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Analytical Study and Fabrication of a 1 kW Class Fully High-Temperature Superconducting Induction/Synchronous Generator

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Kyoto University

Outline

1. Introduction
2. Generation Principle of HTS-ISG
3. Design and FEA Analysis of a 1 kW Class HTS-ISG
4. Fabrication and Experiments
5. Conclusion

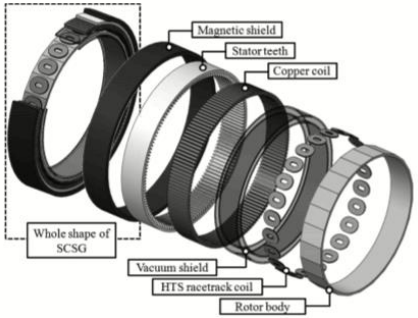
Introduction

Thanks to the extremely less dissipation and high current density of the High temperature superconducting (HTS) conductors, the HTS generator has been a promising application, which has the advantages of light weight, high power density and high efficiency.

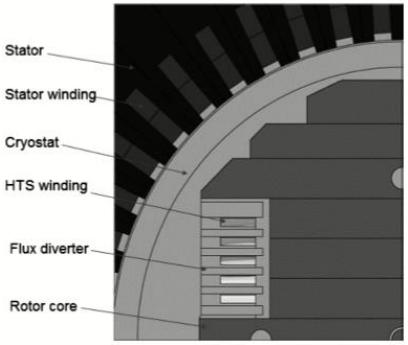
➢ Research Review of HTS generators

- ✓ Ecoswing project (MW class, EU-funded)
- ✓ 10 MW HTS wind generator (South of Korea)
- ✓ 100 kW HTS generator (University of Southampton)
- ✓ etc…

Ecoswing HTS generator



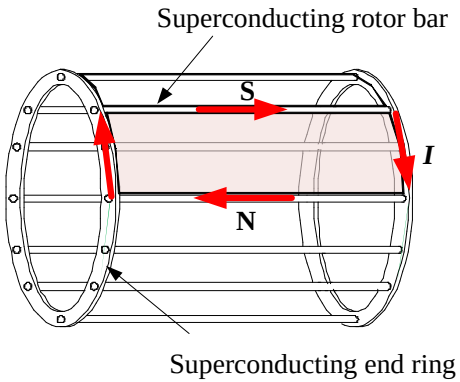
10 MW HTS wind generator



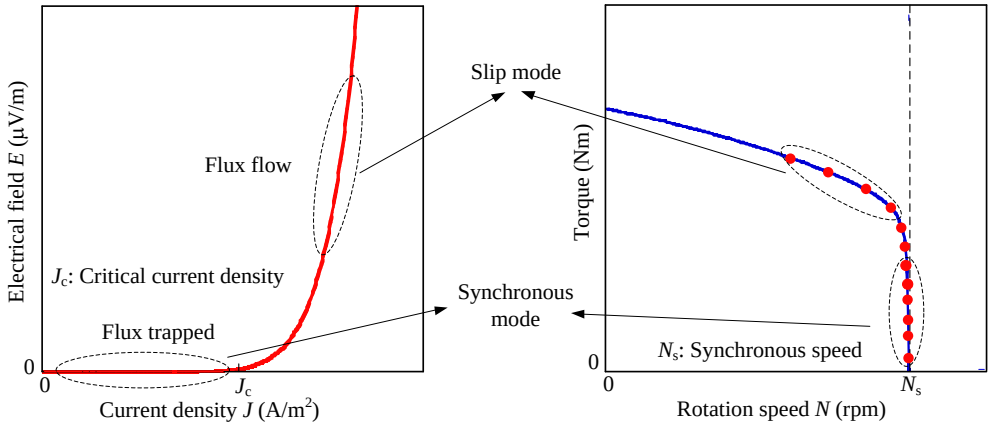
100 kW HTS generator

Our group has been developing a fully HTS Induction/Synchronous Generator (HTS-ISG).

