Magnetic loss measurement of surface-mounted permanent magnet synchronous machines used in explosive environments

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Abstract: High energy-efficient permanent magnet synchronous machines (PMSMs) with low manufacturing costs and easy controllability are in high demand for the automotive and aerospace industries and in explosive environments (hazardous areas) like mines and the petrochemical industries. In explosive environments, the high surface temperature of PMSMs, due to magnetic losses and the irreversible demagnetisation of permanent magnets (PMs), could be a source of ignition leading to explosions. Therefore, this paper presents magnetic losses of a PMSM, which will help engineers to design robust machines with a high tolerance to explosive environments. Analytical calculations and finite element method (FEM) simulations of the magnetic losses of a PMSM are presented and compared with measured values from testing a PMSM.

1 Introduction

In order to prevent effective sources of ignition in PMSMs with the ‘Increased Safety’ ignition protection classification, the temperatures in a stator and rotor [1, 2] should not be high in normal operation and during operation when faults occur. Mostly, a PMSM is driven by an inverter with modulated voltage, which causes additional current harmonics resulting in losses in PMs. The losses cause an increase in temperature in turn causing a higher temperature of the stator winding which could be a source of ignition. The accurate analysis and measurement of the magnetic losses and the rotor temperature are a must for the evaluation of explosion protection relating to a PMSM.

Numerous methods for the analytical and finite element analysis (FEA) calculations of magnetic loss (eddy current losses) in the PMs of surface permanent magnet synchronous motors (SPMSMs) and interior permanent magnet synchronous motors (IPMSMs) are presented in the following papers [3–5]. However, little research work has been done on magnetic loss measurement in PMs of SPMSMs and its validation with analytical and FEA methods. This paper intends to study the basic measurement methods for the estimation of the magnetic losses of SPMSMs with squirrel cage rotors that are used in explosive environments. Here, the authors will first present the influence of high-frequency time harmonics generated in a PMSM fed by a pulse-width-modulated inverter with rotor temperature measurement. Second, the analytical and FEM calculations of magnetic losses are presented for PMs in a PMSM which has a squirrel cage rotor and is used in explosive environments. Subsequently, the PM loss estimation from the measured losses and from the measured rotor temperatures is presented and compared. Finally, analytical and FEM calculation results are compared with the measured magnetic losses of the PMSM.

2 Rotor temperatures of the PMSM due to high-frequency time harmonics generated in an inverter-fed PMSM during normal operation

The PMSM under operation could suffer demagnetisation because of various reasons such as different faults in the PMSM, overheating of the rotor with the PMs and mechanical shock etc. The PM rotor temperature of the PMSM, due to high-frequency time harmonics generated in the inverter fed PMSM during normal operation, is measured and presented. This approach provides a limited insight into a comprehensive understanding of the local demagnetisation behaviour within a magnet with an increasing environmental temperature.

The rotor temperature of the PMSM fed by a pulse-width modulated (4 kHz) inverter is measured after the machine is thermally stable. The heat run test or the continuous operation of the machine at a rated load is assumed to be thermally stable if the temperature increases below 2 K/h at the hottest point from the different measured positions of machines such as the stator housing, bearing etc. [2]. Here, the stator temperature and rotor temperature are directly measured as shown in Fig. 1a. The rotor temperature is measured using an online telemetry system which can measure temperature in continuous operation. The measured rotor temperature is shown in Fig. 1b for the varying speed of the PMSM.

The PMSM fed with the inverter is prone to a high-frequency time harmonics current which increases the eddy current in the PM. The eddy-current loss is proportional to the frequency squared, making it much more susceptible to leakage harmonic components which are several times higher than the operating frequency [6]. Fig. 2 shows the current wave form for 4 kHz which has higher current harmonics and is clearly visualised in the fast Fourier transformation (FFT) spectrum.

