Experimental and Theoretical Study on Power Generation Characteristics of 1 kW Class Fully HTS Induction/Synchronous Generator using a Stator Winding with a Bending Diameter of 20 mm

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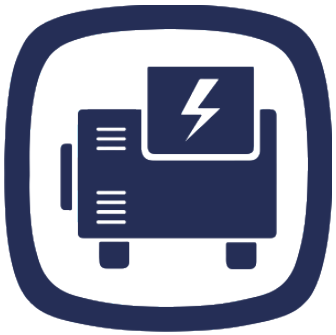
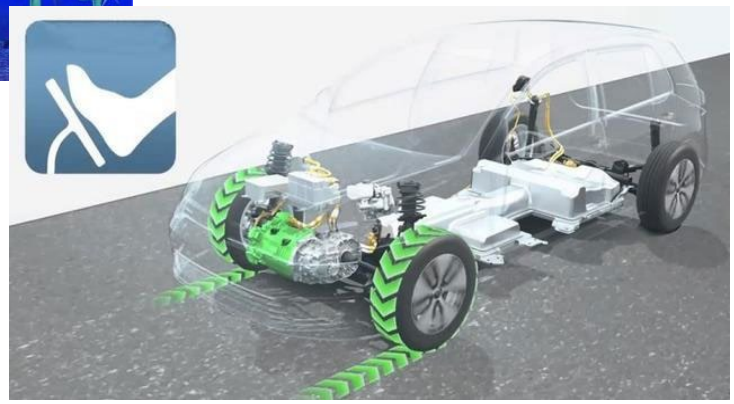
1. Research background

Wind Turbines

Generator plays a very important role in the process of energy saving and emission reduction.

