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Study on Starting and Variable Speed Controllability of 50 kW Class Fully HTS Induction/Synchronous Motor Based on Multidisciplinary Analysis Code

Masaya Okuno, Taketsune Nakamura, Takuro Ogasa, Ryohei Nishino (Kyoto University, Japan)
Masaaki Yoshikawa, Yoshitaka Itoh (IMRA MATERIAL R&D Co., Ltd., Japan)

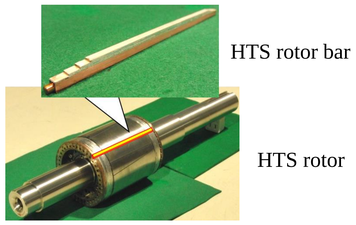
INTRODUCTION

High Temperature Superconducting Induction/Synchronous Motor (HTS-ISM)

for next generation transportation equipment
e.g. train, bus, etc.

Structure

HTS-ISM has the same structure as squirrel-cage induction motor, but its rotor bars and end rings are replaced with high temperature superconducting (HTS) tapes



Photograph of HTS squirrel-cage rotor

Advantages

- High efficiency
- High torque density
- Coexistence of synchronous as well as slip rotation mode

and so on.

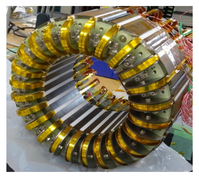
50 KW FULLY HTS-ISM

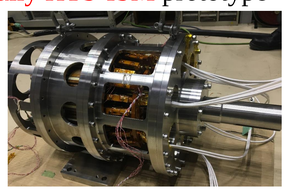
Fully HTS-ISM

In order to improve the efficiency, stator windings are also fabricated by HTS tapes

Fabricated 50 kW class fully HTS-ISM

We fabricated the 50 kW class fully HTS-ISM prototype

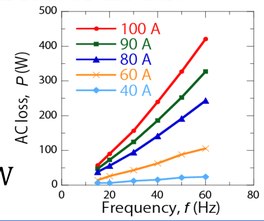

Photograph of Toroidal HTS stator


Photograph of fabricated 50 kW class fully HTS-ISM

AC loss of HTS stator windings

Power losses of HTS stator
- AC loss of HTS windings
- Iron loss of the core

We evaluated AC losses of the HTS stator windings of the 50 kW fully HTS-ISM



$$P_{\mathrm{ACloss}} = 24.69 \times I^{2.47} \times f^{1.25}\ \mu\mathrm{W}$$

ANALYSIS METHOD

Nonlinear voltage equations

$$\begin{bmatrix} v_{\mathrm{as}} \\ v_{\mathrm{bs}} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_{\mathrm{s}} + L_{\mathrm{s}}\frac{\mathrm{d}}{\mathrm{d}t} & 0 & M\frac{\mathrm{d}}{\mathrm{d}t} & 0 \\ 0 & R_{\mathrm{s}} + L_{\mathrm{s}}\frac{\mathrm{d}}{\mathrm{d}t} & 0 & M\frac{\mathrm{d}}{\mathrm{d}t} \\ M\frac{\mathrm{d}}{\mathrm{d}t} & \frac{\mathrm{P}}{2}\omega_{\mathrm{m}}M & R_{\mathrm{r}} + L_{\mathrm{r}}\frac{\mathrm{d}}{\mathrm{d}t} & \frac{\mathrm{P}}{2}\omega_{\mathrm{m}}L_{\mathrm{r}} \\ -\frac{\mathrm{P}}{2}\omega_{\mathrm{m}}M & M\frac{\mathrm{d}}{\mathrm{d}t} & -\frac{\mathrm{P}}{2}\omega_{\mathrm{m}}L_{\mathrm{r}} & R_{\mathrm{r}} + L_{\mathrm{r}}\frac{\mathrm{d}}{\mathrm{d}t} \end{bmatrix} \begin{bmatrix} i_{\mathrm{as}} \\ i_{\mathrm{bs}} \\ i_{\mathrm{ar}} \\ i_{\mathrm{br}} \end{bmatrix}$$

v: voltage
i: current
R: resistance
L: self-inductance
M: mutual inductance
P: pole number (=4)
ω_m: mechanical angular frequency
R_s , R_r : HTS nonlinear resistance

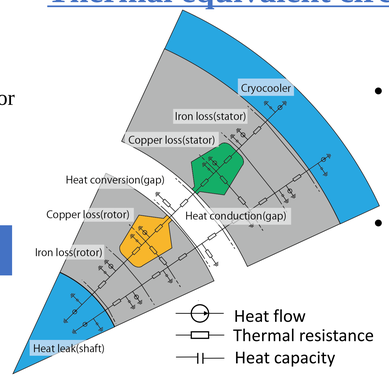
subscripts
'a', 'b': ab-axis values
's', 'r': stator and rotor values

Equation of motion

$$\frac{\mathrm{d}\omega_{\mathrm{m}}}{\mathrm{d}t} = \frac{1}{J}(\tau - D\omega_{\mathrm{m}} - \tau_{\mathrm{load}})$$

τ: torque
J: moment of inertia
D: damping coefficient of rotor
τ_{load}: loaded torque