Basic Principle of HTS Induction/Synchronous Motor (HTS-ISM)



Squirrel-cage HTS rotor

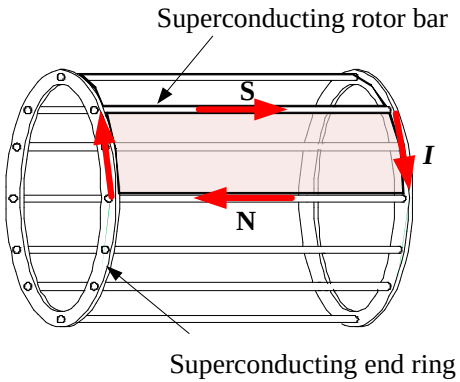


Electrical field (E) vs current density (J) curve and torque characteristics curve of HTS-ISM

Advantages:

- Coexistence of synchronous and slip rotation model.
- High torque density.
- High over-load capacity.
- High efficiency at synchronous model.
- Autonomous stability.

Basic Principle of HTS Induction/Synchronous Motor (HTS-ISM)



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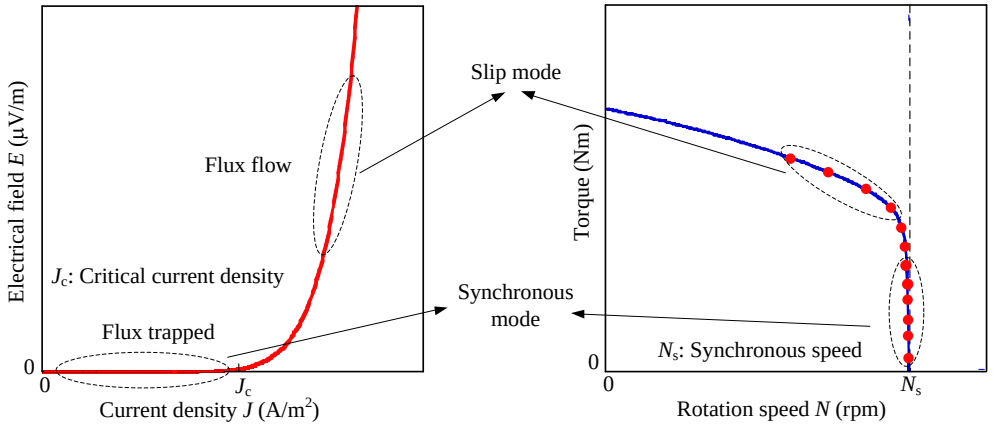
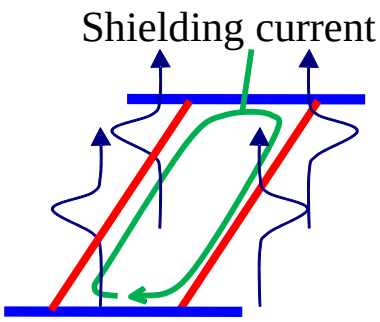
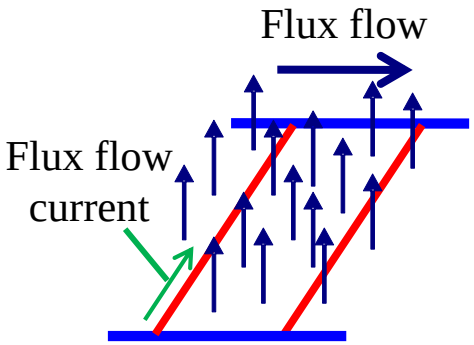


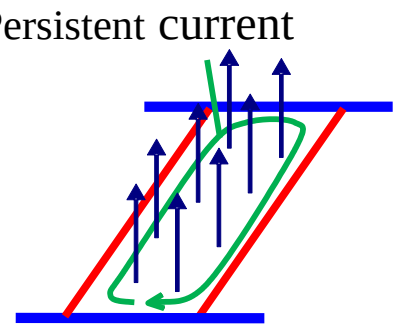
Electrical field (E) vs current density (J) curve and torque characteristics curve of HTS-ISM



(a) Magnetic shielding (Static)



