PERMANENT-MAGNET MAGNETIZATION STATE ESTIMATION USING HIGH-FREQUENCY SIGNAL INJECTION

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Permanent-magnet (PM) magnetization state estimation is important both for torque control and monitoring in conventional permanent-magnet synchronous machines (PMSMs). Furthermore, this can be critical for variable flux machines (VFMs). Use of high-frequency signal injection methods for pm magnetization state estimation in ndfeb magnets has already been proposed. These methods make use of the variation of the pm high-frequency resistance with the PM magnetization state due to the magneto-resistive effect. This paper addresses the generalization of magnetization state estimation using high-frequency signal injection to other types of magnets like SmCo and ferrite, as well as to other magnet structures, e.g., Isolated and non-isolated segmented magnets. Use of the magneto-resitive effect for the detection of irreversible/reversible PM demagnetization will also be shown to be viable.
This paper is organized as follows.

- Physical principles of magnetoresistance effect in PMs are presented;
- The experimental setup used for magnetoresistance effect evaluation is presented
- High-frequency signal injection for PM magnetization state estimation is presented
- Experimental results are provided
- The equivalence between the experimental setup for magnetoresistance effect evaluation and a PMSM is provided

Table 1
Cost and temperature sensitivity of different magnetic materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Alnico 8</th>
<th>Ferrite 9</th>
<th>SmCo 2:17</th>
<th>NdFeB 33EH</th>
<th>NdFeB 48M</th>
</tr>
</thead>
<tbody>
<tr>
<td>$/Kg</td>
<td>35</td>
<td>15</td>
<td>100</td>
<td>200</td>
<td>150</td>
</tr>
<tr>
<td>$\alpha_B (%/^\circ C)$</td>
<td>$-0.01$</td>
<td>$-0.18$</td>
<td>$-0.035$</td>
<td>$-0.11$</td>
<td>$-0.12$</td>
</tr>
</tbody>
</table>
MAGNETORESISTIVE EFFECT IN PMS

Magnetoresistance is defined as the change of the material’s electrical resistance/resistivity with the application of a magnetic field. For large electrical resistance variation (> 10%), this effect is called giant magnetoresistance (GMR). Magnetoresistance was initially discovered in thin-film structures alternating ferromagnetic and nonmagnetic conductive layers.

\[
\text{MR} = \frac{\Delta R}{R(0)} = \frac{R(H) - R(0)}{R(0)} \quad (1)
\]

\[
R(H) = R(0)(1 + \beta(H - H_0)) = R(0)(1 + \beta(\Delta H)). \quad (2)
\]
EXPERIMENTAL SETUP FOR MEASUREMENT OF MAGNETORESISTANCE EFFECT

Fig. 1. (a) Experimental setup used for PM magnetoresistance evaluation and (b) simplified representation of flux lines (blue) and magnet eddy current vectors (red) in the experimental setup.
Measurement of the magneto-resistive effect in the magnets of a PMSM is not easy due to the large number of design parameters that can affect the results, both in the stator (e.g., stator teeth shape, number of stator slots, and number of poles) and rotor (rotor geometry, number of PMs layers, PMs shape and size, and flux barriers).

The high-frequency equivalent circuit of the platform shown in Fig. 1 is given in Fig. 2, where \( v_p \) and \( i_p \) is the coil high frequency voltage and current; \( R_{hfP} \), \( R_{hfFEp} \), and \( R_{hfS} \) are the coil, core, and magnet high-frequency resistances, respectively; \( L_{hfP} \) and \( L_{hfS} \) are the coil and magnet high-frequency inductances; \( \omega_{hf} \) is the frequency of the high-frequency signal; \( i_{hfs} \) is the magnet high-frequency current (eddy current); and \( M_{ps} \) is the mutual coupling between the primary and the secondary.

Fig. 2. Equivalent high-frequency model of the simplified geometry.
\[ v_{hfp}^p = \left( R_{hfp}^p + j\omega_{hfs}L_{hfp} \right) i_{hfp}^p + j\omega_{hfs} M_{ps} i_{hfs}^s \]

\[ 0 = \left( R_{hfs}^s + j\omega_{hfs}L_{hfs} \right) i_{hfs}^s + j\omega_{hfs} M_{ps} i_{hfp}^p \]

\[ i_{hfs}^s = \frac{-j\omega_{hfs} M_{ps} i_{hfp}^p}{R_{hfs}^s + j\omega_{hfs} L_{hfs}} \]

\[ v_{hfp}^p = \left( R_{hfp}^p + j\omega_{hfs} L_{hfp} \right) i_{hfp}^p - j\omega_{hfs} M_{ps} \frac{j\omega_{hfs} M_{ps} i_{hfp}^p}{(R_{hfs}^s + j\omega_{hfs} L_{hfs})} \]