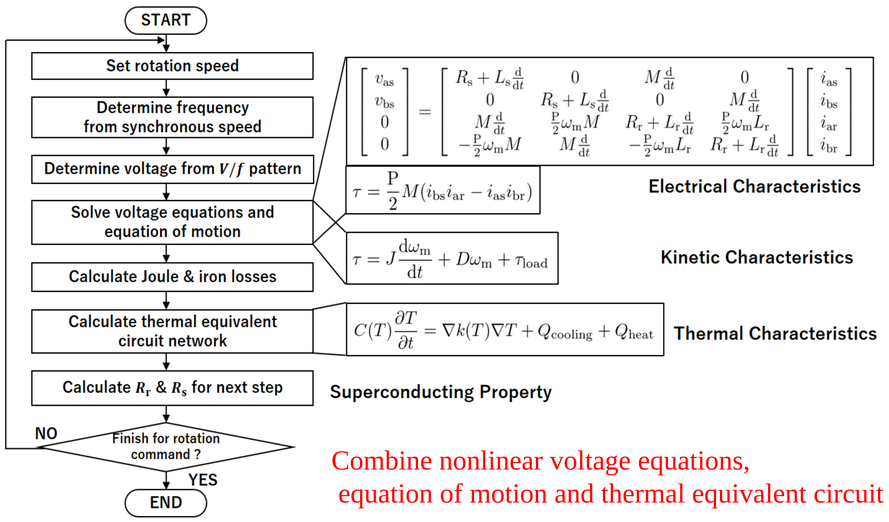
Thermal equivalent circuit



Thermal equivalent circuit of 50 kW fully HTS-ISM

- Outer surface of the stator is cooled by cryocooler.
  $P_{\mathrm{c}} = 5 \times (T - 40\mathrm{K})$ (W)
  (200W@80K ; COP = 0.1)
- Two kinds of gaseous coolant heat transfer
  i. radial-direction heat transfer produced by rotation of rotor
  ii. axial-direction heat transfer produced by axial flow of gaseous coolant (2.4 m/s)

Multidisciplinary analysis code



Flow chart of multidisciplinary analysis procedure for 50 kW fully HTS-ISM

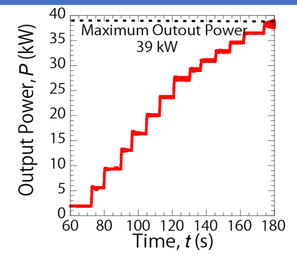
Combine nonlinear voltage equations, equation of motion and thermal equivalent circuit

RESULTS AND DISCUSSION

Load test

in liquid nitrogen (77K)

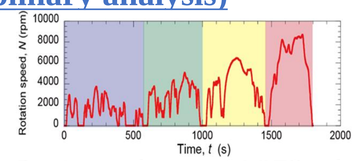
World first success of 39 kW output (at 1500 rpm) for fully superconducting motor



Output power characteristics of load test (1500 rpm)

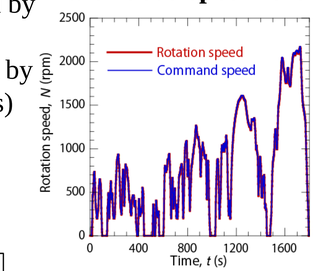
WLTC rotation test (multidisciplinary analysis)

WLTC is a newly adopted global harmonized driving test cycle for measuring fuel consumption and CO2 emission

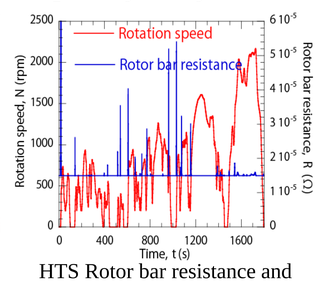


Rotation speed pattern of WLTC cycle

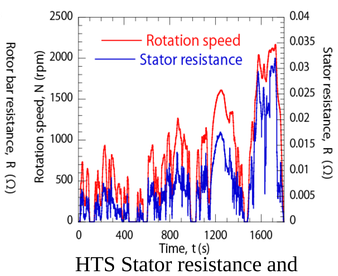
WLTC test of 50 kW fully HTS-ISM was successfully carried out with developed multidisciplinary analysis method



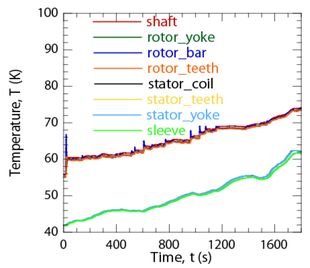
Rotation speed



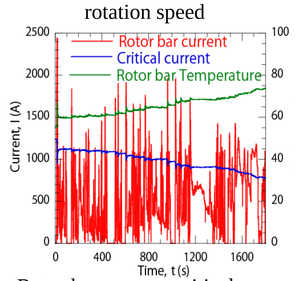
HTS Rotor bar resistance and rotation speed



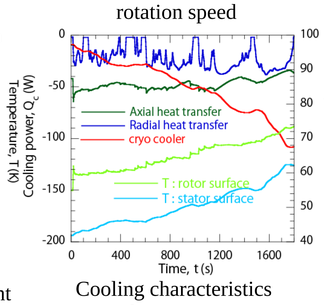
HTS Stator resistance and rotation speed



Temperature



Rotor bar current, critical current and temperature



Cooling characteristics and temperature

- Electric consumption (km/kWh) was calculated：10.7 km/kWh

⇨ Our drive system possesses high efficiency even if considering power consumption of cryocooler (More study is necessary)

CONCLUSION

- We developed multidisciplinary analysis method which combines nonlinear voltage equations, equation of motion and thermal equivalent circuit for 50 kW class fully HTS-ISM.
- The maximum output reached 39 kW at 1500 rpm in load test (World first success).
- WLTC rotation test was carried out with developed multidisciplinary analysis method, and transient rotation and cooling characteristics were investigated.

Acknowledgment

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