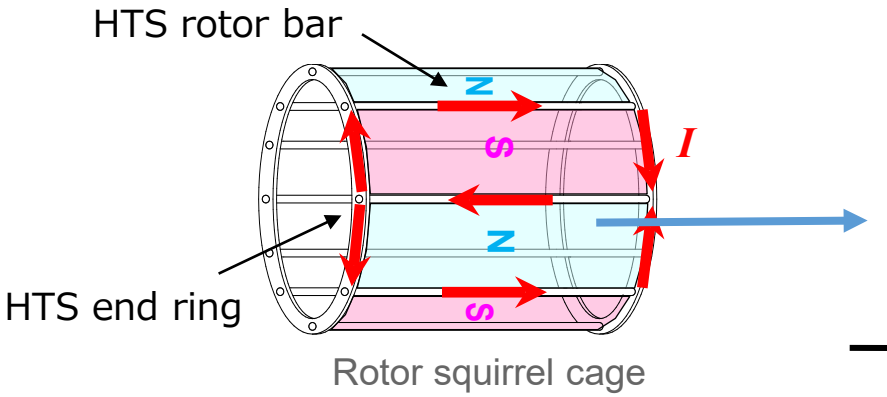
Tidal power generator

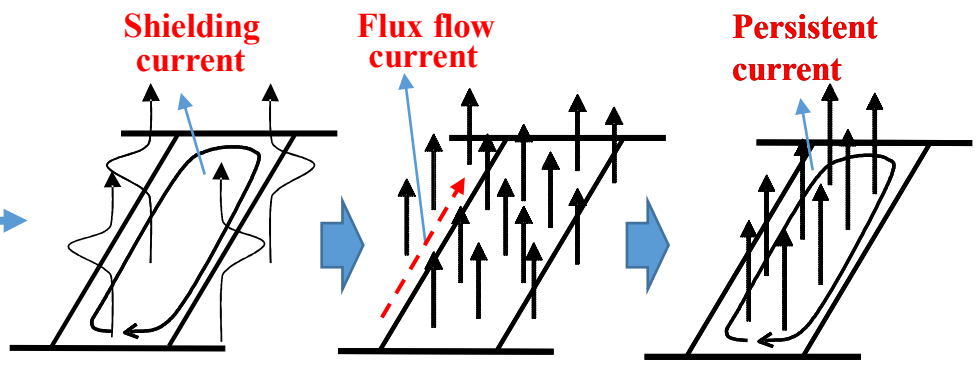


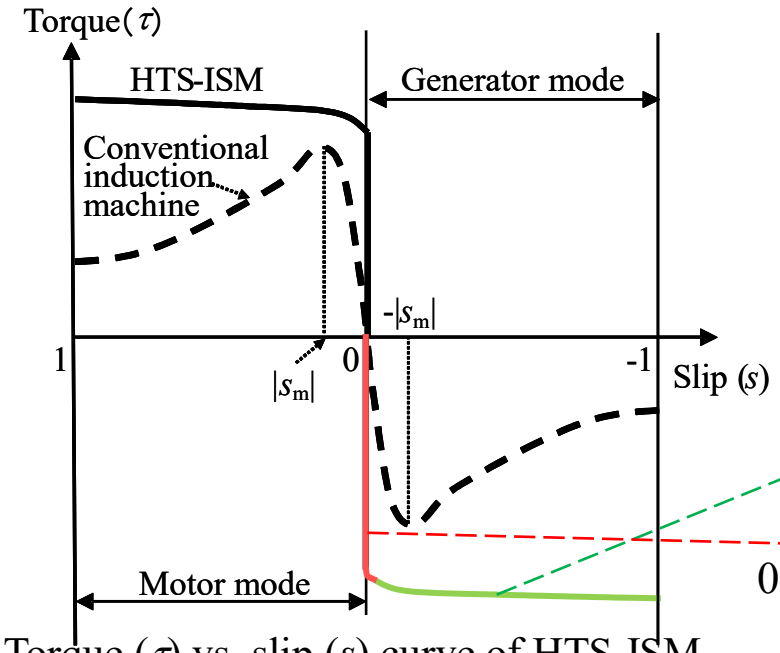


Braking energy recovery

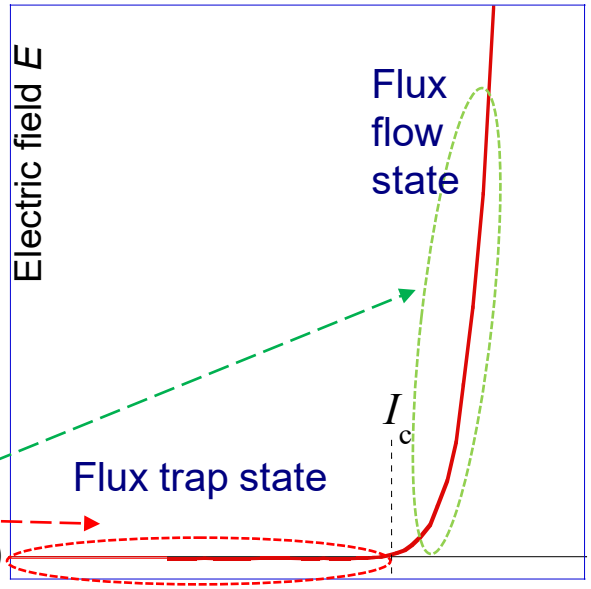
2. Advantage of HTS generator







Torque (τ) vs. slip (s) curve of HTS-ISM.



Advantages:

- High efficiency;
- High torque density;
- Autonomous stability for variable speed;
- High overload capacity.
- …

3. Fully HTS-ISG

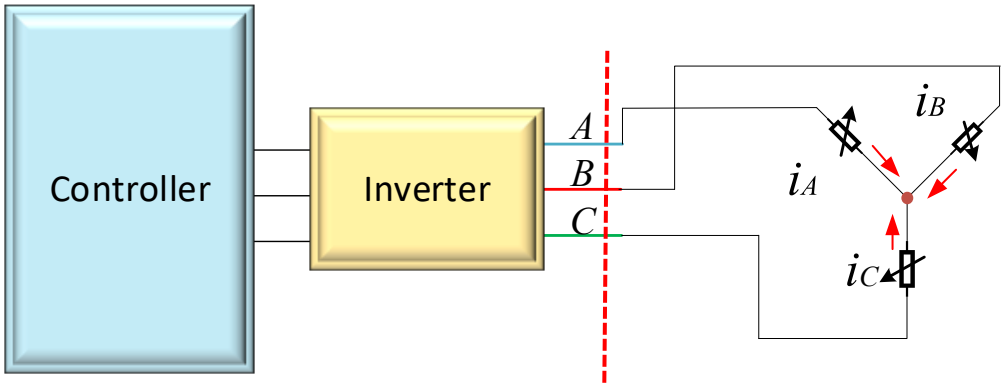
Using HTS conductors in stator windings has great potential to reduce the copper loss and improve the torque density.

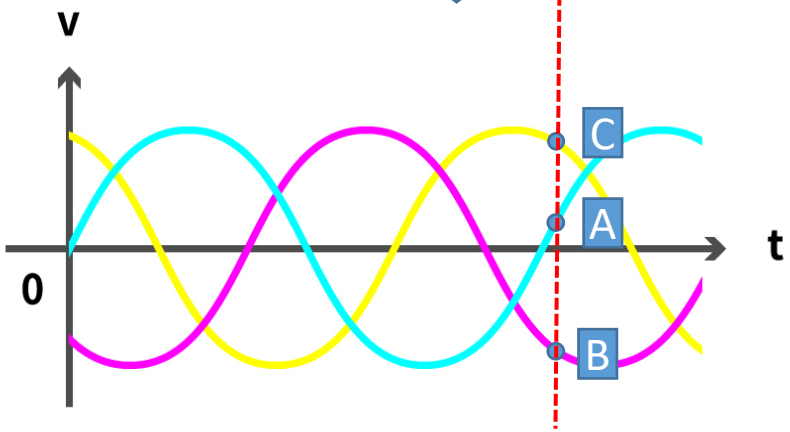
Next step :

Fully HTS induction/synchronous generator

Smaller size machines

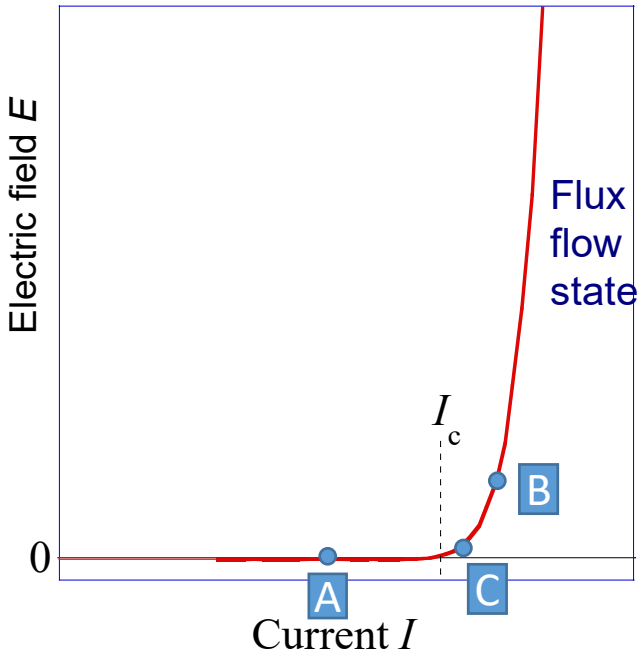
4. Imbalance between the three-phase impedances



