Influence of losses in steel on the specific values of field regulated reluctance machines and traction electric drive control system

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Abstract. The article considers the influence of losses in steel of Field Regulated Reluctance Machine (FRRM) on its specific values and the electric drive control system. Two methods of their determination are analyzed: analytical and field. The second method is preferable, since it requires less information about the properties of materials with the same accuracy in determining losses. It is shown that losses in steel shift the optimal control angle of the stator current vector towards the q-axis of the electric machine. The angle offset when the load is increased to three times is 5 electrical degrees. It is shown that when the load current increases, the losses in steel to eddy currents and hysteresis are equally dependent on induction. With three times the load, losses increase by 60%. As the speed increases, the eddy current losses from the current increase squared, and the hysteresis losses are almost linear. This indicates a different degree of dependence of the loss components on the speed. Regression dependences of losses on the load current and speed of FRRM are given.

1. Introduction

The purpose of the article is to determine the effect of steel losses on the specific values of FRRM and its control system.

The relevance of the topic lies in the possibility of a wide range of applications of FRRM in various fields of electric power and electrical engineering: starting with power plants of traction mechanisms and ending with various mechanisms of the metallurgical, metalworking industry and agriculture.

The problem of work is the insufficient level of research in the field of the impact of losses on the operation of the machine. Moreover, the loss of an electric machine directly determines its energy efficiency. Therefore, the main task of the work is to study the magnetic losses in steel for hysteresis and eddy currents created by the electromagnetic field of the FRRM.

In recent years, due to the wide capabilities of modern computer modeling, which allow us to find the most efficient versions of rotor and stator designs, FRRM are actively developing [1, 2].

To achieve high operating properties, the FRRM is designed to be powered by a frequency converter (FC), which, thanks to the built-in algorithm, eliminates the need for a damped short-circuited winding. In addition, the use of a frequency converter allows you to increase the speed range of rotation of the motor. The main advantages of FRRM are: simplicity of design due to the absence of a short-circuited winding and permanent magnets; low heating, due to the absence of losses in the rotor due to the lack of winding; high overload moments, since heating losses are reduced, the rated current of the motor can be overestimated; a small moment of inertia associated with the relative ease of the rotor; rigid
mechanical characteristics in an open system, which allows you to maintain speed at a given level with great accuracy; the ability to control speed in a wide range, due to the use of inverters. The main disadvantage of FRRM is a slight decrease in power factor, in comparison with an asynchronous electric motor (AM), due to the relatively high magnetizing current of a jet engine. This leads to the fact that the inverter for powering the FRRM must have a slightly higher current rating at the same power.

Magnetic losses, or losses in steel, occur in sections of a magnetic circuit with a variable magnetic flux - in the FRRM stator. These include hysteresis losses and eddy currents caused by the magnetization reversal of steel, as well as additional losses. In the general case, magnetic losses are calculated according to various varieties of the Steinmets formula, which in the classical form looks as follows:

\[ P = c \cdot f^\alpha \cdot B^\beta; \]  

(1)

where \( c \) – coefficient of specific losses; \( f \) – external magnetic field frequency, Hz; \( B \) – magnitude of the magnetic induction of the field, T; \( \alpha \) – coefficient depending on the properties of the ferrimagnetic material; \( \beta \) – a measure of the degree that takes into account the dependence of losses in steel on the frequency of remagnetization.

Each magnetic material has its own hysteresis loss proportional to the frequency of the magnetizing magnetizing field, as well as the area of the hysteresis loop of this material. To reduce hysteresis losses, magnetic materials are used whose coercive force is small, that is, materials with a thin hysteresis loop, for example, a special magnetically soft steel having a certain composition and structure can be used as the core material.

When a magnetic field is reversed in the body of a conductor located in this field, an EMF is induced, under the influence of which eddy currents (Foucault currents) arise. Losses caused by eddy currents depend on the electrical resistance of the magnetized magnetization material and on the configuration of the magnetic circuit.

