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EXPERIMENTAL ANALYSIS OF CHARGING CHARACTERISTICS OF HTS FIELD COILS WITH HTS CONTACTLESS ROTARY EXCITATION DEVICE CONSIDERING VARIOUS HTS LOADS

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43-H2-Power Supplies and Flux pumps, Tue-Af-Po2. 11-04, Tuesday, August 29, 2017, 1:15 PM - 03:00 PM

1. Introduction

- This paper deals with the **charging characteristics of HTS contactless rotary excitation device (CRED)** which operating principle is based on rotary HTS flux pump **to verify the efficient charging method depending on how HTS field coils are connected**.
- HTS Synchronous motors conventionally require current leads to inject the large DC currents into HTS field coils. However heat losses are generated on these current leads due to mechanical connection between the HTS field coils and power supply. For that reason, rotary HTS flux pump is used to remove the physical connection to improve cryogenic efficiency.

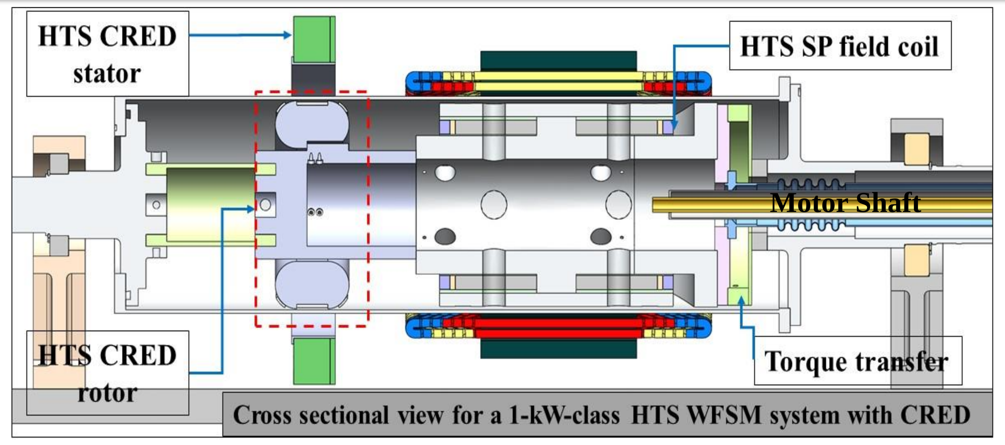


Fig. 1. Conceptual design of HTS synchronous motor with rotary HTS flux pump

- HTS (CRED) is located on the same axis of the HTS motor shaft as shown in Fig. 1.
- Therefore, the size of HTS CRED and minimum air-gap between HTS rotor strand and stator permanent magnet (PM) is limited due to the size of motor.
- **The minimum air-gap is about 8 mm** when considering cryostat, cryogen jacket, and vaccum layer. The intensity of the applied magnetic field penetrating the HTS rotor strand is in inverse proportion to the air gap. It means that only an HTS rotor strand can not guarantee the desired performance for HTS synchronous motor.
- Thus, **the HTS rotor strand is arranged in n-turn toroidal shape to increase total magnet area to achieve the desired performance in limited space. (n : number of HTS rotor strand)**
- In order to verify the proper charging method for HTS field coils, two cases of experiments are performed with rotary HTS flux pump
  - **Type I : HTS coil1 and HTS coil2 are connected in series and charged by n-HTS rotor strands.**
  - **Type II : each of coils is charged by n/2-HTS rotor strands.**
- In those experiments, the current flowing through the HTS coil is measured by hall sensor with rotor speed range, from **100 to 300 rpm**.

