Research on IPMSM considering PM Irreversible Demagnetization at Saturation Temperature

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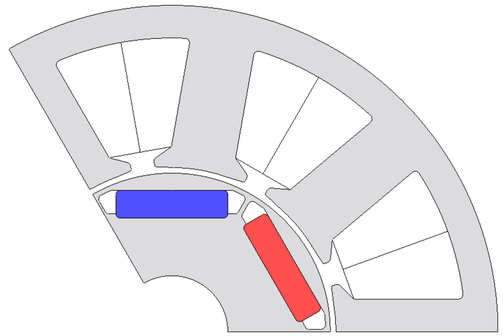
Introduction

- ❖ Operation characteristic of motor is highly effected by the temperature, in terms of permanent magnet irreversible demagnetization and efficiency
- ❖ Permanent magnet suffers from Irreversible demagnetization, in case its operation point is located below knee point
  - Knee point is established considering the operating temperature, which determines the performance characteristic of the motor
- ❖ Conventionally, operation characteristic of the motor is analyzed considering operation temperature
  - Due to the losses and cooling conditions, saturation temperature of the motor's components differs from the given operation temperature
  - To evaluate saturation temperature of motor parts, commercial software MotorCAD, based on temperature equivalent circuit, is used
- ❖ In this paper, operation characteristic of the motor is analyzed and compared, considering saturation temperature derived from MotorCAD

Conclusion

- ❖ In this paper, operation characteristic of EOP motor is studied regarding PM irreversible demagnetization when temperature saturation is taken into account
- ❖ Temperature saturation is analyzed using MotorCAD, which considers actual cooling condition and losses of the system
  - Temperature of PM increased by approximately 11% to 15%, when compared to the ambient temperature
  - Residual flux density of PM is reduced due to the temperature rise, requiring larger current to generate expected output
- ❖ As characteristic of PM is effected by the temperature, the PM demagnetization ratio varies when temperature saturation is considered
- ❖ To derive accurate IPMSM model for EOP, temperature saturation characteristic should be taken in to account at its design stage

Specification of IPMSM



< Configuration of IPMSM for EOP >

- EOP motor is to operate at both low-speed high-torque and high-speed low-torque for low and high temperature, respectively

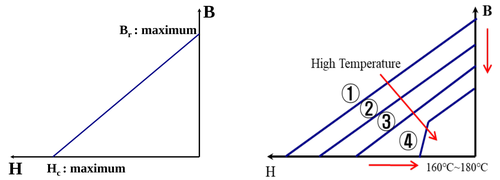
Parameter		Unit	Value
Number of Pole / Slot		-	6 / 9
Stator Inner / Outer Diameter		*mm*	35.2 / 70.0
Rotor Inner / Outer Diameter		*mm*	12.0 / 34.0
Stack Length		*mm*	30.0
Air-gap Length		*mm*	0.6
Rotating Speed	Operating point 1	*rpm*	2,700 (80℃)
	Operating point 2		*2,900* (120℃)
Magnet Br / Hc @ 20℃		T / A/m	1.128 / -900*k*

< EOP motor specification >

PM Characteristic considering Temperature

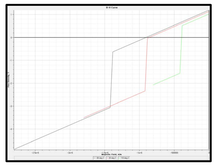
Characteristic of Permanent Magnet

- Permanent magnet is highly effected by the operating temperature, which also has effect on the irreversible demagnetization
- NdFeB PM is known for high residual flux density & coercitivity
  - Vulnerable to high temperature irreversible demagnetization



$$B_T = B_r(20℃)\left[1 - \frac{\alpha(T-20℃)}{100}\right]$$

$$H_T = \frac{B_r(20℃)}{\mu_r \mu_0}{}_r\left[1 - \frac{\alpha(T-20℃)}{100}\right]$$