3 Analytical calculation, 2D and 3D finite element analysis model of PMSM in normal operation

3.1 Analytical calculation and 2D FEM simulation of the PMSM in normal operation

The analytical calculation and the 2D FEM simulation of eddy-current losses in the PM of an SPMSM with a squirrel cage rotor as shown in Figs. 3a and c are presented in this section. The PMSM is a four-pole machine with 7.5 kW rated power, 47.8 Nm rated torque, and 1500 rated speed. The Cartesian coordinate system was used with the following assumptions for the analytical calculation of PM losses [3–5]:

- (i). The relative permeability of iron is considered infinite ($\mu_r = \infty$).
- (ii). Only the normal component of the flux density $B_n$ is considered ($B_x$ and $B_y$).
(iii). Only the components of current density along the x- and z-axes ($J_x$ and $J_z$) are considered ($J_y$)

(iv). The effect of stator slotting is neglected.

The eddy-current losses in each PM segment with an air-gap length $\delta$, width of magnet $a$, magnet thickness $d$, effective air gap $\delta_e = \delta + d$, conductivity of magnet $\sigma$, magnet segmentation $m$, and number of PM segmentation $n$, according to paper [5], are calculated as:

$$P_{PM} = \frac{32}{\pi} \sum_{n=1,3,5,7,\ldots} \sin \left( \frac{n\pi x}{a} \right) \sin \left( \frac{n\pi y}{a} \right) \times \frac{1}{(bn)^2} \left( \frac{1}{(am)^2} \right)$$  \hspace{1cm} (1)

where $B_{sm}$ is the maximum value of the magnetic flux density $B$ which is described in detail in paper [5].

The magnetic source field in the x- and z-directions is:

$$B_s = \frac{16}{\pi^2} \sum_{n=1,3,5,7,\ldots} \sum_{m=1,3,5,7,\ldots} \frac{1}{n \cdot m} \sin \left( \frac{n\pi x}{a} \right) \sin \left( \frac{m\pi z}{b} \right) \cos \left( \frac{n\pi x}{a} \right) \cos \left( \frac{m\pi z}{b} \right)$$  \hspace{1cm} (2)

For the analytical and 2D FEM calculations of magnetic losses, (1) is used. For the analytical calculation, $B_s$ is calculated with the geometrical information of the SPMSM, whereas for the 2D FEM, $B_s$ is generated in tabular data from Opera 2D simulation software.

### 3.2 3D FEM simulations

One of the aims of this study was to validate the analytical calculation of magnetic losses with 2D and 3D FEM simulations. The 3D FEM simulation of the PM losses in the PMSM is calculated by considering the induced eddy current $J_e$ with a volume integral as in (3). The comparison of the analytical, 2D and 3D FEM calculations of the PM losses is presented in Table 1.

$$P_{PM} = \int_{V_e} \frac{J_e^2}{\sigma} \, dV_e$$  \hspace{1cm} (3)

### 4 Measurement of different losses in the PMSM for determining permanent magnetic losses

#### 4.1 Electrical and mechanical power losses for direct efficiency measurement

Here, a direct method for determining the efficiency (IEC/EN 60034-1 [7]) is used, even though there is a small percentage of...
The mechanical output power, determining the efficiency (\( \eta \)), is determined by measuring the overall mechanical speed \( \pi n M \), is determined by measuring the measured output power (mechanical power) \( P_{\text{out}} \) versus input power (electrical power) \( P_{\text{in}} \) is used for determining the efficiency (\( \eta \)) of PMSMs in the direct efficiency measurement method. The nameplate values of the machine studied are shown in Table 2. The mechanical output power, \( P_{\text{out}} = 2\pi n M \), is determined by measuring the overall mechanical speed and the mechanical torque of the motor using the torque and speed transducers. The electrical input power \( P_{\text{in}} = 3 U \cdot I \cos \phi \) is used for measuring the input power and iron loss \( P_{\text{Fe}} \) of the PMSM is measured with a replica rotor with PMs and the efficiency of the PMSM are measured using the power analyser and are shown in Table 3.

