DISTRIBUTION OF MAGNETIC INDUCTION IN LAMINATED MAGNETIC CORE WITH INTERSHEET INSULATION CONTROL

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Review and analysis of existing loss calculation models. Figure 1 provides an overview of the most popular methods for determining steel losses.

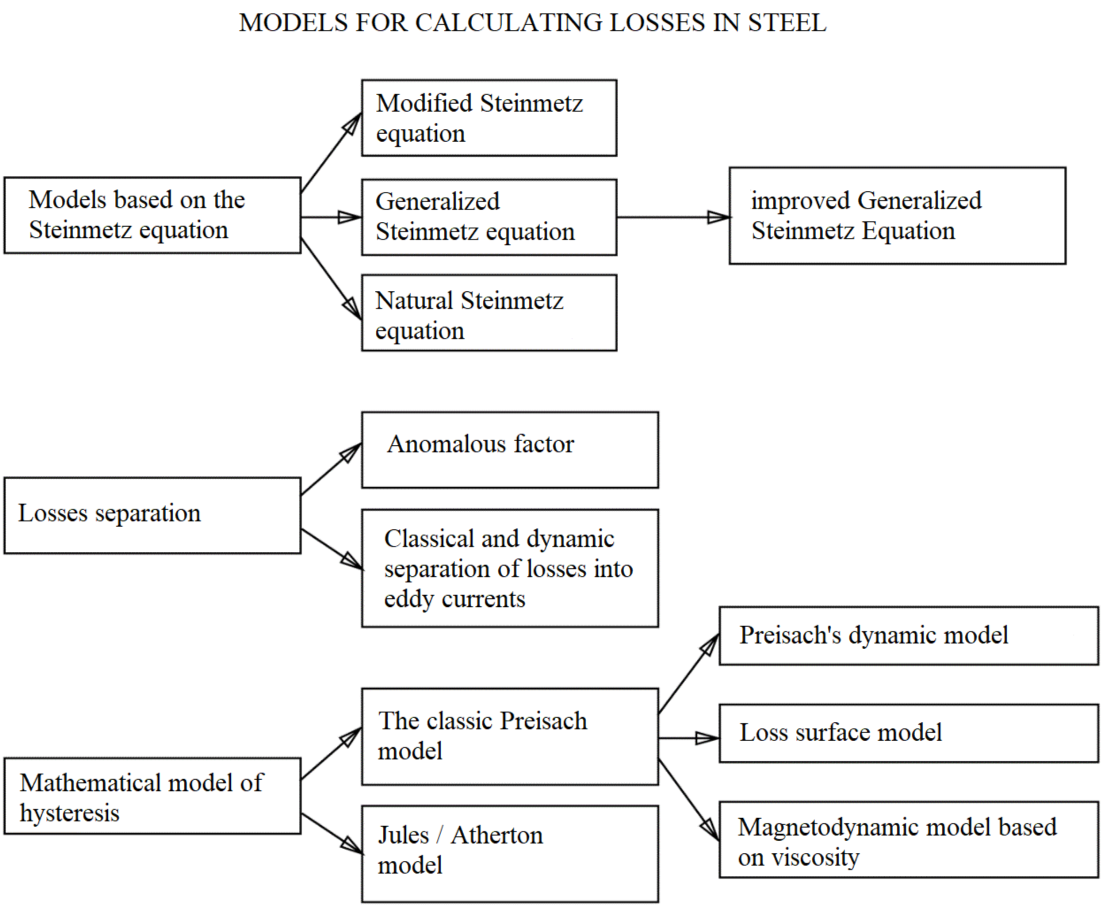

Figure 1 – Models for determining the losses in the steel of an electric machine

Models based on the Steinmetz equation. The first group of models is based on the Steinmetz Equation (SE) equation [1]:

$$p_{St} = C_{SE} f^{\alpha} \hat{B}^{\beta}, \tag{1}$$

where p_{St} – specific losses of steel $\frac{W}{kg}$; $\hat{B}$ – peak value of induction in sheet; f – AC frequency.

Three coefficients C_{SE}, α and β are determined by the mathematical method of approximation of the loss model to the experimental data. Since the classical Steinmetz equation, equation (1) is valid only for sinusoidal voltage, several modifications have been developed over the last few decades to extend the equation and it gave true results for non-sinusoidal signal.

One of these modifications to SE for the calculation of losses in the magnetic circuit for an arbitrary waveform is called the Modified Steinmetz Equation (MSE) [2-4]. The idea behind MSE is that you need to introduce an equivalent frequency that depends on the macroscopic rate of re-magnetization $\frac{dM}{dt}$. Because the rate of re-magnetization is proportional to the rate of change of induction $\frac{dB}{dt}$, the equivalent frequency depending on this speed is determined as follows:

$$f_{eq} = \frac{2}{\Delta B^2 \pi^2} \int_0^{\pi} \frac{dB}{dt}^2 \, dt, \tag{2}$$

where $\Delta B = B_{max} - B_{min}$.

