

ELSYS Note



Iron Losses in PMSMs

This note provides an overview of iron losses in a Permanent Magent Synchronous Machine (PMSM) and explains how to incorporate these losses into an extended motor model. By integrating iron losses into the equivalent circuit of a PMSM, both the accuracy of simulations and the efficiency of the control strategy can be enhanced.

Introduction

PMSMs are widely used in electric vehicles due to their combination of high efficiency, power density, torque characteristics and overall reliability. To achieve energy efficient control of a PMSM, electrical losses must be considered when developing a motor control strategy. With increasing speed, the contribution of iron losses to total electrical losses increases and is likely to exceed the contribution of copper losses at some point. This note introduces iron losses to the equivalent circuit of a PMSM in order to enable the implementation of more accurate and energy efficient torque control.

Iron losses

In electrical machines, iron losses are typially categorized into three types: eddy current losses, hysteresis losses and excess losses.

Eddy current losses refer to the resistive heating losses caused by eddy currents flowing in the electrically conductive laminations. These eddy currents are induced by voltages generated in the stator laminations due to the rotating magnetic field of the rotor. Hysteresis losses result

from the displacement of the Weiss districts and the Bloch walls that surround these districts during the magnetization process of the stator material. Furthermore, hysteresis losses are influenced by the degree of magnetic saturation and the type of lamination used. Materials with lower magnetic coercivity generally exhibit lower hysteresis losses. The last and smallest part of the iron losses are the excess losses. They are caused by local eddy currents flowing because of the abrupt changes in Bloch walls. Due to their small contribution, the excess losses are often neglected [1].

Consequently, the total iron losses $p_{\rm Fe}$ can be approximated as the sum of hysteresis $p_{\rm H}$ and eddy current losses $p_{\rm E}$. Given a sinusoidally varying magnetic flux density with the amplitude \hat{B} and the electrical frequency f, this yields:

$$p_{\rm Fe} = p_{\rm H} + p_{\rm E} = k_{\rm h} \, \hat{B}^{\beta} \, f + k_{\rm e} \, \hat{B}^2 \, f^2.$$
(1)

 $k_{\rm H}$, $k_{\rm E}$ and β are constants depending on the lamination material [2].

Equivalent circuit

To enable motor control of a PMSM, the quantities of the underlying three phase system are transformed into a two phase system with a direct (d) and a quadrature (q) component. The d-axis aligns with the rotor's magnetic flux, while the q-axis is perpendicular. Both are rotating with the electrical angular velocity ω . Assuming a PMSM with saliency, the equivalent circuit of a PMSM in the dqreference frame is given in Fig. 1.





Eq. (2) through (5) fully describe the equivalent circuit in Fig. 1. All quantities are represented in the stator reference frame.

$$v_{\rm d} = R_{\rm s} \, i_{\rm d} + \frac{d\psi_{\rm d}}{dt} - \omega \, \psi_{\rm q} \qquad (2)$$

$$v_{\rm q} = R_{\rm s} \, i_{\rm q} + \frac{a\psi_{\rm q}}{dt} + \omega \, \psi_{\rm d} \qquad (3)$$

- $\psi_{\rm d} = L_{\rm d} \, i_{\rm d} + \psi_{\rm PM} \tag{4}$
- $\psi_{\mathbf{q}} = L_{\mathbf{q}} \, i_{\mathbf{q}} \tag{5}$

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Modelling iron losses

Overall, the iron losses lead to a weakening of the magnetic field and therefore a decline in the produced torque. To take this into account, a parallel resistor $R_{\rm dq,Fe}$ is added to the equivalent circuit. The resulting equivalent circuit is depicted in Fig. 2.