2. Materials and Methods

**ANSYS Electronics Desktop** – this is a universal program that allows you to design and model various electrical, electronic and electromagnetic components, devices and systems. The studies were performed using supercomputer resources of South Ural State University [3]. Interface of ANSYS allows you to create virtual electromagnetic and thermal models of devices, develop system control models, establish relationships between projects. The nominal data of the test machine are presented in Table 1.

| Number | Parameter                        | Dimension | Value |
|--------|----------------------------------|-----------|-------|
| 1      | Rated power, \( P_n \)          | kW        | 16    |
| 2      | Rated speed, \( \omega_n \)     | rpm       | 1500  |
| 3      | Rated moment, \( M_n \)         | N·m       | 98    |
| 4      | Number of phases, \( mf \)      | –         | 6     |
| 5      | The number of pairs of poles, \( p \) | –       | 2     |
| 6      | The number of parallel branches, \( a \) | –     | 2     |
| 7      | Rated phase voltage, \( U_n \)  | V         | 150   |
| 8      | Rated current, \( I_n \)        | A         | 50    |
| 9      | Rated frequency, \( f_n \)      | Hz        | 50    |
| 10     | Outer diameter of the machine, \( D_n \) | mm    | 254   |
| 11     | Stator bore diameter, \( D \)   | mm        | 158   |
| 12     | The length of the active part of the machine, \( L \) | mm | 184   |
| 13     | The number of tines on the stator of the machine, \( Z_l \) | un. | 48    |
| 14     | Rotor outer diameter, \( D_R \)  | mm        | 157   |
| 15     | Rotor shaft diameter, \( D_V \)  | mm        | 64    |
3. Results
For stator core, electrical steel 2013 is used. It is cold-rolled isotropic steel sheet designed for magnetic circuits of electrical machines, apparatuses and devices. The main characteristics of steel 2013: resistivity $R = 140 \text{ Ohm} \cdot \text{m}$; material conductivity $\sigma = 7143857 \text{ Cm/m}$; density $\rho = 7850 \text{ kg/m}^3$; sheet thickness $d = 0,5 \text{ mm}$. Data on specific losses in steel are summarized in Table 2.

| $B$, T | 0 | 0.2 | 0.5 | 0.8 | 1 | 1.2 | 1.5 | 1.8 | 2 |
|-------|---|----|----|----|---|----|----|----|---|
| $P_{sp}$, W/m$^3$ | 0 | 0.1 | 0.625 | 1.6 | 2.5 | 3.6 | 5.6 | 8.1 | 10 |

For the rotor, electrical steel 2412 was used. This is a thin-sheet steel, the mass fraction of silicon in which is not normalized and is equal to 2.8 to 3.8 %. Key features for 2412 steel: resistivity $R = 500 \text{ Ohm} \cdot \text{m}$; material conductivity $\sigma = 2000000 \text{ Cm/m}$; density $\rho = 7650 \text{ kg/m}^3$; sheet thickness $d = 0,35 \text{ mm}$. Specific loss value for 2412 steel with sheet thickness $d = 0,35 \text{ mm}$ will be the same as for steel 2013 (Table 2).

In the ANSYS Maxwell environment, there are two ways to determine losses in steel: the analytical method (Core Loss), using the Steimetz equation; and the field method (Solid Loss), based on eddy current modeling technology. Both methods were used to determine the losses in steel of FRRM [4].

The calculation of Core Loss refers to the analytical method for determining losses and depends on the coefficients of the Steimetz equation calculated by the program. Core Loss consists of hysteresis losses, eddy currents, and additional losses [5].

$$ P_{coreloss} = K_c (f B_m)^2 + p_h = K_h f B_m^2; +p_e = K_e (f B_m)^{1.5}; $$

(2)

where $K_c$ – eddy current loss coefficient; $K_h$ – coefficient of loss per hysteresis; $K_e$ – coefficient for additional losses.

To calculate these losses and determine the necessary coefficients of the Steimetz equation, the material properties are set. The coefficients $K_c$, $K_h$, $K_e$ рассчитываются are calculated based on the magnetization curve $B = f (H)$.