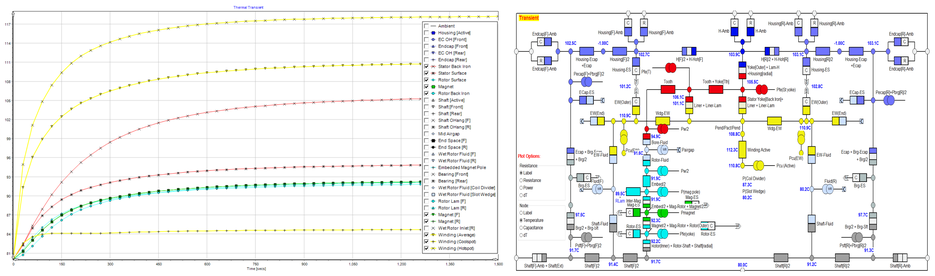
Temp	B_T	H_T
20℃	1.128 T	-812.14 kA/m
80℃	1.006 T	-724.43 kA/m
120℃	0.924 T	-665.95 kA/m

< Characteristic of PM considering temperature >

Analysis & Results

Analysis using MotorCAD

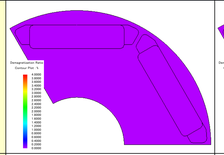
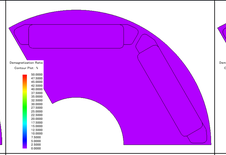
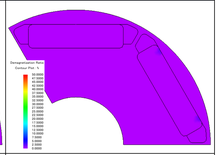
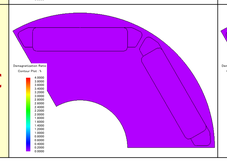
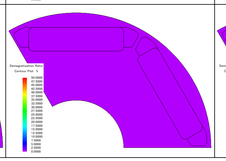
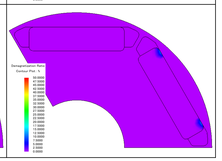
- For analysis, precise cooling condition regarding actual cooling condition should be implemented for accurate result
  - **Cooling Option:** Housing Outer Cooling (Natural convection) / Cooling system (Wet Rotor)
  - **Natural Convection:** Operating point 1 (80℃@2,700rpm) / Operating point 2 (120 ℃@ 2,900rpm)
  - **Wet Rotor:** Fluid property (Skydrol LD-4) Operating point 1 (inlet temp 80℃@2,700rpm) / Operating point 2 (inlet temp 120 ℃@ 2,900rpm) / Fluid Flow (Slot wedge fluid flow & Coil divider fluid flow)
- **Temperature of PM for 80℃ and 120℃ operating points saturated at 92.3℃ and 133.16℃, respectively**



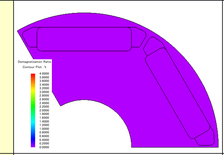
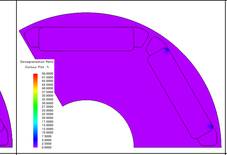
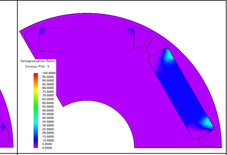
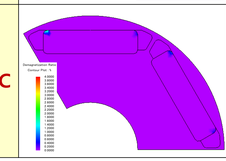
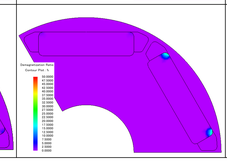
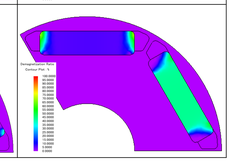
< Temperature saturation analyzed using MotorCAD >

FEM Analysis considering saturation temperature

- **Operating point 1:** Max PM demagnetization ratio for conventional and temperature saturation considered is 6.35% and 18.82%, when maximum current is induced at d-axis
- **Operating point 2:** Max PM demagnetization ratio for conventional and temperature saturation considered is 49.07% and 73.08%, when maximum current is induced at d-axis, as it is 10.34% and 29.66% when rated current is induced. Nonetheless, it suffers from irreversible demagnetization at normal operation, when temperature saturation is considered
- Torque dropped by 1.57% and 1.81%, respectively for operating points 1 and 2, when temperature saturation is taken into account

Temp	Normal operation	d-axis (Rated Current)	d-axis (Max current)
80℃			
92.3℃			

< PM irreversible Demagnetization analysis for 80℃ condition >

Temp	Normal operation	d-axis (Rated Current)	d-axis (Max current)
120℃			
133.16℃			

< PM irreversible Demagnetization analysis for 120℃ condition >