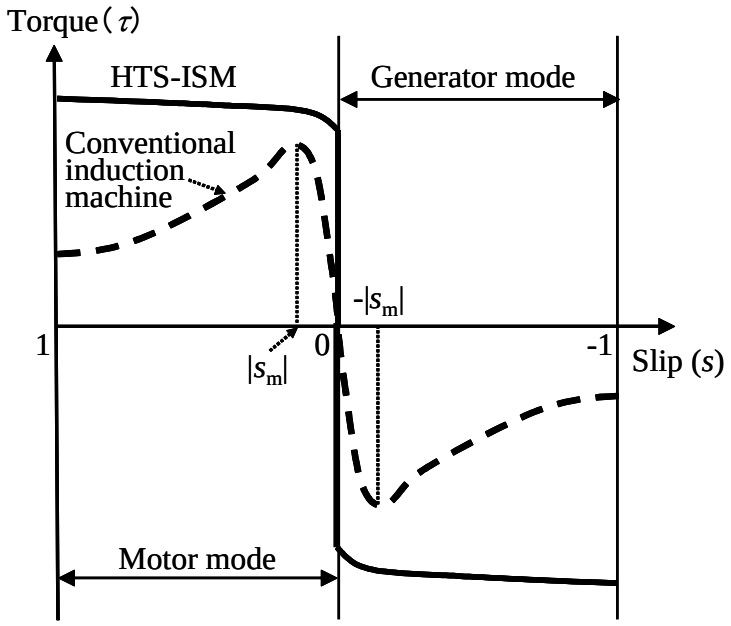
(b) Flux flow (Slip)



(c) Flux trapping (Synchronous)

Operation models

Generation Principle of HTS-ISG

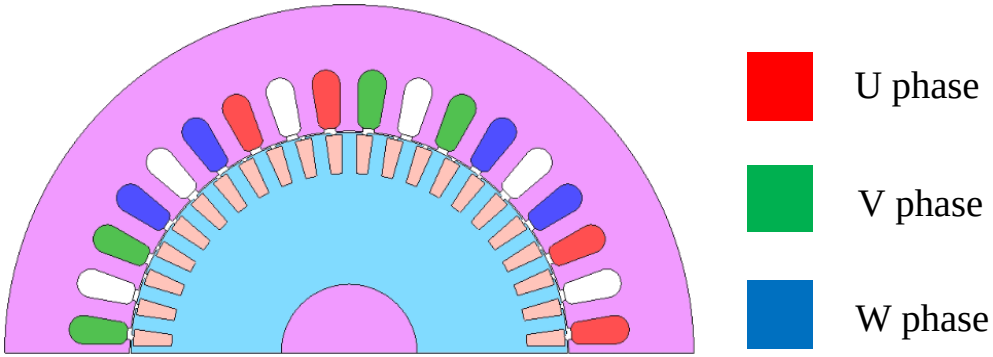


Schematic diagram of torque vs. slip curve of HTS-ISM

- ✓ The HTS-ISG can realize both higher efficiency and robust against overload generation with its simple structure.
- ✓ The rotor and stator winding are fabricated by use of HTS conductor.
- ✓ The synchronous generation mode is realized by rotor winding's zero resistivity, used for steady state highly efficient power generation
- ✓ The slip generation mode is realized by nonlinear flux-flow characteristics, utilized for the overload generation.

Design and FEA Analysis of a 1 kW Class HTS-ISG

A 1kW class HTS-ISG FEA model is established. The stator is concentrated winding, and the rotor is the squirrel-cage rotor winding. Both of stator and rotor winding is fabricated by HTS tapes.



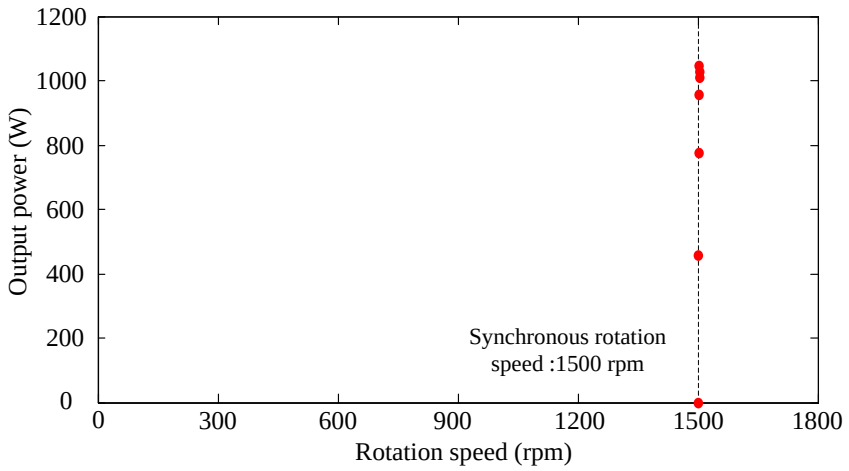
1 kW class HTS-ISG FEA model

The stator core has 36 slots, but the coils should be only 12 coils considering the limitation of the bending diameter.

