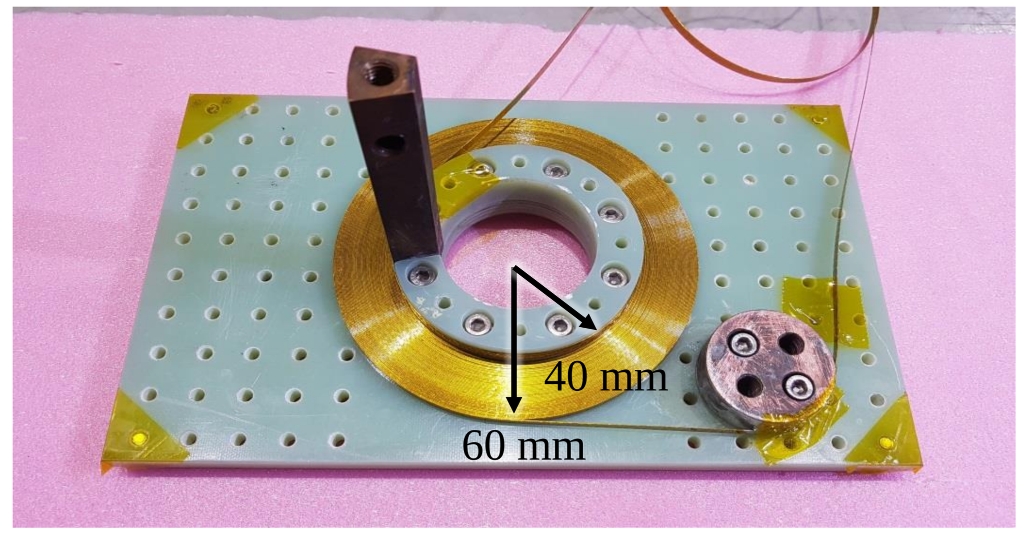

Fig. 2. Dimension of the fabricated test coil for HTS flux pump

Table I
Specifications of the HTS wire and test coil

Items	Value
HTS wire manufacturer	SuNam
Material of the superconductor	GdBCO
Width of the HTS wire	4 mm
Thickness of the HTS wire	0.35 mm (included insulation)
Insulation type of the HTS wire	Kapton tape
Critical current of the HTS wire	200 A(@77K self-field)
Number turns of the HTS coil	57 turns
Inner radius of the HTS coil	40 mm
Outer radius of the HTS coil	60 mm
Critical current of the HTS coil	121 A(@77K)
Central magnetic field	0.089 T
Inductance of the HTS coil	0.488 mH

B. Configuration of the 10 kW superconducting generator with HTS flux pump

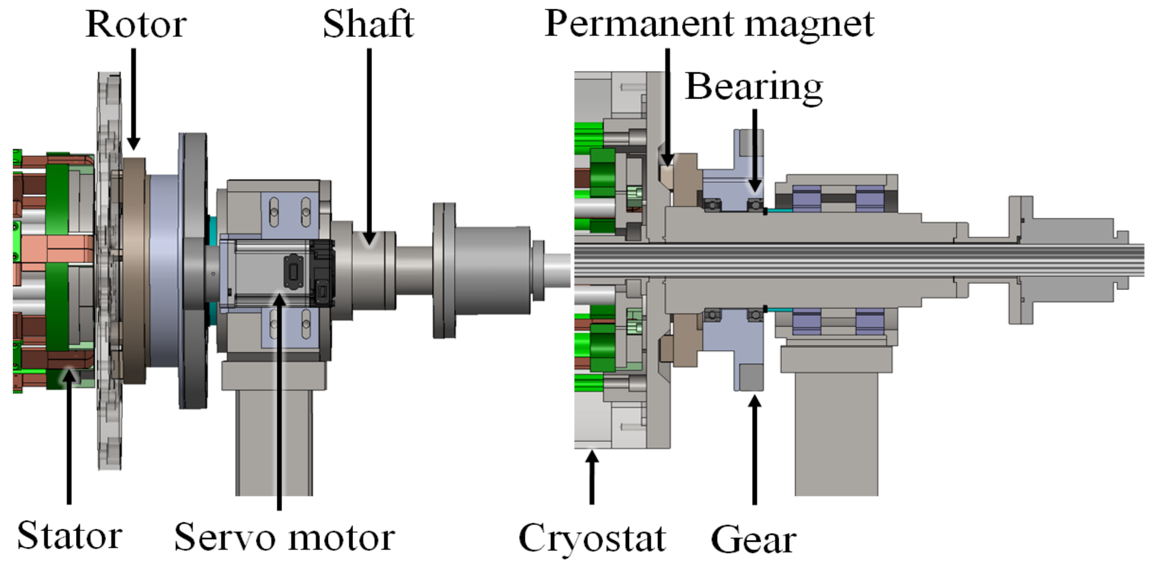

Fig. 3. Cross-sectional view of the 10 kW HTS generator with HTS flux pump

Table II
Design conditions of a 10 kW HTS generator

Items	Value
Rated output power	10 kW
Rated voltage	380 V
Rated rotating speed	400 rpm
Current density of the stator wire	3 A/mm^2
Number of the poles	6
Number of turns of the stator	30 turns
Operating temperature	30 K
Outer diameter of the generator	476 mm