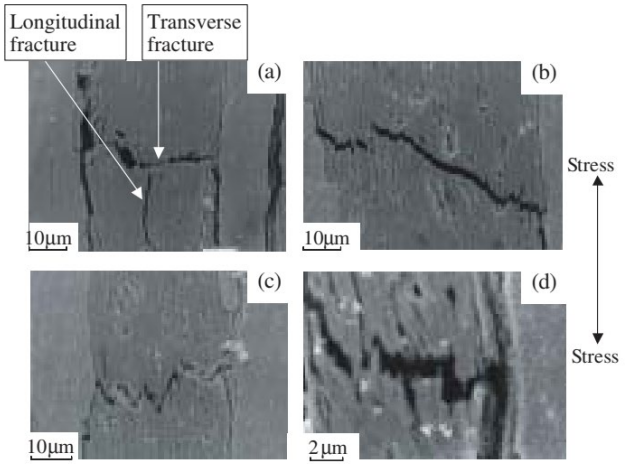


There phase current curves of stator

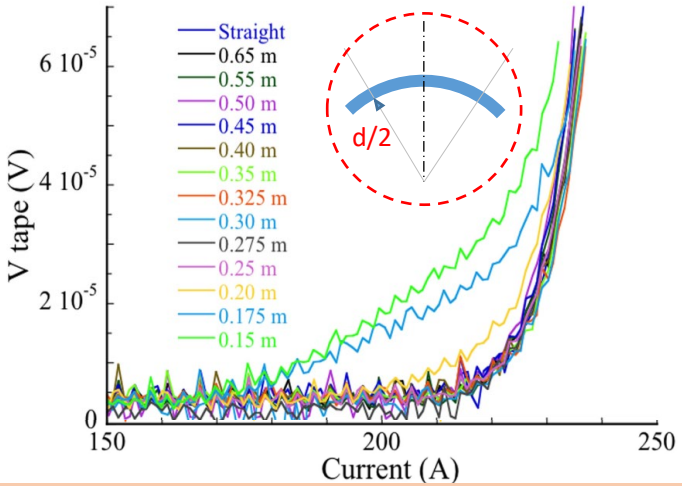
At a specific moment, the superconductors of the A-B-C phases may be at different conducting state, due to the non-liner characteristics of the HTS material.



5. Challenge of making HTS stator coil

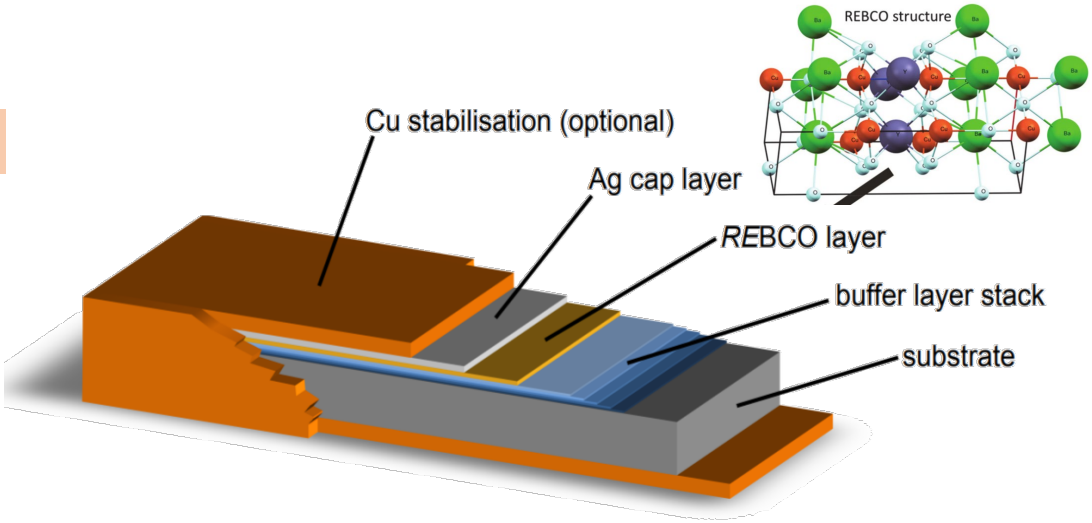


Fracture patterns of filaments in HTS [1]



I-V curve of HTS tape under different bending diameters [2]

High temperature superconducting tape is relatively brittle. It is very susceptible to damage or even fracture when it is bent.



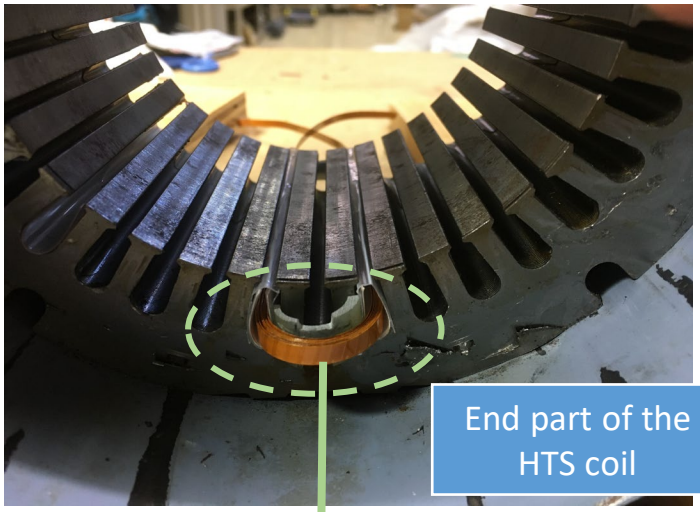
Schematic structure of REBCO tapes[3]

[1]. G. Celentano *et al*., "Bending Behavior of HTS Stacked Tapes in a Cable-in-Conduit Conductor With Twisted Al-Slotted Core," in *IEEE Trans on Applied Superconductivity*, vol. 29, no. 5, pp. 1-5, Aug. 2019

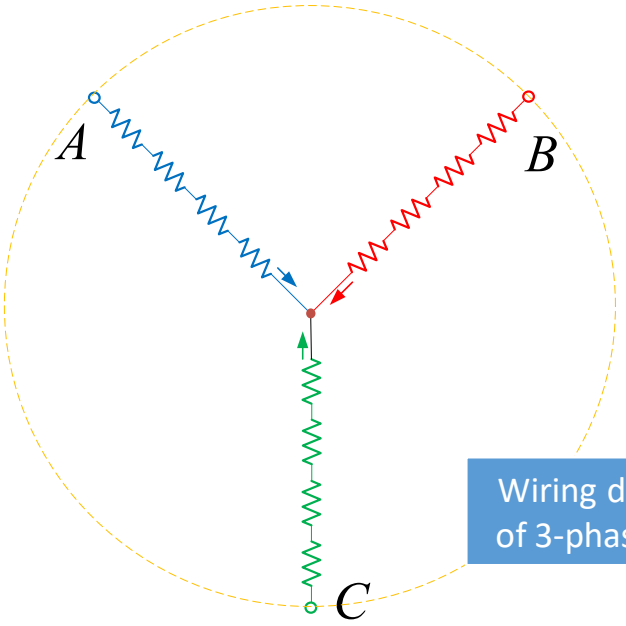
[2] Barth C , Mondonico G , , et al. Electro-mechanical properties of REBCO coated conductors from various industrial manufacturers at 77 K, self-field and 4.2 K, 19 T[J]. Superconductor Science & Technology, 2015.