### Table 1: Comparison of the PM loss calculation using different methods

| Current                      | Analytical method, W | 2D FEM, W | 3D FEM, W |
|------------------------------|----------------------|-----------|-----------|
| fundamental (50 Hz)          | 1.25                 | 1.31      | 1.70      |
| fundamental + harmonics with 4 KHz | 17.33               | 23.98     | 30.37     |
| fundamental + harmonics with 6 KHz | 18.79               | 21.05     | 23.61     |

### Table 2: Rated nameplate values of the tested motor

| Parameter                  | Value          |
|----------------------------|----------------|
| Nominal power, \( P \)     | 7.5 kW         |
| Nominal voltage, \( U \)   | 356 V          |
| Nominal current, \( I \)   | 13.5 A         |

### Table 3: Electrical input power and mechanical output power measurement at rated torque and 500, 1000 and 1500 rpm with switching frequencies of 4 KHz

| \( U \), V  | \( I_{\text{m}}, A \) | \( P_{\text{in}}, w \) | \( F \), Hz | \( N \), rpm | \( M \), Nm | \( P_{\text{mech}}, w \) | \( H \), % |
|-------------|----------------------|----------------------|-------------|-------------|-------------|----------------------|----------|
| 124.10      | 13.62                | 2939.8               | 16.66       | 500.10      | 47.89       | 2508.04              | 85.31    |
| 236.49      | 13.73                | 5590.5               | 33.3        | 1000.0      | 47.8        | 5006.7               | 89.5     |
| 348.66      | 13.81                | 8246.1               | 50.00       | 1500.17     | 47.80       | 7509.8               | 91.07    |

4.2 Indirect loss measurements

This paper presents an indirect method for determining losses (IEC/EN 60034-2-1 [8]) with modifications for PMSMs. The new standards, IEC 60034-2-2 [9] and IEEE1812 [10], which are currently in their test phase (trial use) as well as being under review, have been considered here for measuring the different losses of the PMSM. The loss summation methods, as described in papers [11] and [12], are used in this section for different loss measurements. The method offers an effective way of measuring losses and it is a simple one to perform. The procedure of loss measurement using indirect methods is summarised in Table 4:

4.2.1 No-load test: friction and windage losses, no-load iron, and additional losses: The mechanical losses (friction and windage losses) of the PMSM are measured using a replica rotor which is identical to the mass of the PM rotor. In the replica rotor, the PMs are normally replaced by identical metallic materials of the same mass with a zero magnetic field. The machines without magnetising rotors are coupled with the DC motor, and open circuit testing is performed at different speeds. The mechanical losses, \( P_{\text{Fe}} \), as shown in Fig. 4a, are calculated by using the measured torque \( M_{\text{nm}} \) (\( M \) from non-magnetised rotor) and speed \( N \) (from non-magnetised rotor) values using torque and speed transducers, respectively.

\[
P_{\text{Fe}} = \frac{2\pi \times n_{\text{nm}} \times M_{\text{nm}}}{60} \tag{4}
\]

The no-load iron losses are determined during open circuit testing with a magnetising rotor after the mechanical losses \( P_{\text{mech}} \) are separated from the mechanical output power \( P_{\text{mech}} = (2\pi \times n_{\text{x}} \times M_{\text{L}})/60 \) Here, torque \( M_{\text{L}} \) and speed \( n_{\text{x}} \) (from rotor with PMs) are measured by torque and speed transducers during open circuit testing. The no-load core losses \( P_{\text{60}} \) are calculated as:

\[
P_{\text{60}} = P_{\text{Fe/60}} - P_{\text{mech}} = \frac{2\pi \times n_{\text{x}} \times M_{\text{x}}}{60} - \frac{2\pi \times n_{\text{nm}}M_{\text{nm}}}{60} \tag{5}
\]

The additional no-load losses in inverter-fed PMSMs can be measured using the modern power analyser WT 3000 which is capable of measuring the first fundamental input power \( P_{\text{f0}} \) and the total effective power \( P_{\text{f0+1}} \). The measured addition no-load losses \( P_{\text{e1+2}} \) are shown in Fig. 4b which is calculated according to (6).

\[
P_{\text{e1+2}} = P_{\text{f0+1}} - P_{\text{f0}} \tag{6}
\]
In this section, the indirect loss determination method was used for the calculation of the different losses dependent on voltage, current, and speed with respect to no-load and load losses. The open circuit test, the removed rotor test, and the varying load test with an inverter fed PMSM were used for loss determination.