C. Design of an HTS field coil for the 10 kW superconducting generator

Table III summarizes the specifications of the HTS field coil for the 10 kW HTS generator. The HTS field coil was equipped with queried pancake coil (QPC) type and the insulated with Kapton tape.

Table III
Specifications of the HTS field coil for 10 kW HTS generator

Items	Value
HTS wire manufacturer	SuNam
Width of the HTS wire	4 mm
Thickness of the HTS wire	0.15 mm (included insulation)
Critical current of the HTS wire	220 A (@77K self-field)
Number turns of the QPC	900 turns
Total length of the HTS wire	500 m
Critical current of the HTS coil	44 A (@77K) 150 A (@30K)
Maximum magnetic field	0.8 T (@77K) 1.9 T (@77K)
Perpendicular magnetic field	0.4 T (@77K) 1.4 T (@77K)
Inductance of the HTS coil	130 mH

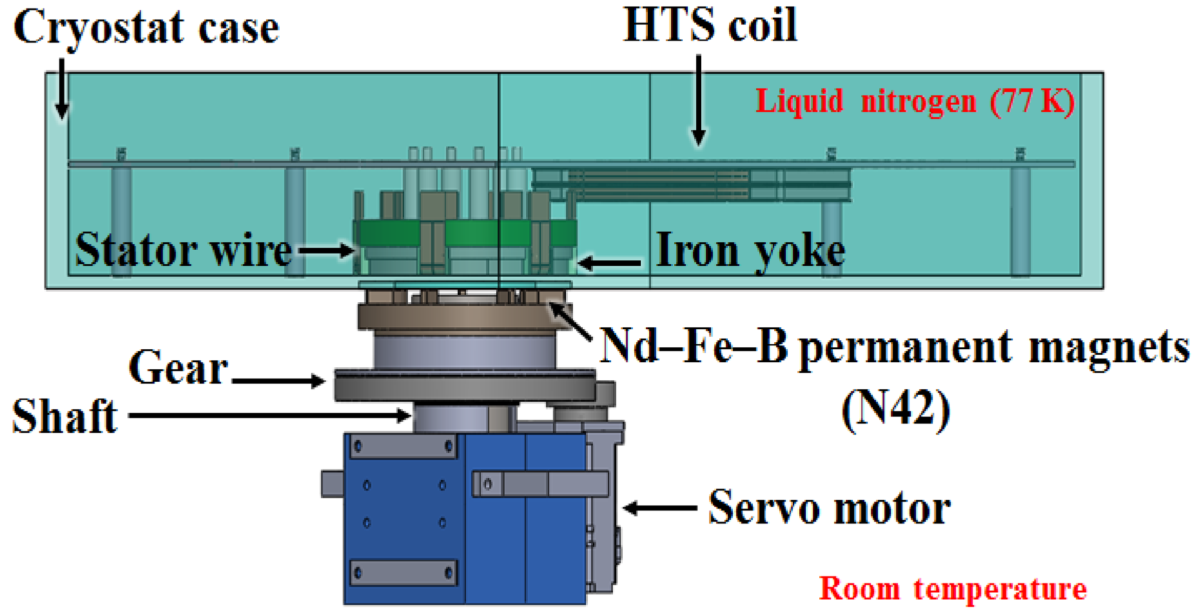

Fig. 4. Schematic diagram of HTS flux pump

D. Configuration of an HTS flux pump

The HTS flux pump can be divided into a rotor part and a stator part. The stator consisted of an internal stationary iron yoke, HTS stator wire and an HTS coil. Six stator wires surround the iron yoke and are connected in series with each HTS coil. The rotor consisted of an iron rotor, Nd–Fe–B permanent magnets (N42) and a servo motor.