\[ v_{hfp}^p = \left( R_{hfp}^p + j\omega_{hfs} L_{hfp} \right) i_{hfp}^p + \frac{\omega_{hfs}^2 M_{ps}^2}{(R_{hfs}^s + j\omega_{hfs} L_{hfs})} i_{hfp}^p \]

\[ Z_{hfp} = \frac{v_{hfp}^p}{i_{hfp}^p} = \left( R_{hfp}^p + j\omega_{hfs} L_{hfp} \right) + \frac{\omega_{hfs}^2 M_{ps}^2}{(R_{hfs}^s + j\omega_{hfs} L_{hfs})} \]

\[ = R_{hf} + j\omega_{hf} L_{hf} \]

\[ R_{hf} = R_{hfp}^p + \frac{\omega_{hfs}^2 M_{ps}^2 R_{hfs}^s}{R_{hfs}^s + \omega_{hfs}^2 L_{hfs}^2} \]

\[ R_{hf} = R_{hfp}^p + \frac{\omega_{hfs}^2 M_{ps}^2}{R_{hfs}^s} \]

\[ R_{hfs}^p = \frac{\omega_{hfs}^2 M_{ps}^2}{R_{hfs}^s} = R_{hf} - R_{hfp}^p. \]
\[ P = Ke^\frac{(B_mf_{hf})^2}{\rho} \]
\[ \delta = \sqrt{\frac{2\rho}{2\pi f_{hf}\mu_0\mu_r}} \]
\[ f_{hf_{\text{max}}} = \frac{2\rho}{2\pi \delta^2 \mu_0\mu_r}. \]

Table 2

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>Height (mm)</th>
<th>Radius (mm)</th>
<th>( \mu_r )</th>
<th>( \rho ) (( \Omega )m)</th>
<th>( f_{hf_{\text{max}}} ) (KHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NdFeB</td>
<td>5</td>
<td>10</td>
<td>1.05</td>
<td>1.44e-06</td>
<td>6.6</td>
</tr>
<tr>
<td>SmCo</td>
<td>5</td>
<td>10</td>
<td>1.05</td>
<td>85e-06</td>
<td>4.0e2</td>
</tr>
<tr>
<td>Ferrite</td>
<td>5</td>
<td>10</td>
<td>1.05-1.10</td>
<td>1e3-1e4</td>
<td>2.0e3</td>
</tr>
</tbody>
</table>

Fig. 3. Ferrite, SmCo, and NdFeB disks.
EXPERIMENTAL RESULTS

A. Signal Injection

Fig. 4. H-bridge power converter.

Fig. 5 Control block diagram of the dc and high-frequency signal injection.
Fig. 6. (a) Induced voltage ($v_{Lp}$) and (b) corresponding frequency spectrum. $I_{dc}=12\text{A}, f_{hf}=250\text{Hz}$ and $V_{hf}=10\text{V}$

Fig. 7. (a) Induced coil current ($i_{Lp}$) and (b) corresponding frequency spectrum. Same operating conditions as in Fig. 9.
Fig. 8. Estimated high-frequency resistance $R_p$ of the iron powder core $hfs$ when the air-gap is equivalent to the height of the magnet and when there is no core $- f_{hf} = 250$ Hz and $V_{hf} = 0.05$ p.u.
C. Magnetoresistance Effect in Demagnetized Samples

Fig. 9. Simplified representation of the experimental setup
(a) when the magnet is removed and
(b) when the magnet is inserted. Placement of field sensor is indicated.

Fig. 10. Coil-reflected magnet high-frequency resistance, $R_{pf}$ of a ferrite $\diamondsuit$, NdFeB $\bigcirc$, and SmCo disks. $f_{hf} = 250$ Hz and $V_{hf} = 0.05$ p.u.
### D. Magnetoresistance Effect in Magnetized Samples

#### TABLE 3
MAGNETIZATION CIRCUIT PARAMETERS

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>External source max. voltage</td>
<td>750 V</td>
</tr>
<tr>
<td>Capacitor “C”</td>
<td>11750 μF</td>
</tr>
<tr>
<td>Diode “D”</td>
<td>1000 V, 1250 A</td>
</tr>
<tr>
<td>IGBT</td>
<td>1700 V, 1400 A</td>
</tr>
<tr>
<td>Coil “L”</td>
<td>1960 turns</td>
</tr>
</tbody>
</table>
E. Magnetoresistance in Magnetized Samples Combined With Flux-Weakening and Flux-Intensifying Current

Fig. 11. FEA results showing the magnetic flux density when the dc current injected in the coil (a) intensifies and (b) weakens the magnet flux.