TABLE I.
Specifications of designed HTS-ISG

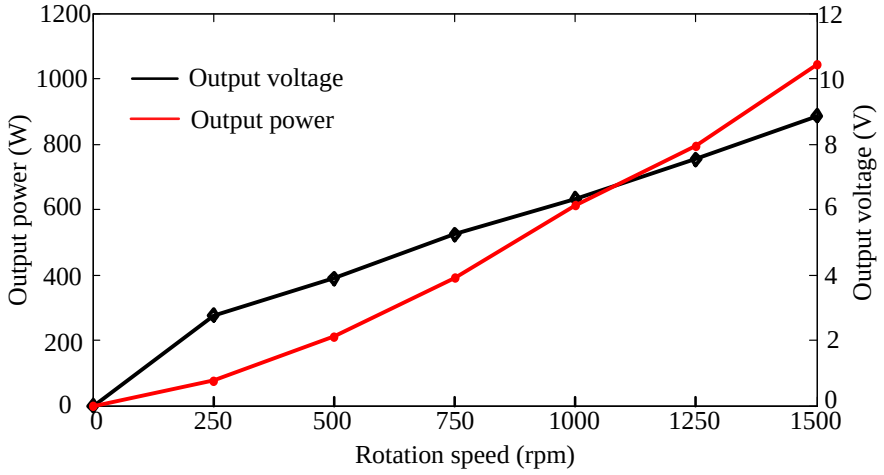
Parameters	Value
Outer diameter of stator (mm)	157
Inner diameter of stator (mm)	100
Outer diameter of rotor (mm)	99.4
Outer diameter of shaft (mm)	31
Air gap length (mm)	0.3
Width of stator tooth (mm)	4.2
Stack length (mm)	90
Number of poles	4
Number of stator coils	12
Number of winding turns	10
Number of rotor slots	44
Bending diameter of a coil (mm)	22

Generation Characteristics of the HTS-ISG



Generation characteristics of the HTS-ISG

(Condition: 60A, 50 Hz)



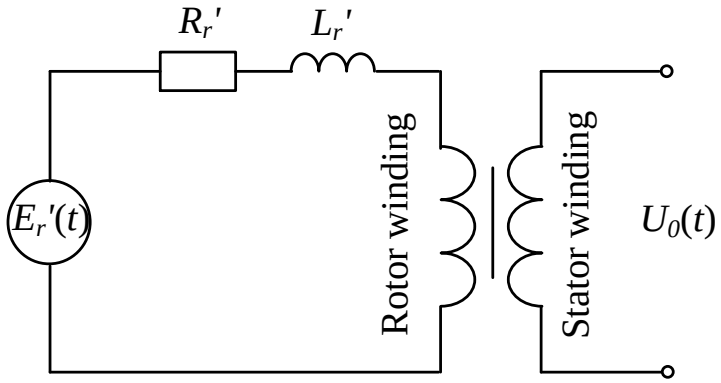
Output power and voltage at different rotation speed

(Condition: 60A, slip is -0.0013)

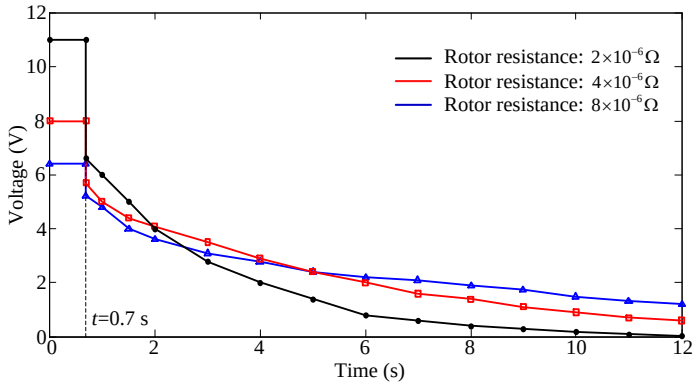
- ✓ The maximum output power is 1044.5 W at 1500 rpm.
- ✓ With very small slip (max:-0.002).
- ✓ The output voltage and power increase with the rotation speed.