[3] Ochiai S , Ishida T , Doko D , et al. A Monte Carlo-shear lag simulation of tensile fracture behaviour of Bi2223 filament[J]. Superconductor Science & Technology, 2005, 18(12):232-240.

6. Stator winding with a small bending diameter

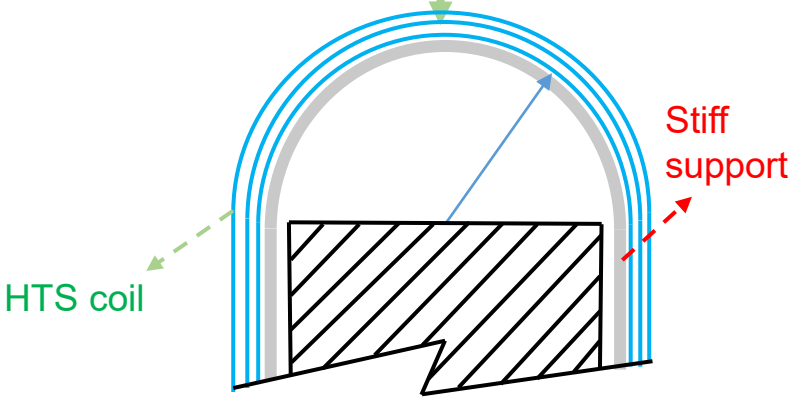


End part of the HTS coil



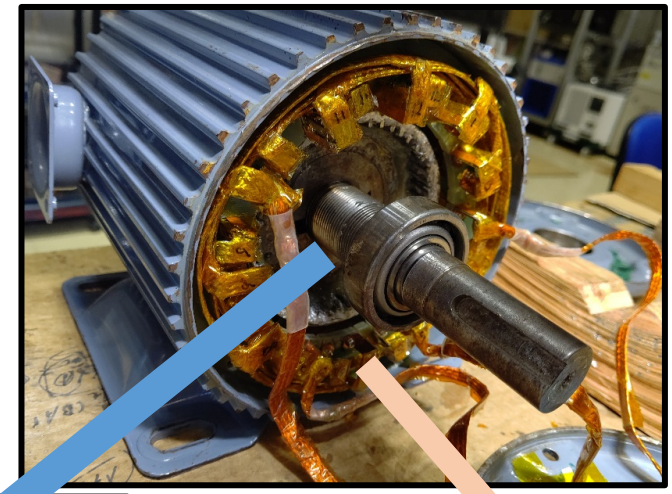
Wiring diagram of 3-phase coils

Minimum bending diameter = 20 mm

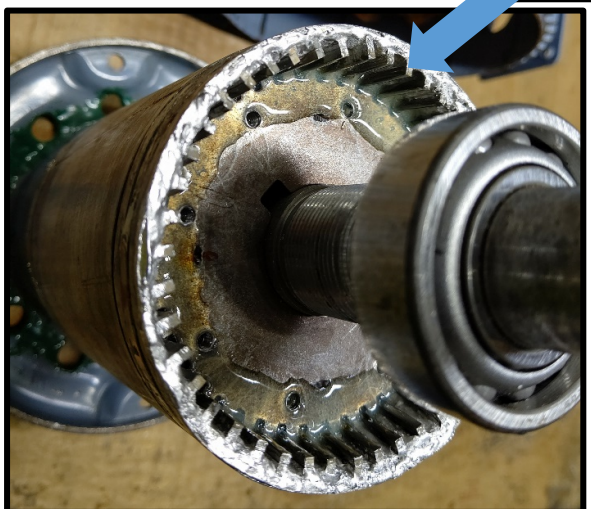


Phase number	3
Pole number	4
Coils per phase	12
Winding Type	Concentrated winding
HTS type of stator	REBCO (SuperPower Inc)
HTS type of rotor	REBCO (Nippon steel Corp)

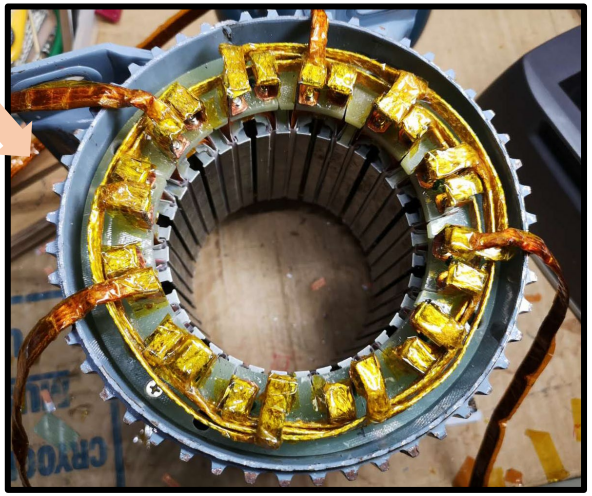
7. Manufacturing of the fully HTS generator