Fig. 2 Equivalent circuit considering iron los-

Consequently, the stator current i_{dq} consists of a torque-generating component $i_{dq,m}$ and a loss component $i_{\rm dq,Fe}$, i.e.

$$\boldsymbol{i}_{\mathrm{dq}} = \boldsymbol{i}_{\mathrm{dq,m}} + \boldsymbol{i}_{\mathrm{dq,Fe}}.$$
 (6)

Therefore, the equations for the flux linkages adapt as they are a result of the magnetization currents $i_{dq,m}$.

$$\psi_{\rm d,Fe} = L_{\rm d} \, i_{\rm d,m} + \psi_{\rm PM} \qquad (7)$$

$$\psi_{\rm q,Fe} = L_{\rm q} \, i_{\rm q,m} \qquad (8)$$

The loss component $i_{
m dq,Fe}$ flows through the iron loss resistance $R_{
m dq,Fe}$ and thereby models the iron count, the torque is calculated using

losses

$$\boldsymbol{p}_{\rm dq,Fe} = \frac{3}{2} (R_{\rm d,Fe} \, (i_{\rm d,Fe})^2 + R_{\rm q,Fe} \, (i_{\rm q,Fe})^2).$$
(9)

Furthermore, using Kirchhoff's voltage law, the voltage equations in the dq-system can be derived as

$$\begin{aligned} v_{\rm d} &= R_{\rm s} \, i_{\rm d} + \frac{d\psi_{\rm d,Fe}}{dt} - \omega \, \psi_{\rm q,Fe} \\ &= R_{\rm s} \, i_{\rm d} + R_{\rm d,Fe} \, i_{\rm d,Fe} \, , \\ v_{\rm q} &= R_{\rm s} \, i_{\rm q} + \frac{d\psi_{\rm q,Fe}}{dt} + \omega \, \psi_{\rm d,Fe} \\ &= R_{\rm s} \, i_{\rm q} + R_{\rm q,Fe} \, i_{\rm q,Fe} . \end{aligned}$$
(10)

Motor control

In most cases where torque control is employed, directly measuring the actual torque is often impractical due to cost or space limitations. As a result, closed-loop control of torque becomes unfeasible. Instead, setpoint modules are used to determine the reference currents for the current controllers. The calculations underlying the setpoint modules are based on the torque equation - see (12). Optimisation functions are used to calculate the ideal i_{dq} -pair under certain conditions, e.g. MTPA or Maximum Efficiency (ME) [1].

Assuming a PMSM with saliency, the torque equation is given in (12).

$$T_{\rm e} = \frac{3}{2} p \cdot (\psi_{\rm PM} i_{\rm q} + (L_{\rm d} - L_{\rm q}) \cdot i_{\rm d} i_{\rm q})$$
(12)

When iron losses are taken into ac-

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the torque-generating component of $i_{\rm dq}$, which corresponds to the magnetization current $i_{dq,m}$.

$$T_{\rm e,Fe} = \frac{3}{2} p \cdot (\psi_{\rm PM} \, i_{\rm q,m} + (L_{\rm d} - L_{\rm q}) \cdot i_{\rm d,m} \, i_{\rm q,m})$$
(13)

Neglecting iron losses in torque control therfore results in greater deviations from setpoint to actual torque. While i_{dq} can easily be measured during operation, $i_{\rm dq,m}$ can only be calculated if $R_{dq,Fe}$ is known. Here, it is important to emphasise that $R_{\rm dq,Fe}$ is a method of modelling the iron losses rather than an actual resistance. Unlike measuring $R_{\rm s}$ by applying Ohm's law to v_{dq} and i_{dq} , it is not easy to measure on a test bench. Values for $R_{dq,Fe}$ can either be obtained by FEM data or by test bench measurements [3].

Conclusion

Understanding iron losses is crucial for analyzing PMSM characteristics and developing efficient control strategies. In this note, iron losses are integrated into the equivalent circuit of a PMSM using a parallel resistor $R_{dq,Fe}$. Based on the extended circuit, the corresponding system equations are derived. The comparison of torque equations with and without consideration of iron losses highlights their importance in torque control. By accounting for these losses, the accuracy of simulations and the performance of control systems are improved.

Literature

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