Open-Circuit Characteristics of the HTS-ISG

Due to the contact resistance of the rotor bar and end ring as well as the flux flow resistance, the EMF E_r'(t) and open-circuit voltage of stator winding will decay based on rotor resistance R_r'.



Equivalent circuit of the HTS-ISG when the stator winding is open



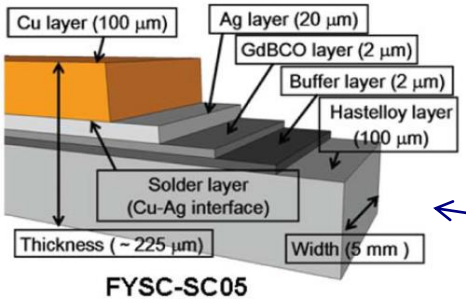
Open-circuit characteristics of the HTS-ISG

- ✓ When t=0.7 s, the stator winding is open, the stator winding will induce the open-circuit voltage.
- ✓ When the rotor resistance is larger, the decay time constant will be smaller, the open-circuit voltage decays more quickly.

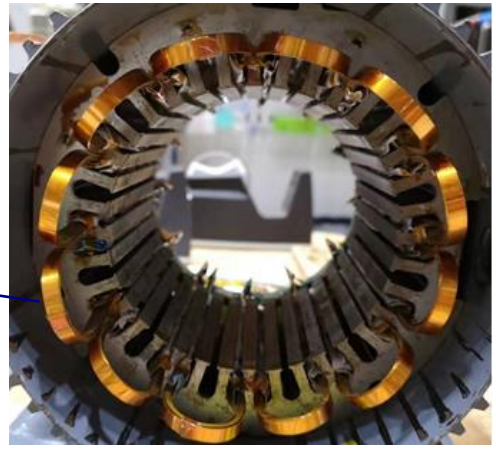
Fabrication and Experiments

➢ Fabrication of the HTS-ISG

We challenge to fabricated the GdBCO windings with its bending diameter of 22 mm, in order to examine the possible fabrication of ultimately small volume. Single pancake structure and concentrated winding are chosen for stator windings.



GdBCO coted conductor (I_c: 300A) [1]



HTS stator winding

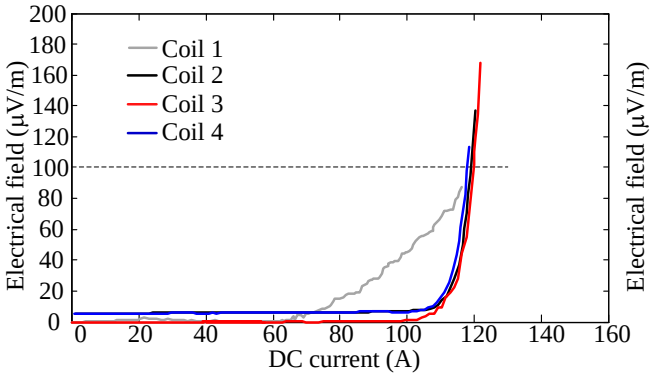
HTS squirrel-cage rotor (BSCCO tape)

Ref. [1]: K. Kawai, et al. “Optimization of a Mechanical Bridge Joint Structure in a Stacked HTS Conductor,” *IEEE Trans. Appl. Supercond.*, vol. 23, no. 4, Jan. 2013, Art. no. 4801704.