2. Experimental Setup

- **Configuration of rotary HTS flux pump**

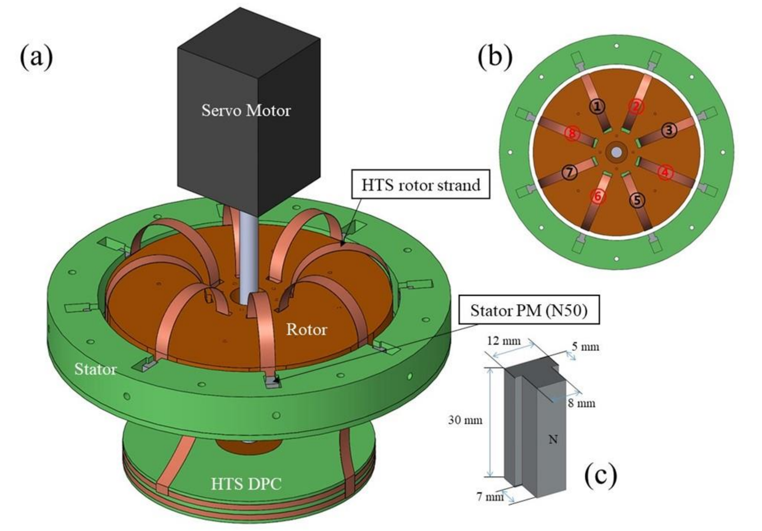


Fig. 2. Schematic diagram of (a) Rotary HTS flux pump, (b) cross section view for HTS strand numbers, (b) and (c) stator PM (N50)

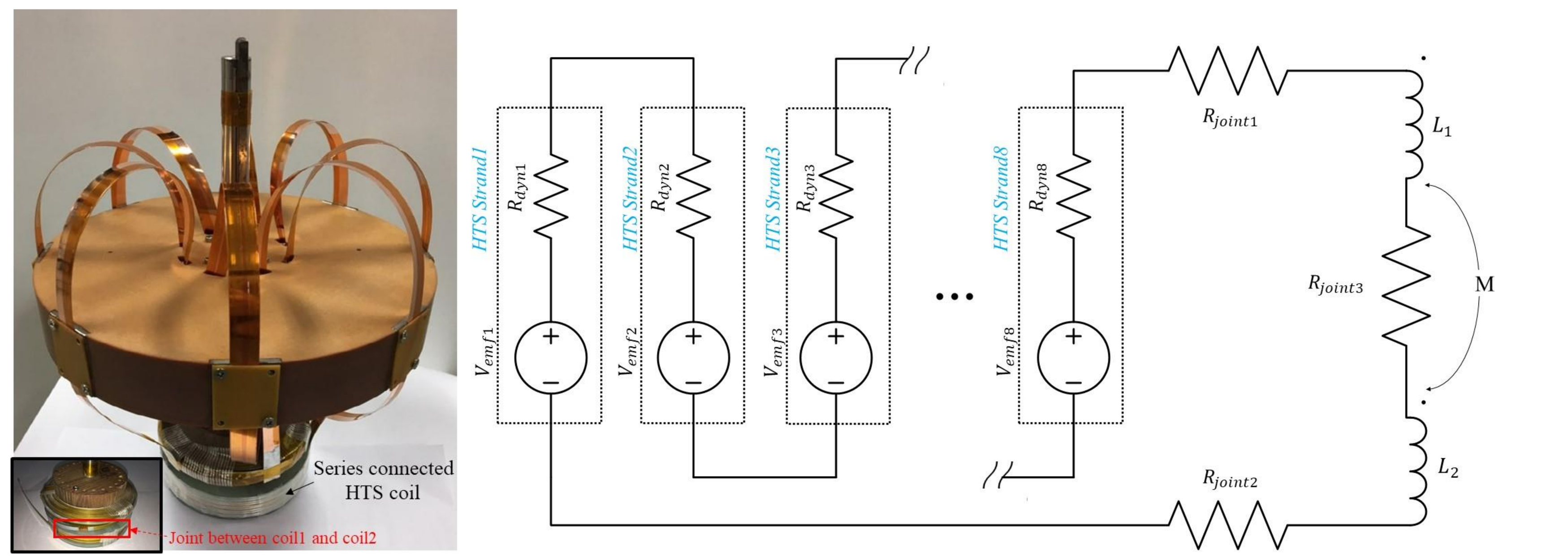


Fig. 3. Photograph of rotating components of Type I with 8-turn toroidal shape HTS strand and equivalent circuit

- **Specification of HTS double pancake coils**

Parameters	Values
HTS conductor (width / thickness)	GdBCO tape with Brass lamination / SuNam (4.0 / 0.22)
Winding ID / OD [mm]	80 / 100
Turns per layer (turns)	33
Critical current [A]	116
Self-inductance [mH]	1.1

