Design of Vernier Motor considering Irreversible Demagnetization in Permanent Magnet

Dae-Woo Kim,1 Tan-Yong Lee,1 Yong-Jae Kim,2 Sang-Yong Jung2
1 School of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, 16419, Republic of Korea
2 Department of Electronic Engineering, Chosun University, Gwangju, 61452, Republic of Korea

Introduction

- As demand for high-torque direct drive motor is increasing, interest in vernier motor is gaining its importance
- Vernier motor is a type of permanent magnet (PM) motor, targeted for low speed and high torque operation applications
- PM used in vernier motor should be prevented from irreversible demagnetization in both operating and abnormal conditions, for its consistency
- Flux Modulation Pole(FMP) type vernier motor that has PM placed in its stator coupled with SPM type rotor is selected as base model for analysis
- Bar and delta type flux barrier is applied to the stator PM to prevent its irreversible demagnetization for different operation conditions
- Vernier motor is analyzed with different design parameters regarding flux barrier, as its PM irreversible demagnetization ratio and output performance characteristics is compared to that of the base model

Operating principle of VM

- Using the derived MMF and air-gap permeance, the air-gap flux density of vernier motor is derived as follows:
  \[ B(\theta, \theta_m) = B_{1s} Z_s \left( \theta - \theta_m \right) - B_{2s} Z_s \left( \cos(\theta_0 - \theta) - \cos(Z_s \theta) \right) \]
- First term: air-gap flux density component equal to conventional PM motor
- Second term: flux element generated by harmonic component (additional)
- Due to the second term of air-gap flux density component, additional torque component is generated, compared to that of the conventional PM motor
- The pole-slot combination of vernier motor is determined by the equation shown below, which is derived from the air-gap flux density equation above:
  \[ Z_s \theta_0 = Z_s \theta + p \]
- \( Z_s \): the number of winding pole pair

Features of Specified VM model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar type</td>
<td></td>
</tr>
<tr>
<td>Delta type</td>
<td></td>
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</table>

Conditions for analysis

- \( 4a_0 \) is assigned as operation current in phase with q-axis, for the FMP type vernier motor
- However, abnormal conditions when larger current is supplied in phase with q-axis should be taken into account, to assure reliability of the motor
- Two conditions are taken into account for PM irreversible demagnetization analysis
  1) AA input current in phase with q-axis (normal operation)
  2) BA input current in phase with d-axis (abnormal operation)
- To ease irreversible demagnetization and to improve performance of the motor, 2 different type of flux barriers are selected for analysis

Analysis & Results

<table>
<thead>
<tr>
<th>Design variables</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Bar type</td>
<td></td>
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Conclusion

- In this paper, design of flux barrier for FMP type vernier motor considering irreversible demagnetization in PM is studied
- Analysis on demagnetization ratio of FMP vernier motor is carried out, with different design parameters applied
  - In operation condition, demagnetization ratio of stator PM is reduced to approximately 0%, as it dropped by approximately 5.7% for both bar and delta type flux barrier applied FMP vernier motor
  - Applied flux barrier not only reduced the demagnetization ratio of PM in stator, but also reduced its leakage flux
  - Output torque is improved by 5.86% and 5.76% for bar and delta type flux barrier, respectively
  - Delta type: Advantageous in achieving low and stable PM demagnetization ratio, regarding change in its design parameter
  - Bar type: Advantageous in generating higher output torque, although demagnetization ratio is effected by its design parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Name</td>
<td>Unit</td>
</tr>
<tr>
<td>Number of Pole / Electric Slot</td>
<td>38 / 24</td>
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<tr>
<td>Stator Inner / Outer Diameter</td>
<td>230.0 / 280.0</td>
</tr>
<tr>
<td>Rotor Inner / Outer Diameter</td>
<td>180.0 / 208.0</td>
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<tr>
<td>Stack Length</td>
<td>50.0</td>
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<tr>
<td>Air-Gap Length</td>
<td>1.0</td>
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<tr>
<td>Resolving Speed</td>
<td>300</td>
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<tr>
<td>Magnetic flux ( f_{ph} )</td>
<td>0.30 / 206k</td>
</tr>
</tbody>
</table>

< Base model of FMP vernier motor>

< Base FMP vernier motor specification>

< Torque generated for each flux barrier>

< Demagnetization ratio for bar and delta type flux barrier>

< Demagnetization ratio and output torque for bar and delta type flux barrier>

< Flux barrier configuration>

< Flux barrier design parameter>