4.3 Validation of iron losses with FEM simulation

Here, the Steinmetz method was used for the calculation of the iron losses of stator and rotor cores using FEM simulations. Initially, the magnetic flux density was plotted in Opera 2D as in Fig. 3 and was exported in the form of tabular data. In Matlab, tabular data yielded by magnetic flux density were used to calculate the iron losses of the PMSM. The parameters in the Steinmetz model were unknown at the beginning, but those parameters could be identified by the Excel Solver tool with the measured data from the M450P-50K non-oriented electrical sheets. The iron losses based on the Steinmetz equations [13, 14] are separated into hysteresis $P_h$ and eddy current $P_{ec}$:

$$P_f = P_h + P_{ec} = \frac{K_n B_n^2}{p} + \frac{K_c B_{ec}^2}{p}$$  \hfill (9)$$

where $K_n$ is the hysteresis loss coefficient, $K_c$ is the eddy loss coefficient and the coefficient $n$ varies with the maximum flux density $B_m$. The coefficient $n$ depends on $B_m$ and varies depending on the frequency. For simplification, coefficient $n$ is expressed as a second-order polynomial function as in (10).

$$n = a B_m^2 + b B_m + c$$  \hfill (10)$$

where $a$, $b$, and $c$ must be determined from the main operating frequency.

For the proper calculation of the iron losses, the introduction of a process factor is required. The process factor should be considered for the iron losses as described in paper [15]. The comparison of the iron losses after the introduction of the process factor is shown in Fig. 5.

The deviation of the measured and simulated iron core losses in the PMSM can be compared using Figs. 4d and 5. The difference between the measurements and the FEM simulations is 23.14, 20.95 and 17.89% for 500, 1000 and 1500 rpm for M400-50 (0.5 mm non-oriented electrical steel sheet iron core) with switching frequencies of 4 kHz from the inverter supply.

5 PM loss estimation and measurement

5.1 PM loss estimation from direct and indirect loss measurements

Different losses present in the PMSM are measured indirectly and presented in Section 4.2. Normally, for low-rated power PMSMs, the mechanical losses of PMSMs are negligible. However, here, the mechanical losses are also measured to minimise the error for PM loss measurement. After all the losses have been measured using indirect methods, the PM losses are estimated with the help of the direct measurement of the input and output power losses.

The direct loss measurements are calculated using (11) in Section 4.2:

$$P_{losses\text{direct}} = P_{in} - P_{out} = P_{dc} - P_{mech} = 3U . I . \cos(\phi) - 2\pi . n . M$$  \hfill (11)$$

Fig. 4 Indirect loss measurement of PMSM
(a) Measured friction and windage losses of PMSM, (b) Additional no-load losses with inverter fed supply at no load, (c) Ohmic and additional losses for varying load current, (d) Iron losses in load test with inverter fed supply at no load

Fig. 5 Iron losses calculated using FEM simulation of the PMSM

4.22 Load test: current dependent stator ohmic and iron losses. A removed rotor test is performed to determine the stator ohmic losses $P_{einB}$ in the stator winding with the additional losses from the leakage flux in the stator winding as shown in Fig. 4c. The stator ohmic losses are obtained by subtracting the iron losses $P_{FeB}$ from the electrical input power $P_{einB}$ as described in papers [11] and [12]:

$$P_{cos} + P_{oad} = P_{einB} - P_{FeB} = P_{einB} - P_{rol} \left(\frac{U_{SB}}{U_s}\right)^2$$ \hfill \hfill (7)$$

where $U_{SB} = U_{sn} - R_{rol} I_{sn}$ is the reactance voltage which is calculated during removed rotor testing.