There are two models for the analytical calculation of losses: Electrical Steel – this is a way of accounting for losses, as a kind of correction in the calculations without hysteresis modeling, without calculation of eddy currents as a field problem; Hysteresis Model – this is a hysteresis model in non-stationary solvers ANSYS Maxwell 2D and 3D for very accurate determination of losses in steel and simulation of hysteretic behavior of ferromagnets taking into account private loops. However, this method requires sufficient material properties data.

Losses Solid Loss, relate to the field method, in which it is necessary to determine the coercive force and the main magnetization curve. This model is well suited for non-sinusoidal excitation, since it takes into account the particular hysteresis loops. Losses Solid Loss depend on the conductivity of the material.

A feature of FRRM is the effect of steel losses on the control system. Without such a consideration, the drive’s specific torque deteriorates and the power factor decreases. To control the position of the rotor, a sensor is used, the signal from which is fed to the frequency converter.

To determine the effect of losses in the rotor and stator on the control system, we change the amplitude of the current supplied to the stator windings, fix the values and select the angle of rotation of the rotor corresponding to the maximum moment, taking into account the change in load. All changes were determined at a speed equal to the nominal 1500 rpm. The obtained data represented in Table 3.
Table 3. The angle of deviation of the current vector from the axis of the rotor.

| $I$, A | $\omega = 1500$ rpm | $M_{\text{av}},$ N\cdot m | $\alpha, ^\circ$ |
|--------|---------------------|--------------------------|--------------|
| 25     | 34.1                | 74                       |
| 100    | 233                 | 69                       |
| 150    | 327                 | 68                       |

According to the results obtained, it can be concluded that when the load increases, the angle of rotation of the rotor is shifted towards the q-axis of the engine, to maintain maximum torque. The shift of the angle when increasing the load to three times is 5 electrical degrees [6].

The study of the dependence of losses on time was carried out with a change in the amplitude of the current supplied to the stator and a change in the rotor speed. The values of eddy current losses calculated by the Solid Loss method are very close to the values obtained by the Core Loss method. Compare the data obtained when the load and speed (Table 4) in relative units.

Table 4. The results of calculation of losses in steel.

| When $\omega = 1500$ rpm | Solid Loss. r.u. | Hysteresis losses. r.u. | Eddy current loss. r.u. | Corel Loss. r.u. |
|--------------------------|------------------|------------------------|------------------------|-----------------|
| $I_H$                    | 1                | 1                      | 1                      | 1               |
| $0.5 \cdot I_H$          | 0.39             | 0.51                   | 0.48                   | 0.47            |
| $2 \cdot I_H$            | 1.42             | 1.32                   | 1.38                   | 1.34            |
| $3 \cdot I_H$            | 1.66             | 1.46                   | 1.62                   | 1.55            |

| When $I_H = 50$ A        | $0.1 \cdot \omega$ | 0.01                   | 0.007                  | 0.05            |
|--------------------------|---------------------|------------------------|------------------------|-----------------|
| $0.5 \cdot \omega$      | 0.25                | 0.49                   | 0.22                   | 0.58            |
| $2 \cdot \omega$        | 3.74                | 1.92                   | 3.72                   | 2.83            |

With an increase in the amplitude of the current supplied to the stator windings, the total losses increase by 60%. Under high-speed operating conditions, eddy current losses are the main component of total losses in steel. Eddy currents depend on the frequency square of the remagnetizing magnetic field, so when working in the high frequency region, they will make up the bulk of the losses in iron [7].

Eddy current losses calculated by the SolidLoss and Core Loss change the same when the load and speed change [8].

The graph of the dependence of losses on load changes in relative units is shown in Fig. 1. Analyzing the graph, you can see the similarity of the shape of the magnetization curve in coordinates B-H and the graph of the dependence of losses on hysteresis and eddy currents. This feature confirms the dependence of losses in steel on the value of induction, and the losses for hysteresis and eddy currents depend on the induction in approximately equal measure [9].
We approximate the obtained graphs and perform a regression analysis of the results. Let's find out which analytical dependence changes the losses. We get that when the load changes, the losses increase by the following function [10]:

$$P(I) = -0.01954 \cdot I^2 + 1.1032 \cdot I - 0.003,$$

where $I$ – amplitude of the current applied to the stator windings, r.u.; $P$ – magnetic losses, r.u.