1 kW class fully HTS induction/synchronous generator

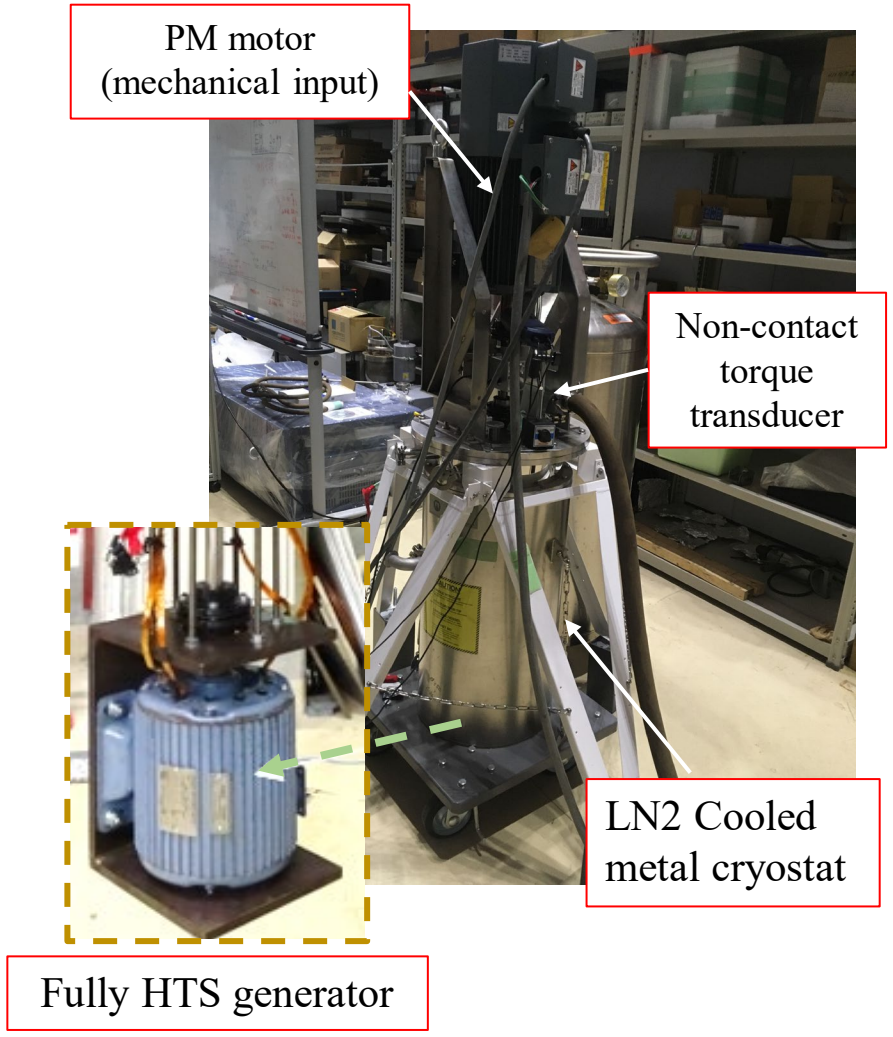


HTS rotor fabricated with the REBCO bulk superconducting conductor.

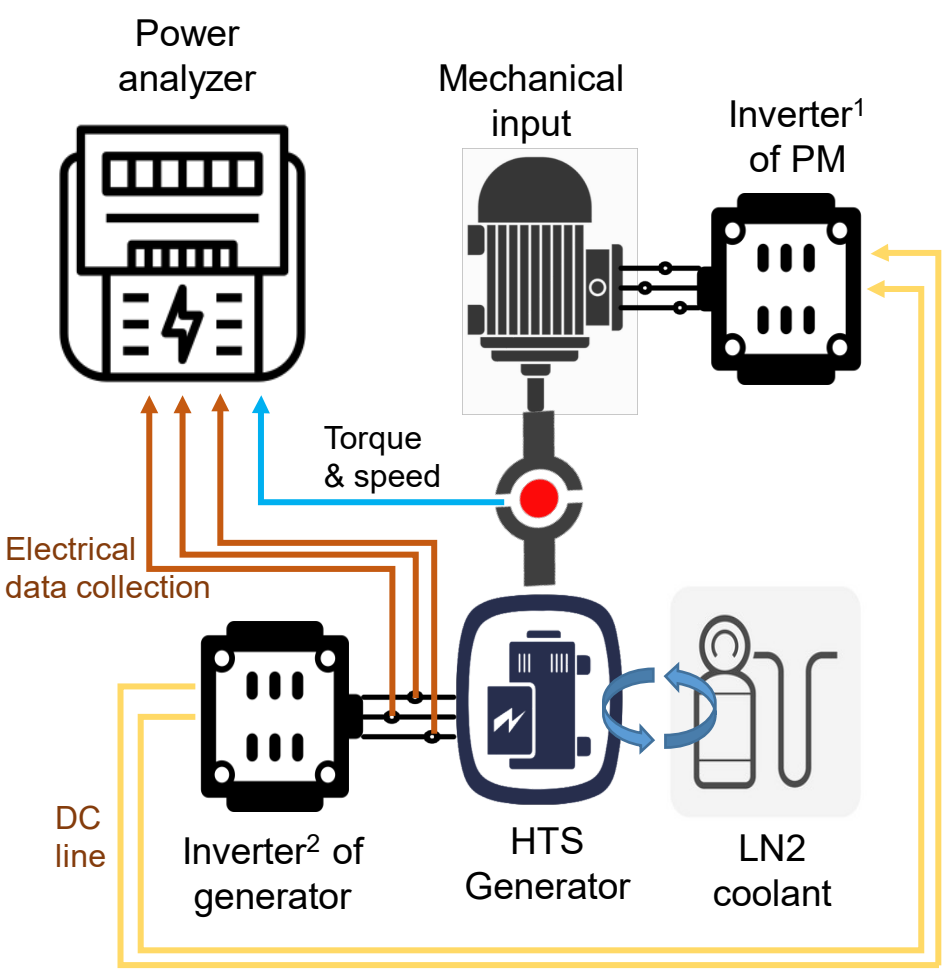


HTS stator fabricated with the REBCO coated superconducting conductor.