- 12 mm GdBCO coated-conductor rotor strand is arranged n-turn toroidal shape in rotor according to the dimension.
- The dimension of the rotor is 114 mm outer diameter, 35 mm inner diameter and 35 mm.
- The HTS rotor strand were jointed with HTS load coil.
- The rotor is composed of a Bakelite bobbin and 8 Iron plates adjacent to HTS rotor strand.
- The stator is composed of GFRP material and 8 permanent magnets (N50) which were mounted on the inner circumference of a cylindrical stator.
- **Magnetic flux density of N50 in 8 mm air-gap** between rotor and stator was about **0.14 T in liquid nitrogen.**

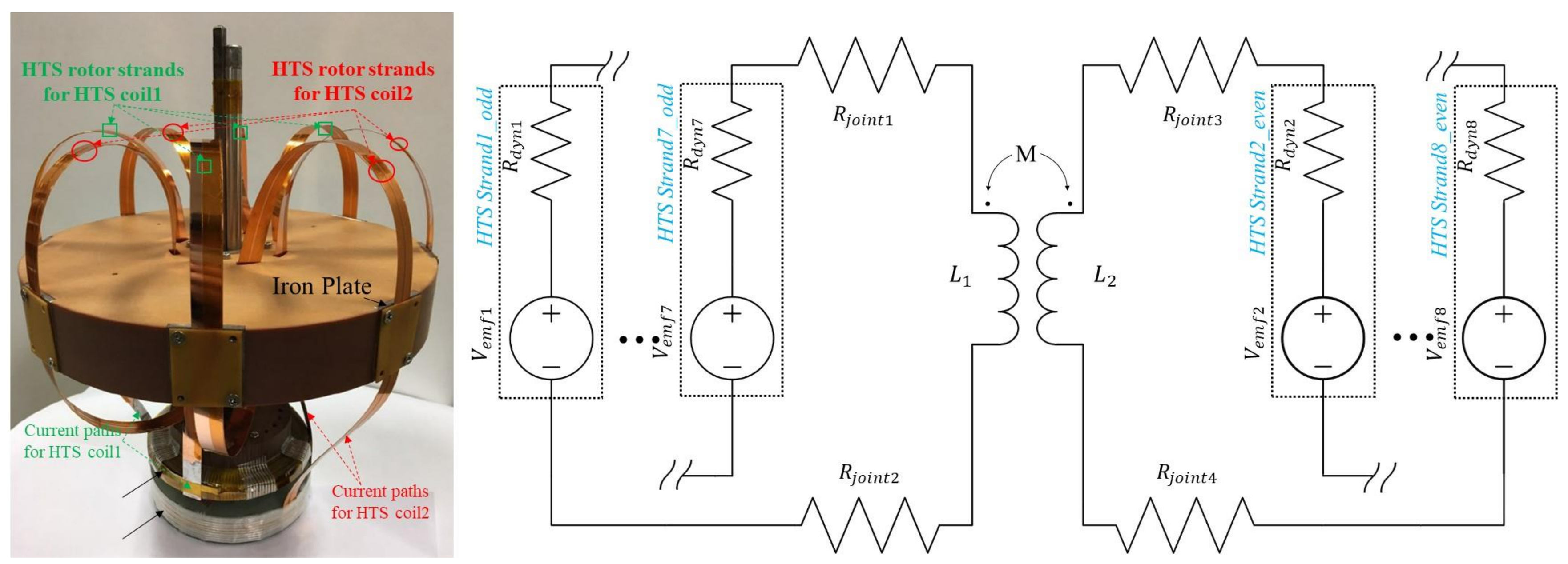
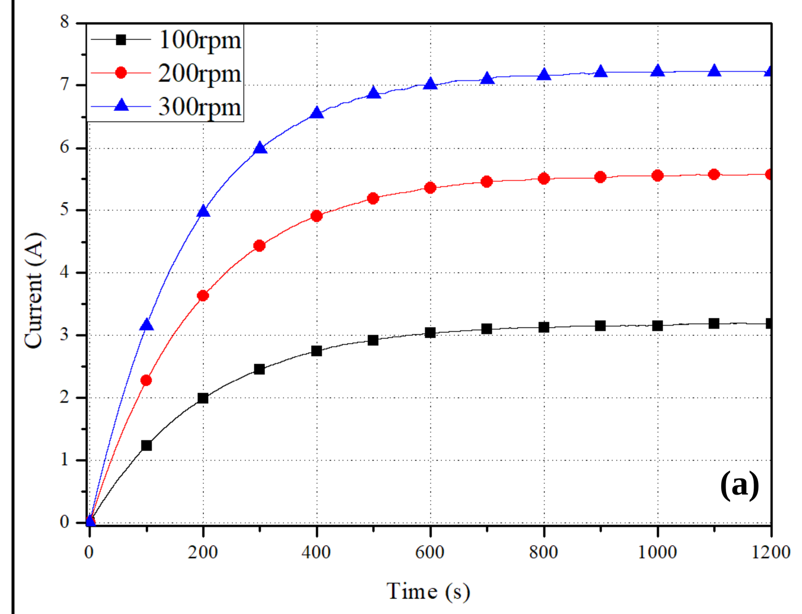


