Analysis of Simulated Iron Losses in Electrical Machines by Using Different Iron Loss Models

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Abstract - For the simulation of electrical machines different iron loss models can be used. These models differ in their ability to consider various effects. Especially the effect of rotational magnetic flux density loci in certain geometric locations of a machine is often disregarded by conventional iron loss models. Adapted and further developed models as the rotational IEM formula incorporate the rotating characteristics of the magnetic flux into their formulation. In this paper the simulated iron losses using four different iron loss models in various geometric locations are calculated and analysed.

I. INTRODUCTION

Quantifying the efficiency of electrical machines by simulation requires accurate loss models at the development stage. In particular, iron losses are gaining importance in magnetically highly utilized machines and high-speed applications. To model the iron losses various model approaches are in common use. The range of values and the level of detail of the individual models differ widely in some cases. Depending on the operating point and the geometric location of the machine this may result in differences in the simulated and calculated iron losses as it is demonstrated in this paper.

II. IRON LOSS MODELS

For the calculation of the iron losses in this paper four different methods and approaches are considered. Three of them calculate the iron loss density in the frequency and one of them in the time domain. A frequency domain iron loss model was given by a modified Bertotti model [1], [2]:

\[ P_{Fe,Bertotti} = k_{hyst} B_m^a f + k_{cl} B_m^2 f^2 + k_{exc} B_m^{1.5} f^{1.5}, \]

(1)

where \( k_{hyst} \), \( k_{cl} \), \( k_{exc} \) are the hysteresis, eddy current and excess loss factors fitted to the measurements [2], \( B_m \) the magnetic flux density, \( f \) the frequency and \( \alpha \) an additional loss parameter. The strength of this model is its comprehensive physical explanation. A disadvantage of the Bertotti model is that it underestimates the losses at high magnetic flux densities and high frequencies, which is crucial in modern machine designs [3]. The second loss model improves the loss determination at high magnetic flux densities and frequencies. It is based on the Bertotti model and adds an additional term considering the non-linear material behaviour [3]. This IEM-formula is given by:

\[ P_{Fe,IEM} = a_1 B_m^{a+\beta_m} f + a_2 B_m^2 f^2 + a_3 B_m^{1.5} f^{1.5} + a_4 a_5 B_m^{a+2} f^2, \]

(2)

where \( a_1 \), \( a_2 \), \( a_3 \) are the hysteresis, eddy current and excess loss factors and \( a_2 \) and \( a_4 \) are loss parameter describing the non-linear saturation losses. The IEM-formula, as well as the Bertotti model, have still the disadvantage that they do not consider rotational magnetization and were developed for unidirectional magnetization. To overcome this drawback the third iron loss model is introduced in [4] and given by:

\[ P_{Fe,IEM,rot} = (1 - r_{hyst} f_{Ax}^2) (a_1 + a_{1,90°} f_{Ax}^{a+\beta_m}) B_m^{a+\beta_m} f + a_2 (1 + f_{Ax}^2) B_m^2 f^2 \]

\[ + (1 - r_{exc} f_{Ax}^2) (a_9 + a_{5,90°} f_{Ax}^{1.5}) B_m^{1.5} f^{1.5} \]

\[ + a_2 a_3 (1 + f_{Ax}^{a+2}) B_m^{a+2} f^2 \]

(3)

where \( a_4 \) and \( a_5 \) are the hysteresis and excess loss parameters in rolling, \( a_{1,90°} \) and \( a_{5,90°} \) those in transvers direction, and \( r_{hyst} \) and \( r_{exc} \) are 2D-loss parameters. The variable \( f_{Ax} \) describes the axis ratio of the rotational magnetization.