Table IV
Specifications of the flux pump

Items	Value
HTS wire manufacturer	Superpower
Inner radius of the stator	69.75 mm
Outer radius of the stator	95.75 mm
Width of the stator wire	24 mm
Width of the stator yoke ring	26 mm
Number of the stator poles	6
Inner radius of the rotor	50 mm
Outer radius of the rotor	100 mm
Number of the N42	7

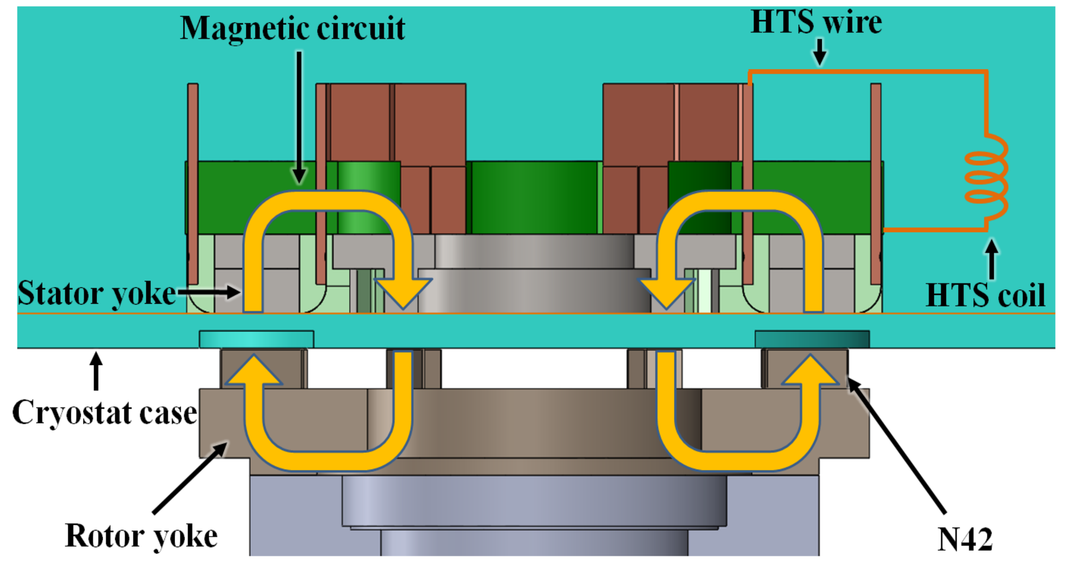

Fig. 5. Magnetic circuit formed between the stator and rotor of the HTS flux pump

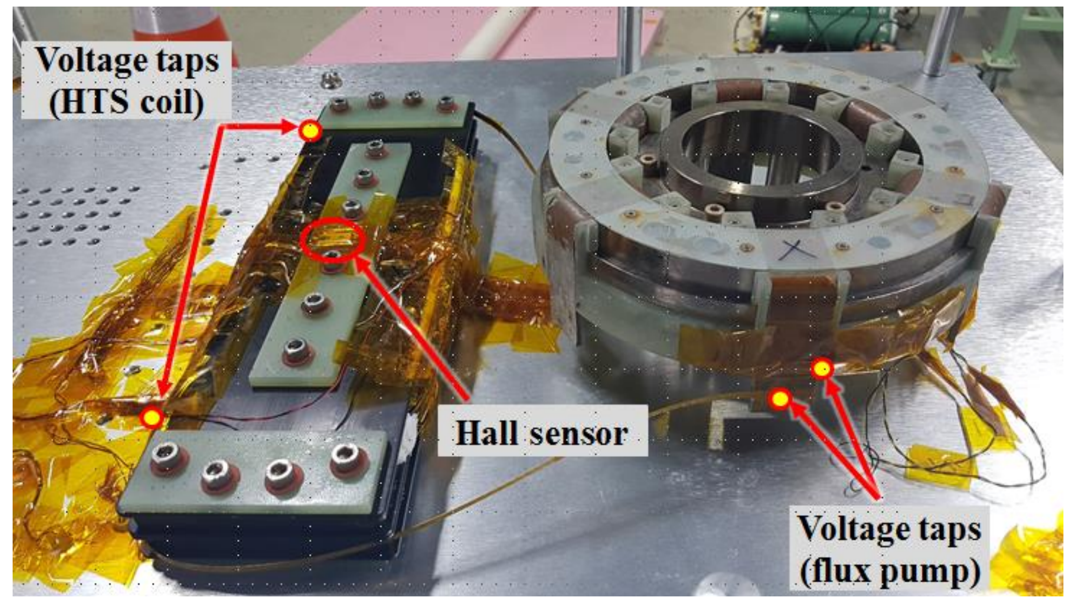

Fig. 6. Position of four soldered taps and hall sensors of the HTS field coil and flux pump

4 Experimental results and discussions

A. Experimental results of the test coil

When the rotational speed of the flux pump increased from 500 rpm to 2,500 rpm, the induced DC current of the flux pump connected to the HTS field coil increased proportionally. As the air gap of the flux pump increased from 7 mm to 10 mm, the induced DC current decreased..