8. Benchmark test system



Experimental test setup



Schematic diagram of the test system

9. Benchmark test procedures

Control the mechanical input (PM) to a predetermined speed

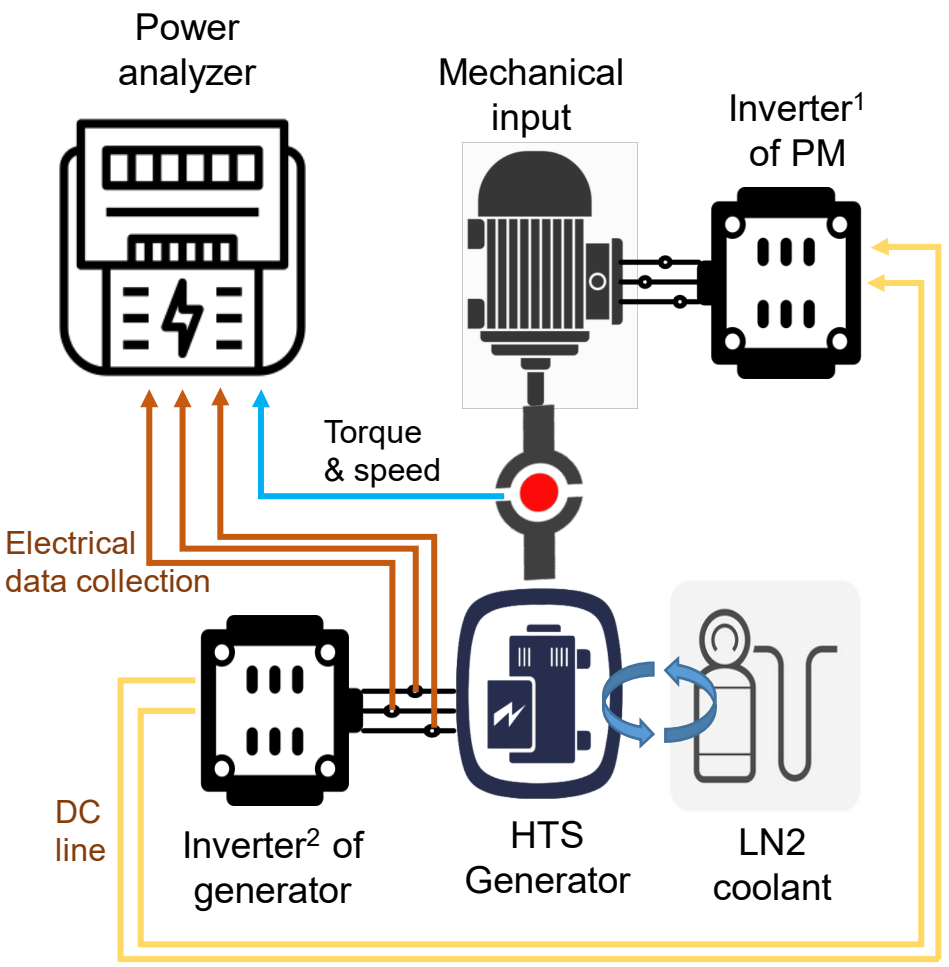
Excite the HTS generator at the Sync frequency by inverter

Gradually reduce the generator's frequency in small range

Adjust and maintain the voltage at different slip rates

Measurement

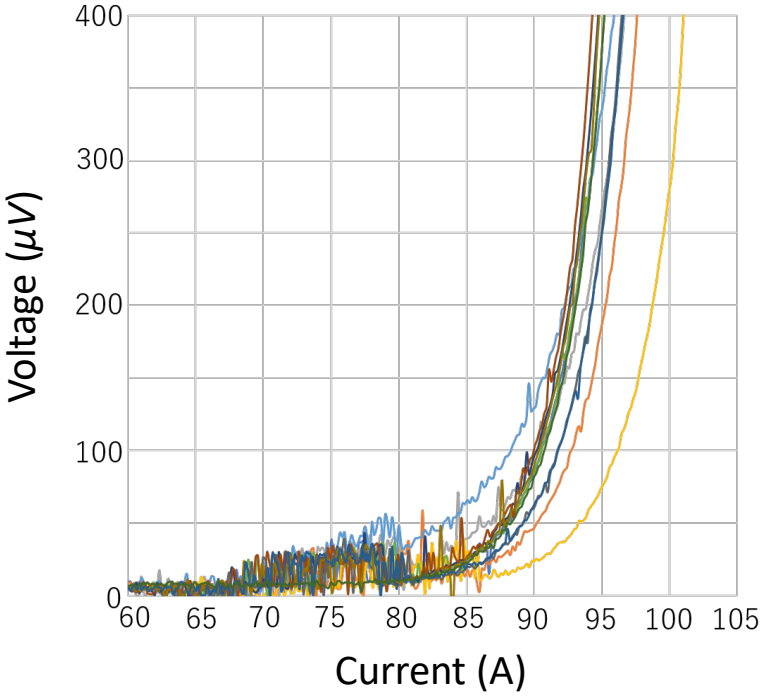
Procedure of bench test



Schematic diagram of the test system

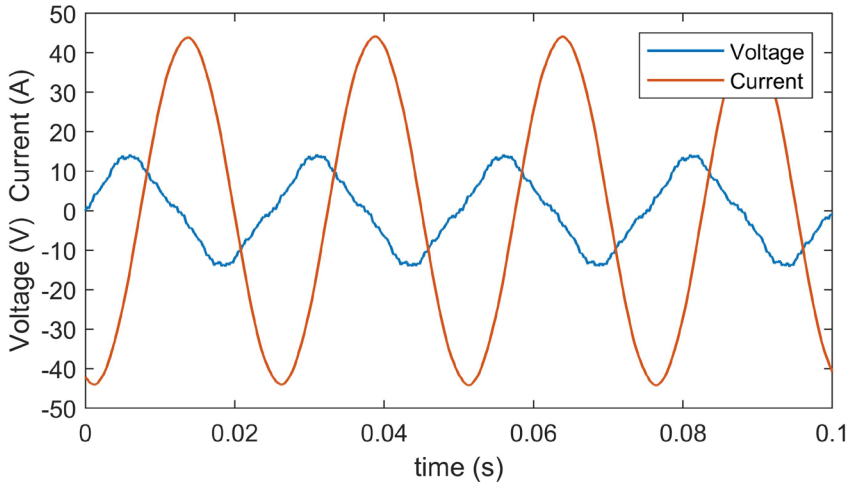
10. Test result

Critical current with 90 A is realized In liquid nitrogen.