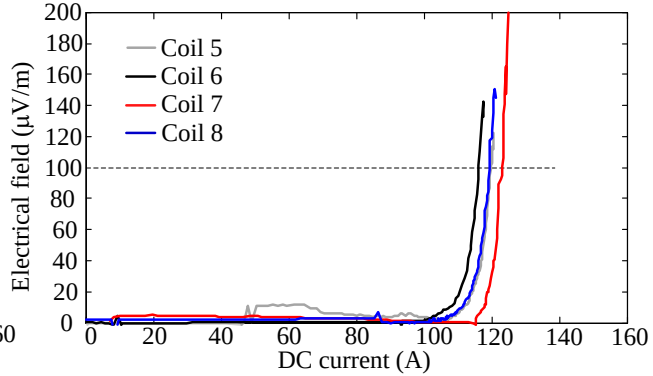
Fabrication and Experiments

➢ DC Property of HTS Stator Windings

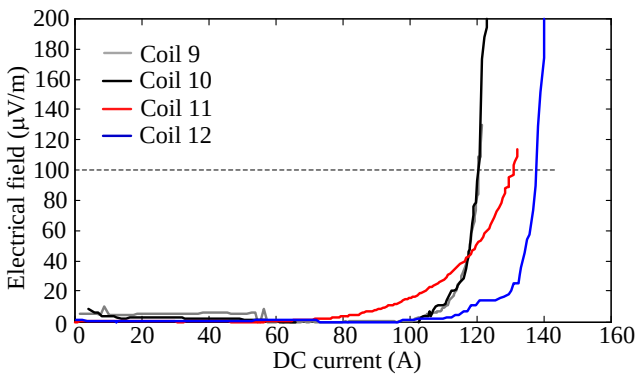
We measured the DC property of all HTS stator coils in liquid nitrogen (77 K). The fabricated coils reproducibly realize critical current of around 120 A with bending diameter of 22 mm.



(a) Coil 1-Coil 4



(b) Coil 5-Coil 8



(b) Coil 9-Coil 12

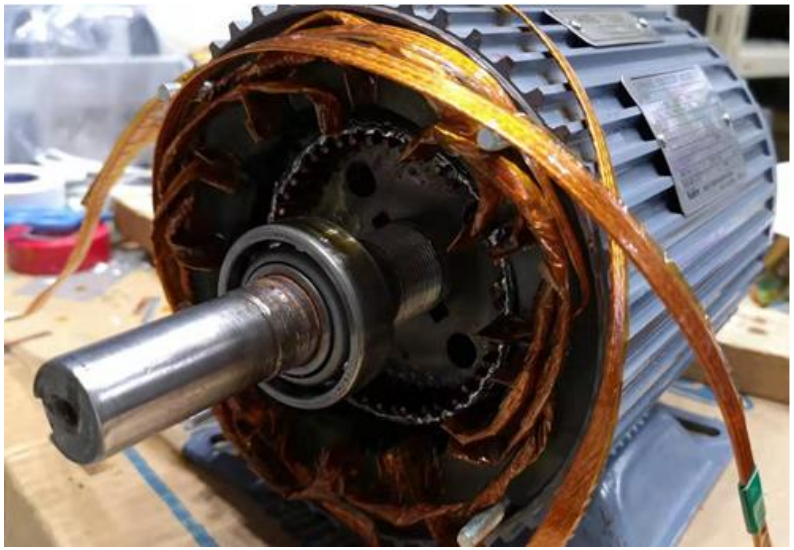
Measured results of DC current (I) vs. voltage (V) characteristics in liquid nitrogen (77 K).

✓ The reason for the decline of critical current (300A/120A) is the situation of the coil in the iron core, self-field effect, and mechanical bending.

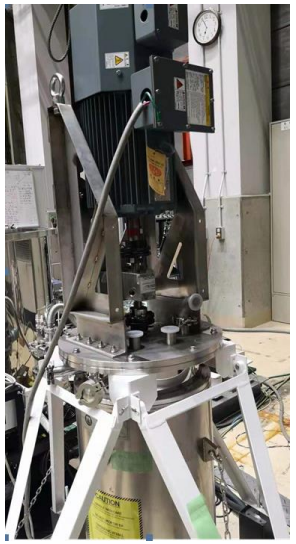
Fabrication and Experiments

➢ Assemble of the HTS-ISG

After the DC I-V measurement of each coil, the stator coils are connected in Y-shape configuration, 3-phase, 4-pole, concentrated windings. Then it is coupled with already fabricated BSCCO squirrel-cage rotor.



Photograph of the assembled HTS-ISG.



PM motor

Cryostat

Testing system

✓ The generation tests of fully HTS-ISG will be done in October 2019.

Conclusion

1. A 1 kW class fully superconducting induction/synchronous generator is developed.
2. The fabricated stator coil possesses its critical current of around 120 A@77 K, even its bending diameter is 22 mm.
3. The simulation results show the fabricated generator could successfully generate 1044.5 W at 50 Hz with very small slip.
4. The stator winding will induce the open-circuit voltage which will decay when the stator winding is not fed.
5. The generation tests of the 1 kW HTS-ISG prototype will be done in the future. We are also moving on developing larger capacity generator at lower speed.

Thank you very much for your attention!