Fig. 4. Photograph of rotating components of Type II with 4-turn toroidal shape HTS strand for each coil and equivalent circuit

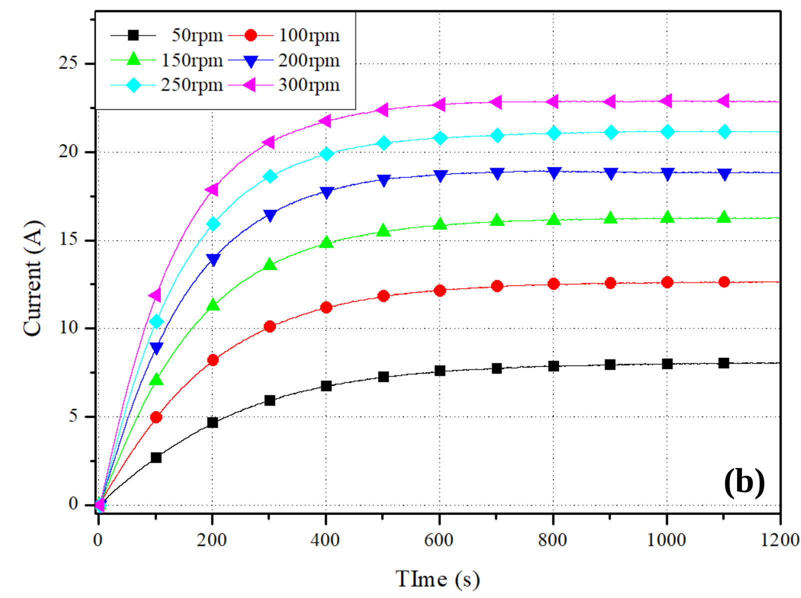
- Figs. 3 and 4 show rotating components, 8-turn and 4-turn toroidal shape HTS strand and HTS load coils, and equivalent circuits of Type I and II, respectively.
- Mutual inductance between HTS coil1 and HTS coil2 is existed due to the distance between two coils is too short (20 mm).
- The mutual inductance calculated by the brute force method is about 0.3 mH.