The iron losses are the combination of the eddy current and hysteresis losses, which are proportional to the square of the magnetic flux density as shown in (9). It is known that the magnetic flux density is proportional to the induced voltage. This leads us to conclude that the iron losses are proportional to the square of the reactance voltage $U_s = U_{sn} - R_{r} I_{sn}$, where $U_s$ and $I_s$ are the stator voltage and current, respectively. Therefore, the load currents dependent on the iron losses $P_{Fe}$ shown in Fig. 4b are calculated in [11] and [12] as:

$$P_{Fe} = P_{rol} \left(\frac{U_s}{U_s}\right)^2$$ \hfill (8)$$

In this section, the indirect loss determination method was used for the calculation of the different losses dependent on voltage, current, and speed with respect to no-load and load losses. The open circuit test, the removed rotor test, and the varying load test with an inverter fed PMSM were used for loss determination.


The PM loss in a single PM is determined using the measured temperature curve of the PM and the material properties of the PM as:

$$P_{PM_T} = \rho \times c \times \frac{\Delta \theta}{\Delta \theta} \times \left( \frac{W}{m} \right)$$  \hspace{1cm} (14)

where \( \rho \) is the specific mass density \((kg/m^3)\) of the PM, \( c \) is the specific heat capacity \((J/Kg)\) of the PM, and \( \Delta \theta/\Delta \theta \) is the rate of change of temperature \((K/s)\) which was directly taken from the measured temperature curve at the rated torque and speed as shown in Fig. 6. The total PM losses in the PMSM rotor are calculated as:

$$P_{PM,T} = N_{PM} \times \rho \times c \times V_{1,PM}(W)$$  \hspace{1cm} (15)

where \( N_{PM} = 36 \) is the total number of the PMs in the rotor of the PMSM and \( V_{1,PM} \) is the total volume \((cm^3)\) of the single PM.

5.3 Comparison of PM loss measurements

In this section, we present the comparisons of the PM losses that are obtained from estimating the loss measurement and temperature measurement for rated loads with varying speed. Different losses present in the PMSM are measured indirectly using two methods as shown in Fig. 6. \( P_{E} \) is the PM loss estimation with the help of loss measurement, whereas \( P_{T} \) is the PM loss measurement using the measured temperature in the PMs in the PMSM.

6 Comparison of analytical, FEM, and measurement results

The comparison of the PM losses of analytical, FEM, and measurement methods at a rated speed and current is shown in Fig. 8. The PM losses presented here are the difference of the input power with copper losses to stator and rotor iron losses and mechanical losses. The experimental setup as shown in Fig. 1a is used to measure the input power in the PMSM, and mechanical output power. A removed rotor test was used to measure the stator winding \( FR \) losses which was further used to measure iron losses with the help of no-load test FEM simulations. Almost negligible mechanical losses were also measured which shows very little influence in magnetic loss measurement. An inverter (Danfoss FC 302) is used to drive the test PMSM. The rated speed of 1500 rpm was reached with the rated current, and it was assumed that all losses result from \( FR \) and iron losses. The PM losses in the bar graph are presented with different methods for fundamental, 4 and 6 kHz switching frequencies. It is seen that the 3D FEM simulation is close to the measurement result. The measurement results are only available for 4 kHz inverter switching frequencies and, in future, measurements with 6 kHz are also planned.

7 Summary and conclusions

The findings of the research into PM loss estimation from measured losses and temperatures are quite convincing with FEM and analytical calculations. From the research that has been carried out to estimate and measure the PM losses in electrical machines, it is to be concluded that the simulation results could not be trusted fully without any validation from measurement. The proposed method for PM loss determination from temperature measurements in PMs can be readily used in practice. However, PM loss measurement with the help of loss summation needs better attention relating to the measurement uncertainty of individual measurement methods. On the basis of the promising findings of PM loss estimation through temperature measurements presented here, work on the remaining issues with 6 kHz switching frequencies of the inverter is continuing and will be presented in future papers. More tests and calculations will be needed to verify the PM losses which will be addressed in future research.
8 References

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