Similarly, we will plot the change in speed losses (see Fig. 2) [11]. Analyzing the graph of the dependence of steel losses on speed, we can conclude that the eddy current losses from the current increase squared, and the hysteresis losses are almost linear [12]. This indicates a different degree of dependence of the loss components on the speed [13]. The total current loss depends on the current according to the regression relationship (3).

After approximation we get the function of changing the speed loss [14]:

$$P(\omega) = 1.0629 \cdot \omega^{1.44}$$

Figure 1. Graph of changes in load losses.

Figure 2. Graph of changes in speed losses.
The power factor values were also calculated for changes in the load and speed of rotation of the rotor. The nominal data corresponds to \( \cos \phi = 0.72 \) [15], the Graph of \( \cos \phi \) changes in relative units with changes in load and speed is shown in Fig. 3 [16].

![Graph of power factor changes from load and speed](image)

**Figure 3. Graph of power factor changes from load and speed.**

4. Discussion
In the proposed traction electric drive, the best power factor is obtained in the nominal operating mode. Low values at overload are explained by a large magnetization current due to saturation of the magnetic system. At low loads with a constant excitation current the proportion of active power to full power decreases.

It was found that in a traction electric drive, when the speed changes, the reactive and active powers change linearly, but because of the difference in the values of the proportionality coefficients, the power factor increases slightly with increasing speed.

5. Conclusions
According to the results of the study, we can draw the following conclusions:

1. It is shown that in electric drives of traction mechanisms, losses in steel shift the optimal angle of control of the stator current vector towards the q-axis of the electric machine. The shift of the angle when increasing the load to three times is 5 electrical degrees;
2. It is shown that for electric drives of traction mechanisms with increasing load current, losses in steel due to eddy currents and hysteresis are equally dependent on induction. With a triple load, losses increase by 60%;
3. It is shown that with an increase in the speed of the traction electric drive, the losses due to eddy currents from the current increase in the square, and the losses due to hysteresis are almost linear. This suggests a different degree of dependence of the loss components on speed.

References
[1] Men’shenin A S and Grigor’yev M A 2018 *Russian Electrical Eng.* **89(4)** 228
[2] Grigor’yev M A 2017 *Russian Electrical Eng.* **88(4)** 189
[3] Belykh I A and Grigor’yev M A 2018 *Russian Electrical Eng.* **89(4)** 234
[4] Gryzlov A A, Grigor’yev M A and Imanova A A 2017 *Russian Electrical Eng.* **88(4)** 193
[5] Gorozhankin A N, Bukhanov S S, Gryzlov A A and Grigorev M A 2019 *Russian Electrical Eng.* **90(5)** 357
[6] Zhuravlev A M and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 222
[7] Gryzlov A.A. and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 245
[8] Khayatov E S and Grigor’ev M A 2017 Russian Electrical Eng. 88(4) 197
[9] Chupin E S and Grigorev M A 2019 Russian Electrical Eng. 90(5) 375
[10] Gryzlov A A and Grigorev M A 2019 Russian Electrical Eng. 90(5) 364
[11] Belykh I A and Grigorev M A 2019 Russian Electrical Eng. 90(5) 370
[12] Belykh I A, Grigor’ev M A and Belousov E V 2017 Russian Electrical Eng. 88(4) 205
[13] Naumovich N I and Grigorev M A 2019 Russian Electrical Eng. 90(5) 380
[14] Belousov E V, Grigor’ev M A and Gryzlov A A 2017 Russian Electrical Eng. 88(4) 185
[15] Chupin S A and Grigor’ev M A 2018 Russian Electrical Eng. 89(4) 240
[16] Gorozhankin A N, Gryzlov A A, Tsirkunenko A T and Zhuravlev A M 2018 Russian Electrical Eng. 89(4) 217