The loss model calculating the iron loss density in the time domain is introduced in [5]. The loss density results from the time average of the hysteresis \( P_{hyst}(t) \), eddy current \( P_{cl}(t) \) and excess loss \( P_{exc}(t) \) density and can be described by:

\[ P_{Fe,Dyn} = \frac{1}{T} \int_{t=t_0}^{t=t_0+T} (P_{hyst}(t) + P_{cl}(t) + P_{exc}(t)) \, dt \]

(4)

where, \( t_0 \) is an arbitrary time and \( T \) the time period of the electromagnetic field. In a certain geometry the individual loss components can be calculated by considering the flux density \( B_{rd} \) in the rolling direction and the flux density \( B_{td} \) in transvers direction of the material:

\[ P_{hyst}(t) = \frac{\| H_{irr} \| dB_{rd} \| dt \|}{\| H_{irr} \| dB_{td} \| dt \|}, \]

(5)

\[ P_{cl}(t) = \frac{k_{cl}}{2 \pi^2} \left( \| dB_{rd} \| \right)^2 + \left( \| dB_{td} \| \right)^2, \]

(6)

\[ P_{exc}(t) = \frac{k_{exc}}{C_e} \left( \| dB_{rd} \| \right)^2 + \left( \| dB_{td} \| \right)^2 \cdot 0.75, \]

(7)

where, \( k_{hyst}, k_{cl}, k_{exc} \) are the loss parameters of the Bertotti model. The irreversible component of the magnetic field strength \( H_{irr} \) is given by:

\[ H_{irr}(\theta) = \pm \frac{k_{hyst}}{C_a} \cdot \| B_m \| \cos(\theta) \| \alpha^{-1}, \]

(8)

with \( C_a = 4 \int_0^{\pi/2} \cos^\alpha \theta \, d\theta, \ \theta = \arcsin \left( \frac{B}{B_m} \right) \) and \( \alpha \) being the loss parameter of the Bertotti model.
III. EXEMPLARY MACHINE

The proposed iron loss models are used in a Finite Element Method simulation of an exemplary aluminum die-cast squirrel cage induction machine (IM). The iron loss density in three different locations (P3, P2 and P4) of the stator lamination are calculated. The cross sectional area and the different geometric positions are shown and defined in Fig. 1. Location P3 is in the middle of the stator tooth where an unidirectional magnetic flux achieves. Location P2 is located at the transition from the stator tooth to the stator yoke where typically rotational magnetization occurs. Location P4 is at the stator tooth tip, where high harmonics of the flux density occure. The flux density locus at all three locations for an exemplary operating point are depicted for one electrical stator period in Fig. 2. At this operating point the IM has a stator frequency of \( f_s = 86 \text{ Hz} \), a stator slot current density of \( J_s = 7 \text{ A/mm}^2 \) and a rotor current frequency of \( f_r = 4 \text{ Hz} \). The sampling frequency is choosen to \( f_{\text{samp}} = 20 \text{ kHz} \) to consider the losses due to high harmonics as explained in [6].

IV. IRON LOSS SIMULATION RESULTS

The iron loss parameters for the different loss models are determined by measurements and are noted in [4]. For the loss models in the frequency domain the amplitudes and frequencies of the harmonic components are calculated by applying the Fourier transformation. The flux density \( B_m \) for each order is the maximum magnitude of the magnetic flux density vector. The resulting specific iron loss densities at the location P3, P2 and P4 considering the four proposed loss models are given in Fig. 3. In the case of unidirectional magnetization at location P3, the loss densities calculated by (2) and (3) are equal and slightly higher than those of (1) and (4). The different hysteresis losses by (1) and (4) at each location results from the harmonic part of the flux density which are overestimated by (4). At the location P2 of rotational magnetization, the calculated hysteresis, eddy current and excess losses by the rotational loss model (3) are higher than those of (1), (2) and (4). This results from the consideration of the rotating flux density curve by using the axis ratio \( f_{\text{Ax}} \) and the parameters \( r_{\text{hystr}} \) and \( r_{\text{exc}} \). The losses at location P4 are higher than in P2 and P3 due to the high number of harmonics. The effect of the rotational flux density is not as high as in P2 and therefore the difference between (2) and (3) is lower than in P2.

IV. CONCLUSION AND FURTHER WORK

The simulation of the iron losses of an IM in this paper shows that the differences in the calculated losses considering four different iron loss models depend on the geometric location. Models such as Bertotti and the IEM formula do not consider the effect of a rotational flux density curve on the losses, while the rotational IEM formula does. In further work, the iron loss simulations of the IM will be analysed in more detail. The losses at different operating points with different and especially higher saturation states and frequencies will be analysed. Also, the differences of the iron losses calculated with the proposed models in the entire stator and rotor laminations and for the entire operating range of the IM will be considered.

REFERENCES