3. Experimental Results

- **Current charging characteristics - Type I**

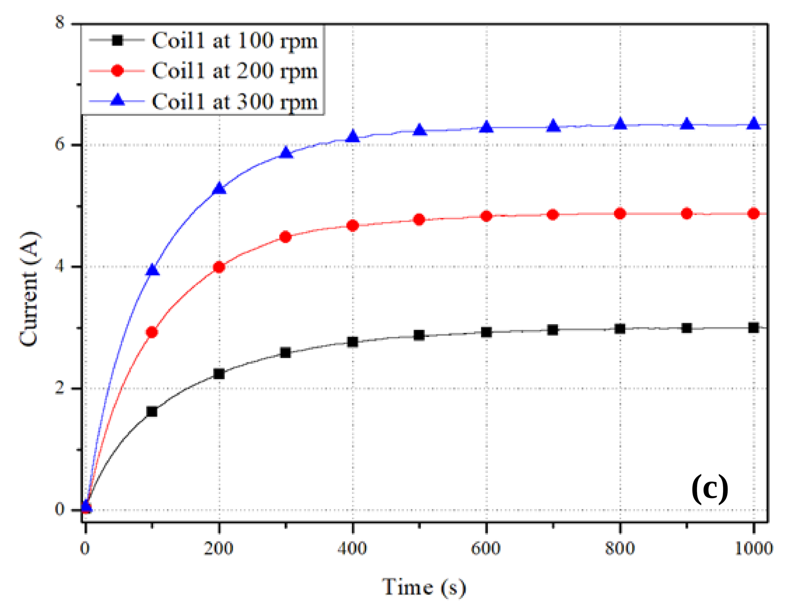


1 HTS rotor strand with 8 N50

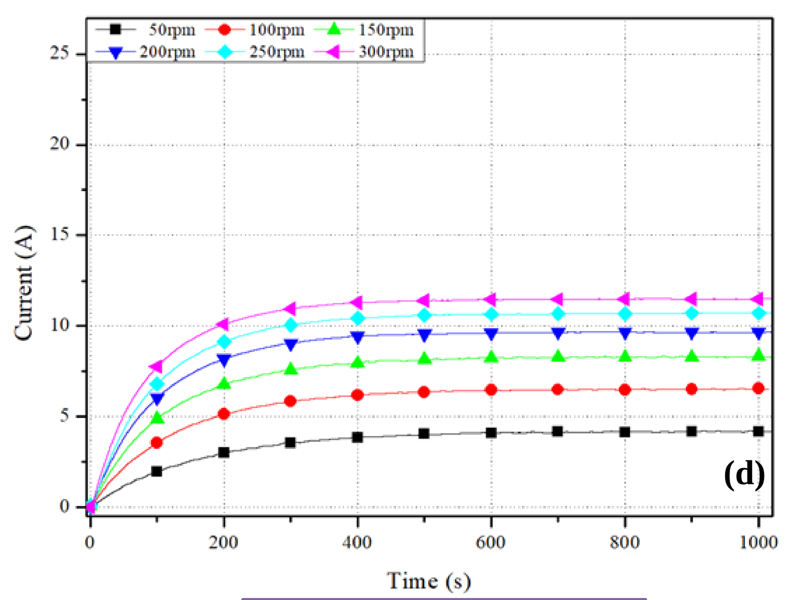


8 HTS rotor strands with 8 N50

- **Current charging characteristics - Type II**
  - **HTS Coil1**

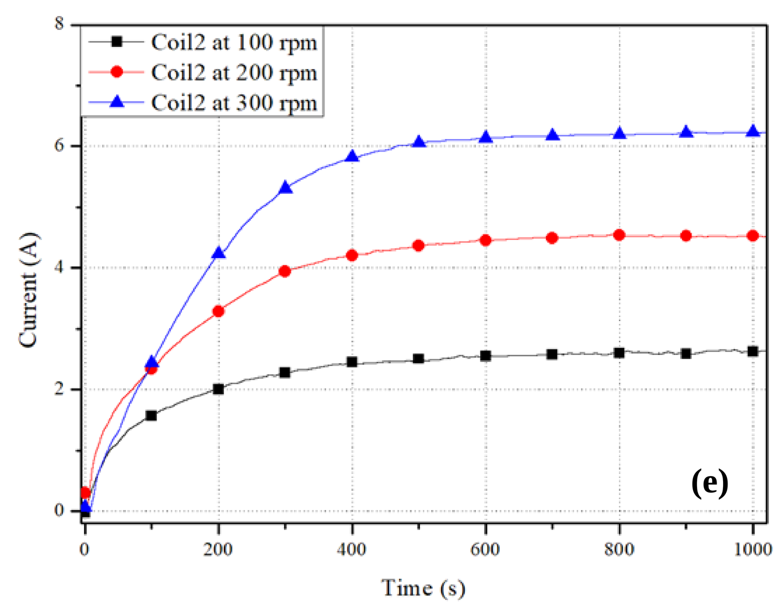


1 HTS rotor strand with 8 N50

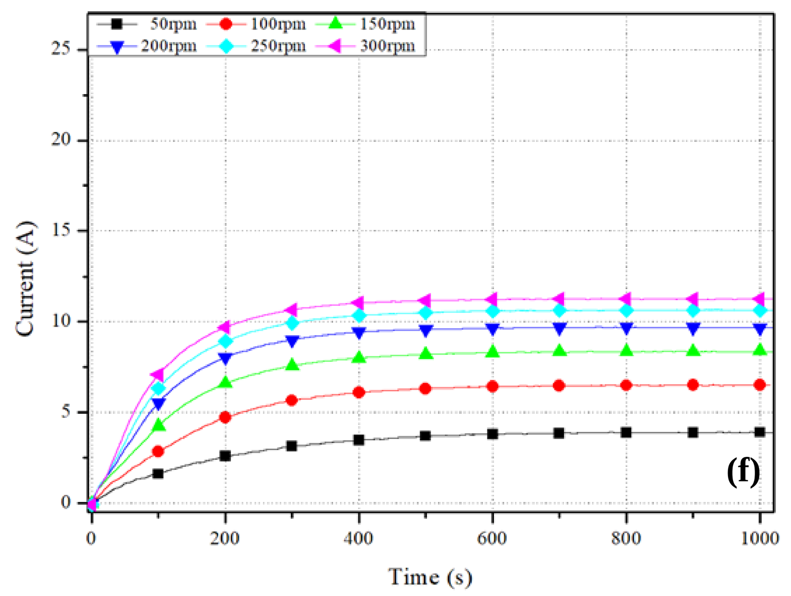


4 HTS rotor strand with 8 N50

  - **HTS Coil2**



1 HTS rotor strand with 8 N50



4 HTS rotor strand with 8 N50

- **Test results of (a)** [Table 1]

Rotor Speed	Saturated current [A]	Saturation time [s]
100 rpm	3.18	1100
200 rpm	5.57	1100
300 rpm	7.22	1100

- **Test results of (b)** [Table 2]

Rotor Speed	Saturated current [A]	Saturation time [s]
50 rpm	8.04	1100
100 rpm	12.61	1000
150 rpm	16.20	850
200 rpm	18.85	700
250 rpm	20.95	700
300 rpm	22.82	700

- **Test results of (c) and (e)** [Table 3]

Rotor Speed	Saturated current [A] Coil1 / Coil2	Saturation time [s] Coil1 / Coil2
100 rpm	2.98 / 2.61	800
200 rpm	4.88 / 4.54	800
300 rpm	6.33 / 6.20	700

- **Test results of (d) and (f)** [Table 4]

Rotor Speed	Saturated current [A] Coil1 / Coil2	Saturation time [s] Coil1 / Coil2
50 rpm	4.15 / 3.90	800
100 rpm	6.50 / 6.50	800
150 rpm	8.28 / 8.26	700
200 rpm	9.68 / 9.69	700
250 rpm	10.66 / 10.61	600
300 rpm	11.48 / 11.24	600

- **Joint resistance (From current discharging tests)**

	Model	Joint Resistance [$\mu\Omega$]
(a)	Type I	7.89
(b)	Type I	7.69
(c)	Type II	4.71
(d)	Type II	4.14
(e)	Type II	9.50
(f)	Type II	5.93

- As shown in Tables 1 and 2, the number of HTS rotor strand is increased 8 times, but the saturated current is increased by about 3.97, 3.35 and 3.16 times for 100, 200 and 300 rpm, respectively.
- As shown in Tables 3 and 4, the number of HTS rotor strand is increased 4 times, but the saturated current is increased by about 2.34, 2.06, 1.81 times for 100, 200 and 300 rpm, respectively.