Fig. 12. Coil-reflected magnet high-frequency resistance for different values of the remanent field, and no dc current. For ferrite (●), NdFeB (○), and SmCo (ρ) disks $f_{hf} = 250$ Hz and $V_{hf} = 0.05$ p.u.
Fig. 13. Schematic representation of the circuit used for PM magnetization and demagnetization.

Fig. 14. Coil reflected magnet high-frequency resistance for NdFeB magnets versus the flux density, for different values of the remanent field. $f_{hf} = 250$ Hz and $V_{hf} = 0.05$ p.u.

Fig. 15. Coil-reflected magnet high-frequency resistance for a ferrite magnet versus the flux density, for different values of the remanent field. $f_{hf} = 250$ Hz and $V_{hf} = 0.05$ p.u.
Fig. 16. Coil-reflected magnet high-frequency resistance for a SmCo magnet versus the flux density, for different values of the remanent field. \( f_{hf} = 250 \) Hz and \( V_{hf} = 0.05 \) p.u.

Fig. 17. Coil-reflected magnet high-frequency resistance in 5- and 2.5-mm NdFeB-segmented magnets when magnets are electrically isolated and ◼, and when there is no electric isolation ○ and ♦.
Fig. 18. Coil-reflected magnet high-frequency resistance in 5-mm SmCo-segmented magnets when magnets are electrically isolated and when there is no electric isolation.

Fig. 19. Segmented magnet arrangements (SmCo and NdFeB).
**F. Magnetoresistance Effect in Segmented Magnets**

Fig. 20. Coil-reflected magnet high-frequency resistance, \( R_p \) of nonisolated hfs segmented (5 mm) NdFeB magnets. \( f_{hf} = 250 \text{ Hz} \) and \( V_{hf} = 0.05 \text{ p.u.} \)

Fig. 21. Coil-reflected magnet high-frequency resistance, \( R_p \) of nonisolated hfs segmented (5 mm) SmCo magnets. \( f_{hf} = 250 \text{ Hz} \) and \( V_{hf} = 0.05 \text{ p.u.} \)
EQUIVALENCE WITH A PMSM

Fig. 22. Equivalent $d$-axis high-frequency model of a PMSM.
<table>
<thead>
<tr>
<th>Variables in the experimental setup high frequency model</th>
<th>Variables in the PMSM high frequency model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{hp}'$ : primary high frequency voltage</td>
<td>$v_{dhh}':$ stator $d$-axis high frequency voltage</td>
</tr>
<tr>
<td>$i_{hp}'$ : primary high frequency current</td>
<td>$i_{dhh}'$ : stator $d$-axis high frequency current</td>
</tr>
<tr>
<td>$L_{hp}'$ : primary high frequency self-inductance</td>
<td>$L_{dhh}':$ $d$-axis high frequency inductance</td>
</tr>
<tr>
<td>$R_{hp}'$ : primary high frequency resistance</td>
<td>$R_{dhh}':$ stator $d$-axis high frequency resistance</td>
</tr>
<tr>
<td>$R_{hFFE}'$ : core high frequency resistance</td>
<td>$R_{dhhFFE}'$: stator core $d$-axis high frequency resistance</td>
</tr>
<tr>
<td>$i_{bh}'$ : magnet high $i_{arh}'$ frequency current</td>
<td>$i_{dhh}'$: rotor core and magnet $d$-axis high frequency current</td>
</tr>
<tr>
<td>$M_{ps}$ : mutual coupling between the primary and the secondary</td>
<td>$M_{Dd}$ : mutual coupling between stator $d$-axis and rotor $d$-axis</td>
</tr>
<tr>
<td>$L_{hsf}$ : secondary high frequency self-inductance</td>
<td>$L_{dhh}':$ magnet high frequency self-inductance</td>
</tr>
<tr>
<td>$R_{hsf}'$ : secondary high frequency resistance</td>
<td>$R_{dhh}':$ magnet high frequency resistance</td>
</tr>
<tr>
<td>Does not exist in the experimental setup</td>
<td>$R_{hFFE}'$: rotor core $d$-axis high frequency resistance</td>
</tr>
</tbody>
</table>
This paper has presented a method to estimate the PM magnetization state, using the relationship between the PM electrical high-frequency resistance and the PM magnetization state.

The proposed method has been evaluated using NdFeB, SmCo, and ferrite magnets, which are the most commonly used magnets in electrical machines.

Experimental verification has been conducted in an experimental setup using a simple geometry.

This is advantageous for the analysis of the phenomena occurring in the magnet and the validation of the method.

It has been concluded that the magneto-resistive can be used for magnetization state estimation in machines equipped with NdFeB, SmCo, and ferrite magnets.

It has also been shown that the estimated high-frequency resistance can be potentially used to distinguish between permanent and temporal demagnetization, which is an important feature for fault prediction purposes.

CONCLUSION
REFERENCES


THANK YOU