Design principle of WFSM for Electric Vehicle based non-linear magnetic equivalent circuit

Jae-Jun Lee1, Jae-Kwang Lee2, Gang-Seok Lee2

1. Samsung Electronics Co., Ltd., Republic of Korea
2. University of Hanyang, Republic of Korea

Background

Because main flux path is sensitive to the magnetic saturation, Wound Field Synchronous Motor (WFSM) has to be designed considering magnetic saturation, especially for the applications requiring high torque density such as EV. Thus Magnetic Equivalent Circuit (MEC) should be constructed considering the nonlinearity of the electrical steel sheet.

Objectives

- Construct non-linear magnetic equivalent circuit for Wound Field Synchronous Motor.
- Make design algorithm of WFSM considering magnetic saturation.

Non-linear Magnetic Equivalent Circuit

Non-linear MEC for WFSM is constructed and calculated using Newton-Raphson Method.

Methods

- Case 1: Stator teeth width = half of the slot pitch
- Case 2: Stator teeth width > half of the slot pitch

Design WFSM

Construction of air gap reluctance is divided into 2 cases.

- Case 1:
  - Stator teeth width = half of the slot pitch
  - \( R_{sl} = R_{sl\text{avg}} = R_{sl\text{min}} \)
  - \( R_{sw} = R_{sw\text{avg}} = R_{sw\text{min}} \)
  - \( R_{sw} = R_{sw\text{avg}} = R_{sw\text{min}} \)
  - \( R_{sw} = R_{sw\text{avg}} = R_{sw\text{min}} \)

- Case 2:
  - Stator teeth width > half of the slot pitch
  - \( R_{sl} = R_{sl\text{avg}} = R_{sl\text{min}} \)
  - \( R_{sw} = R_{sw\text{avg}} = R_{sw\text{min}} \)
  - \( R_{sw} = R_{sw\text{avg}} = R_{sw\text{min}} \)
  - \( R_{sw} = R_{sw\text{avg}} = R_{sw\text{min}} \)

Design algorithm:

- When stator outer diameter is given as a constraint, iteration is performed according to the turns of stator and current phase angle.
- Find shape and current phase angle that generate maximum torque in unit core length and calculate the core length satisfying the required torque.

Conclusion

- Non-linear MEC of WFSM is constructed to consider magnetic saturation.
- Design algorithm using non-linear MEC is presented.
- Torque of design model finally selected is compared with that of FE Analysis and verified accuracy of non-linear MEC
- Experiment was conducted for the final design model.

Non-linear Magnetic Equivalent Circuit

- Magnetic Source & Field Excitation
- Losses & Harmonics
- Stator Core Losses
- Stator Iron Losses
- Stator Slot Losses
- Stator Magnetic Losses
- Stator Winding Losses
- Stator + Rotor Fractions
- Stator + Rotor Total Losses
- Stator + Rotor Temperature

Design WFSM

- Calculate Magnetic Flux Interlinkage
- Calculate Torque
- \( T( k, j) < T( k, j+1) \)
- \( j = j+1 \)

Result

- Required Torque & Speed
- \( T_{req}, RPM \)
- Set Initial Current Density
- \( J_{DC}, J_{peak} \)
- Set Fixed Value
- \( (D_{so}, K_{sf}, I_a, ...) \)

Design result

- Current Phase-Angle
- Nonlinear MEC
- PMB
- Error

Torque, Efficiency Test

- Stator & Rotor sheet
- Load Motor
- WFSM in Housing

Efficiency Map [Motor]

- Stator & Rotor assembly
- Power Cable
- Water Tube

MT25-Mon-Af-Po1.04-12