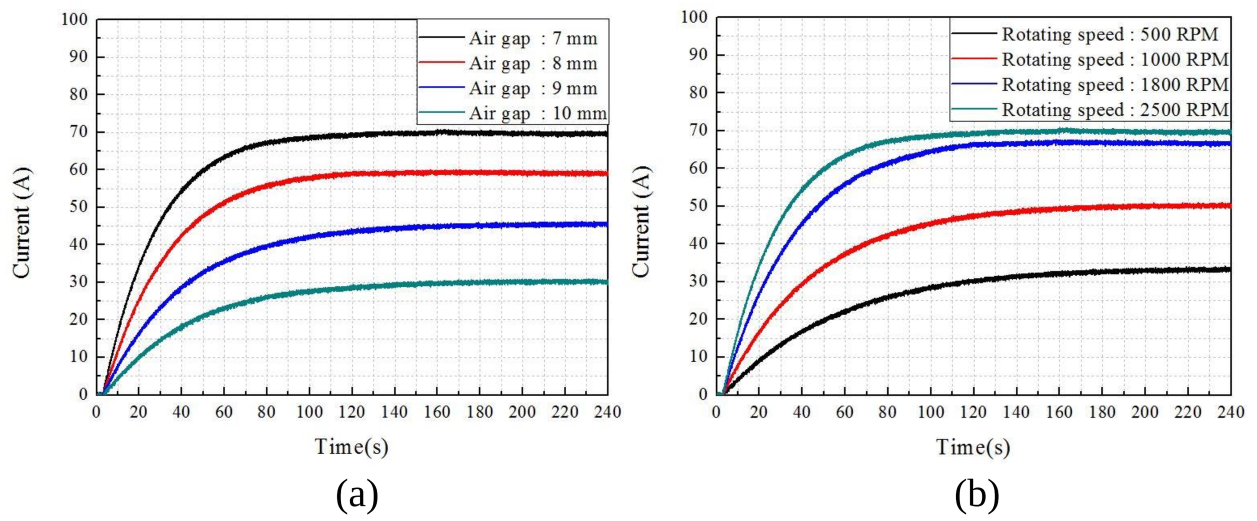

Fig. 7. The DC current induced in the HTS test coil according to (a) the rotational speed and (b) the air gap

B. Experimental results of the field coil for the 10 kW superconducting generator

The maximum induced current was 35 A, when the rotational speed and the air gap were 2,500 rpm and 7 mm, respectively.

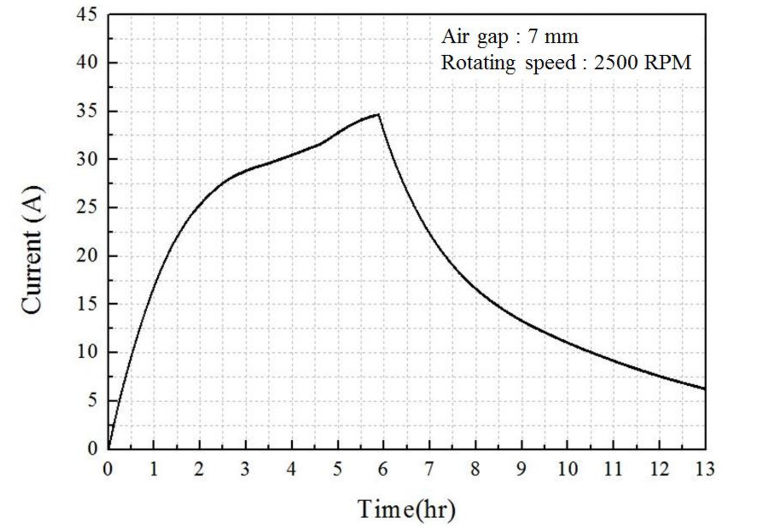

Fig. 8. The DC current induced in the HTS field coil for 10 kW superconducting generator

5 Conclusions

This paper describes the design and performance analysis of a dynamo-type HTS flux pump for a 10 kW superconducting generator. First, to verify the feasibility of the flux pump, the test bed and the HTS test coils for the experiment were designed and manufactured and tested at various rotational speeds and air gaps. Based on the results obtained, the HTS field coil and the flux pump for the 10 kW superconducting generator were designed, fabricated and verified. As a result, when the rotational speed and the air gap were 2,500 rpm and 7 mm, the HTS field coil excited 35 A induced current at a temperature of 77 K by the operation of the HTS flux pump. This induced current is a sufficient amount of current to excite the field coil of the 10 kW HTS generator while operating at 30 K temperature. This result helps to apply a flux pump to excite the HTS field coil of a superconducting rotating machine.

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