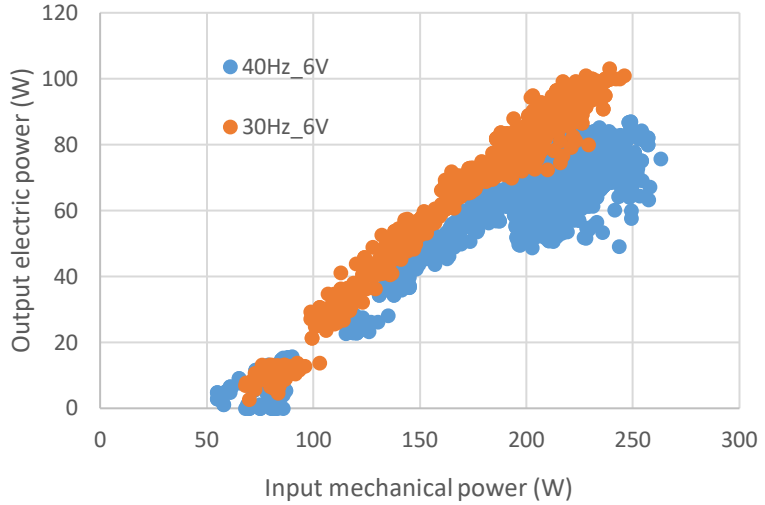
V-I curves of HTS stator in liquid nitrogen (77 K)

Stable electric power generation is achieved in full HTS-ISG.

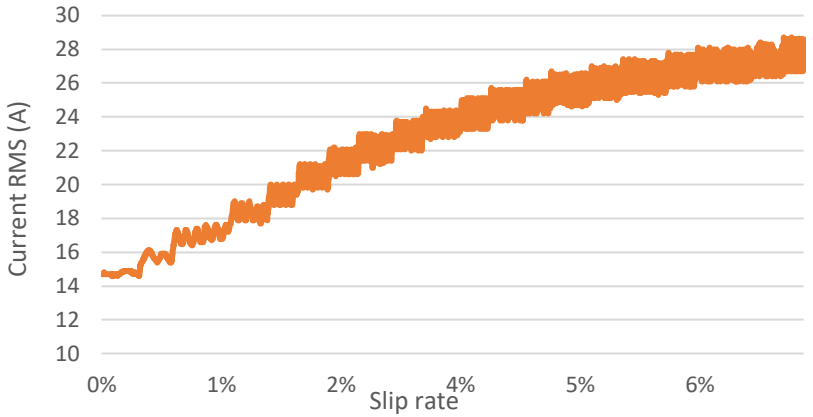


Power generation waveform under load: f=40 Hz & excitation current= 30 A

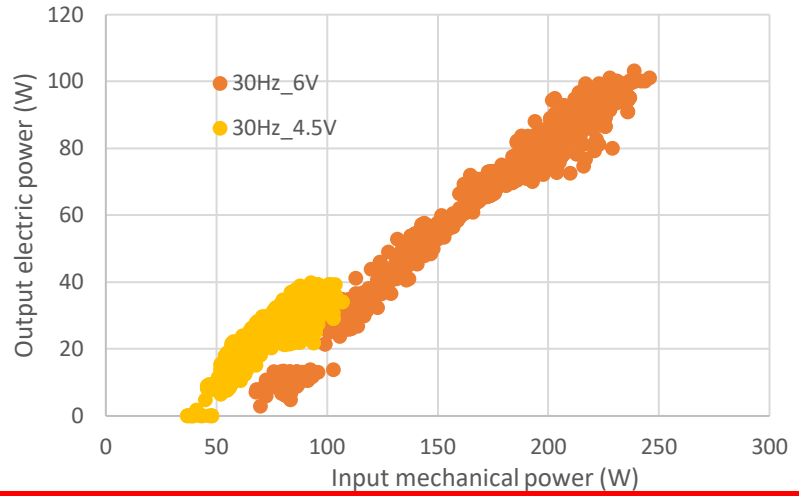
10. Test result



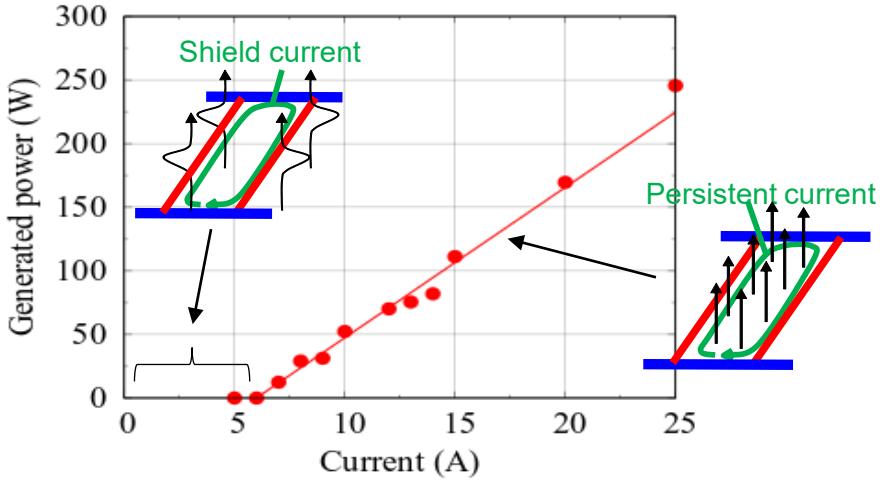
Power generation characteristics at different excitation frequency



Ascending curve of current with slip rate (40Hz 6V)