- The saturated currents of Type I and Type II are almost same when the number of HTS rotor strands is one as shown in Tables 1 and 3.
- [rpm] Compared based on the same rpm from Tables 2 and 4, the saturated current of Type I is greater than that of Type II.
- [freq.] When the saturated current at 50, 100 and 150 rpm of Table 2 is compared with that of 100, 200 and 300 rpm, Type I is better than Type II in terms of current charging capability.
- [Balance of saturated currents] Error rate of Type II is 6.02, 0.08, 0.18, 0.16, 0.47, 0.05, 1.47, 1.25, 2.02, 2.24 and 6.77 % for each rpm, respectively.

4. Conclusion

- As the number of HTS rotor strands increases, the total magnet area increases equally, but the saturated current increased by half.
- As the rotational speed increases, the increase rate of the saturated current decreases when the number of HTS strands increase.
  ⇒ These results are expected to be incurred due to the long length of air-gap : Not completely penetrate the strand.
- Mutual inductance exists between HTS coils. Since governing equation of Type I changes only the inductance part from the existing governing equation, it is easy to predict the charging current based on the contents that have been researched, but in case of Type II, the governing equation become very complex.
  ⇒ For this reason, difference in saturated current occurs even if both Types operate at the same frequency.
- In the case of synchronous motors, current balance between field coils is important as they become larger.
  ⇒ Because HTS coils of Type I were connected in series, charging current is better distributed to each coil. So it is better than Type II in terms of current balance.

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