Power generation characteristics at different voltages

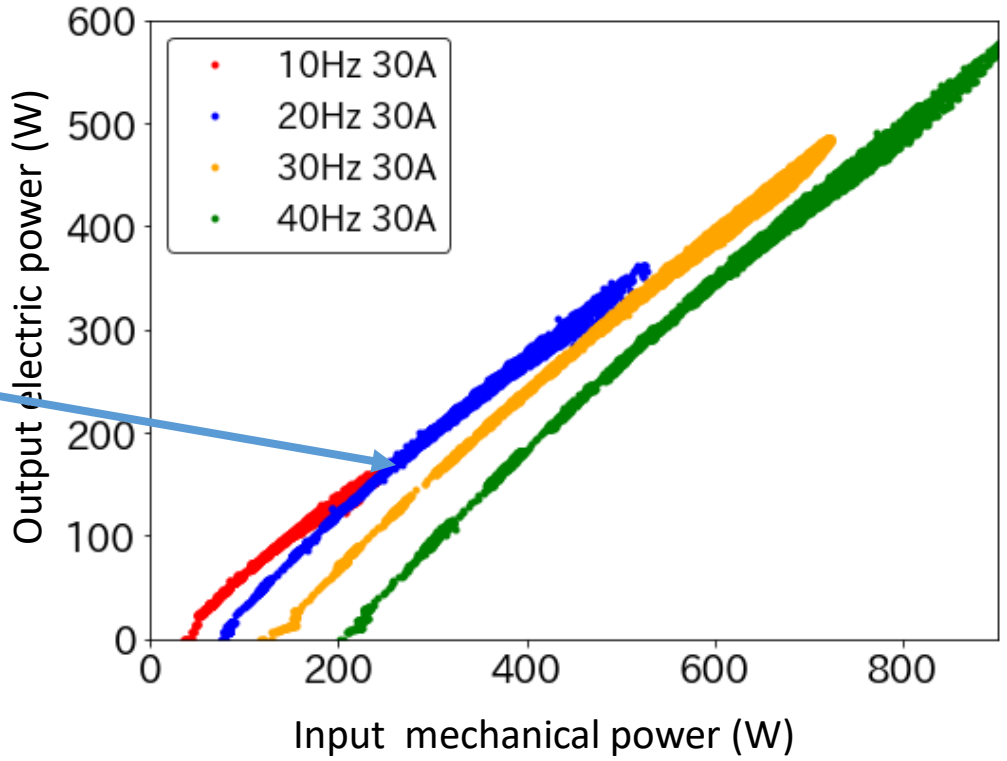


Conducting states of HTS coil during power generation

11. Past reference result

Rotor fabricated with BSCCO tape

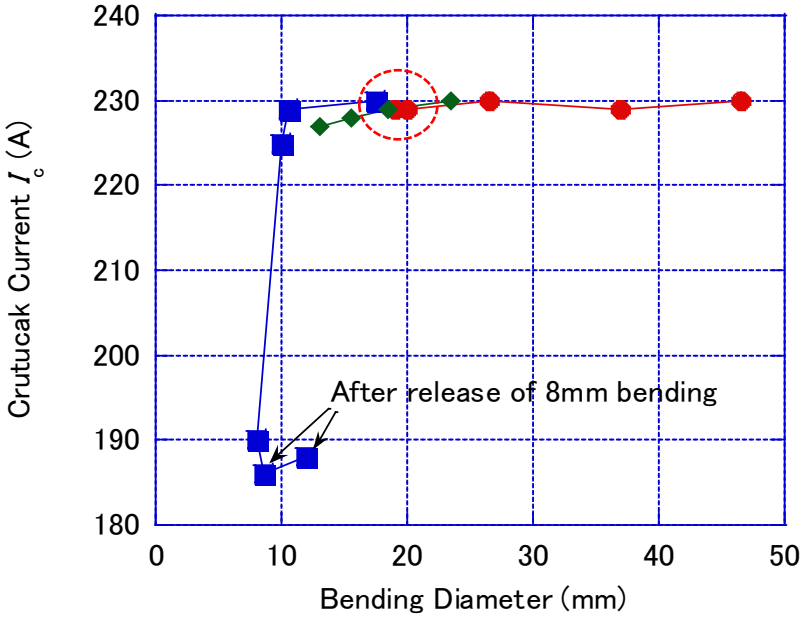
T.Nakamura, et al., "First test results of fully superconducting induction/synchronous generator with GdBCO stator winding", **ISS 2020**, Tsukuba, Japan, Dec. 1-3

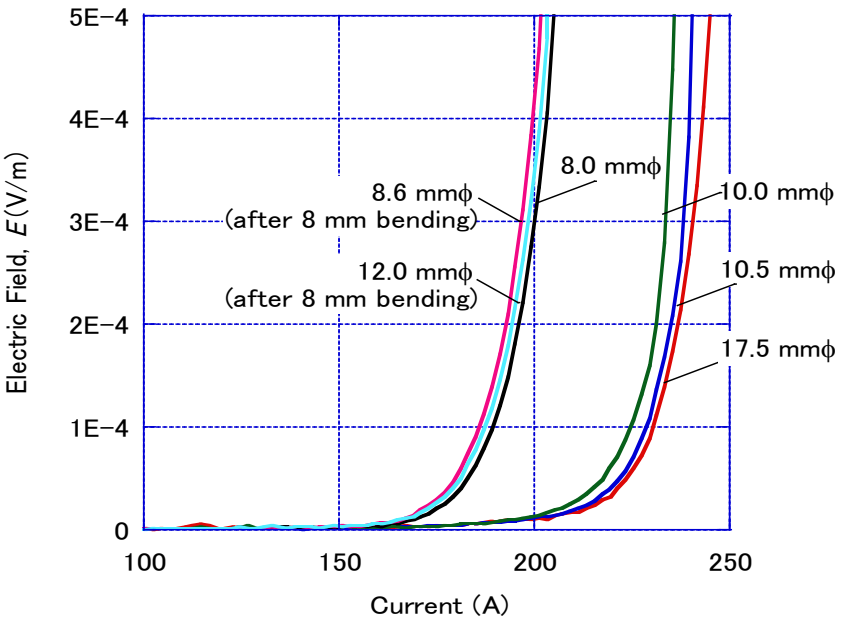


In conclusion, larger critical current capacity on the stator is necessary for realizing 1 kW.

12. Future work to improve HTS-ISG performance

Use specially developed Face-to-Face Double Stack (FFDS) conductor to increase stator coil current and motor torque density.





Bending properties of the Face-to-Face Double Stack (FFDS) conductor

13. Conclusions and prospects

- The HTS tape can maintain good super-conducting after being bent with a diameter of 20mm.
- The critical current of HTS conductor decreases after being bent. That means in addition to the magnetic field and the temperature, the manufacturing process should also be considered in the design stage.
- Stable power generation requires special control methods to assist.

✓The study will also benefit the realization of the braking energy recovery in the electric drive system with HTS motor.

✓The relationship between the mechanical input threshold of electricity generation and the excitation frequency needs further exploration.

Thanks for your attention!