Combining equation (2) with SE we obtain the following equation:

$$p_{St} = C_{SE} f_{eq}^{-\alpha} \hat{B}^{\beta} f. \tag{3}$$

The disadvantage of MSE is that it loses accuracy for waves with a small fundamental frequency.

A newer modification of SE is called the Generalized Steinmetz Equation (GSE), described and compared with the modified Steinmetz equation in [5]. This modification is based on the idea that the instantaneous value of losses in steel is a unique function that depends on the induction *B* and the rate of change of induction $\frac{dB}{dt}$, not taking into account the history of the shape of the induction curve. There is a formula that uses this unambiguous function and combines it with the coefficients with SE.

$$p_{\text{Ст}} = \frac{1}{T} \int_0^T C_{GSE} \left| \frac{dB}{dt} \right|^{\alpha} |B(t)|^{\beta - \alpha} dt, \tag{4}$$

where C_{GSE} – the coefficient is related to C_{SE}.

The advantage of GSE over MSE is that GSE takes into account DC offsets without requiring additional coefficients or measurements. In addition, GSE can also be used to obtain an equivalent frequency or equivalent amplitude that can be used in the classical Steinmetz equation.

The disadvantage of GSE is the limitation of accuracy if the third or slightly higher induction harmonic becomes significant. This is the case when there are several peaks in the form of an induction curve. Due to the small loops in the hysteresis loop in such cases, it may be necessary to consider analytical models of hysteresis losses. To overcome this problem, the previously obtained GSE is optimized for the so-called improved Generalized Steinmetz Equation (iGSE) [5]. The idea of the iGSE is to divide the signal into one main and one or more minor loops to consider minor loops in the full main hysteresis loop to calculate losses. Therefore, in [4] a recursive algorithm is presented, which divides the shape of the flux density signal into main and small cycles and calculates the iron loss for each determined loop x separately by formula (5).

$$p_{St_x} = \frac{1}{T}\int_0^T C_{GSE} \left|\frac{dB}{dt}\right|^{\alpha} |\Delta B|^{\beta-\alpha} dt, \tag{5}$$

where ΔB – peak-peak induction of the current large or small loop curve.

The disadvantage of iGSE is that it is not sensitive to DC bias, like GSE, because iGSE is a function of ΔB and not B(t).

A similar approach to iGSE has been published as a more natural equation of Steinmetz (Natural Steinmetz Equation – NSE) [6], which also takes into account the peak-peak value of induction ΔB:

$$p_{St} = (\frac{\Delta B}{2})^{\beta-\alpha} \frac{C_{SE}}{T}\int_0^T \left|\frac{dB}{dt}\right|^{\alpha} dt. \tag{6}$$

In this approach, the waveform is not divided into main and small loops. Instead, it is directly applied to the wave of the whole period (minor loops in the hysteresis loop are neglected). It actually focuses on the influence of rectangular switching signals (for example, pulse width modulation schemes).

Summing up the various approaches based on the Steinmetz equation and their coefficients, it can be noted that they offer a simple and fast way to predict iron losses without the need to pre-measure the loss of material used.

Loss-sharing models. In [5], Jordan divided the losses on the principle of their dependence on frequency changes (f and f ^ 2). This means that the losses were divided into static, ie losses on hysteresis and dynamic, ie losses on eddy currents.

$$p_{St} = p_h + p_e = C_h f \hat{B}^2 + C_e f^2 \hat{B}^2, \tag{7}$$

where C_h and C_e – coefficients of hysteresis and eddy currents, respectively.

In Jordan's approach, it is assumed that the hysteresis loss is proportional to the area of the material magnetization curve at low frequencies (f → 0 Hz). The component of losses from eddy currents p_e can be obtained by approximating Maxwell's equations:

$$p_{\text{В}} = \frac{d^2\left(\frac{dB(t)}{dt}\right)^2}{12\rho\gamma}, \tag{8}$$

where $B(t)$ – induction as a function of time; d – the thickness of the insulated sheet; ρ and γ – esistivity and density of the material of the sheets, respectively.

It was proved that equation (7) gives correct results for nickel-iron alloys, but has insufficient accuracy for silicon-iron alloys [7]. Because of this, Pri and Bin [8] introduced the imperative correction factor η_{exc}, which is called the factor of excessive losses. Thus equation (7) takes the form:

$$p_{St} = p_h + \eta_{exc} p_e = C_h f \hat{B}^2 + \eta_{exc} C_e f^2 \hat{B}^2, \quad (9)$$

where $\eta_{exc} = \frac{p_{e\_measured}}{p_{e\_calculated}} > 1.$

For anisotropic (oriented) electrical steel η_{exc} reaches values in the range from 2 to 3 [9].

Separation of losses. To do this, the Jordan method was chosen, the formula of which is as follows:

$$p_{St} = p_h + p_e = C_h f \hat{B}^2 + C_e f^2 \hat{B}^2. \quad (10)$$

Therefore, to calculate the component losses, it is necessary to obtain the values of the coefficients C_h and C_e. These coefficients are empirical. To determine them, experiments were conducted to determine the losses in the magnetic core at different values of frequency at induction B = 1 T according to the scheme in Figure 2 [10, 11]. The results of the study of the magnetic core are shown in table 1.

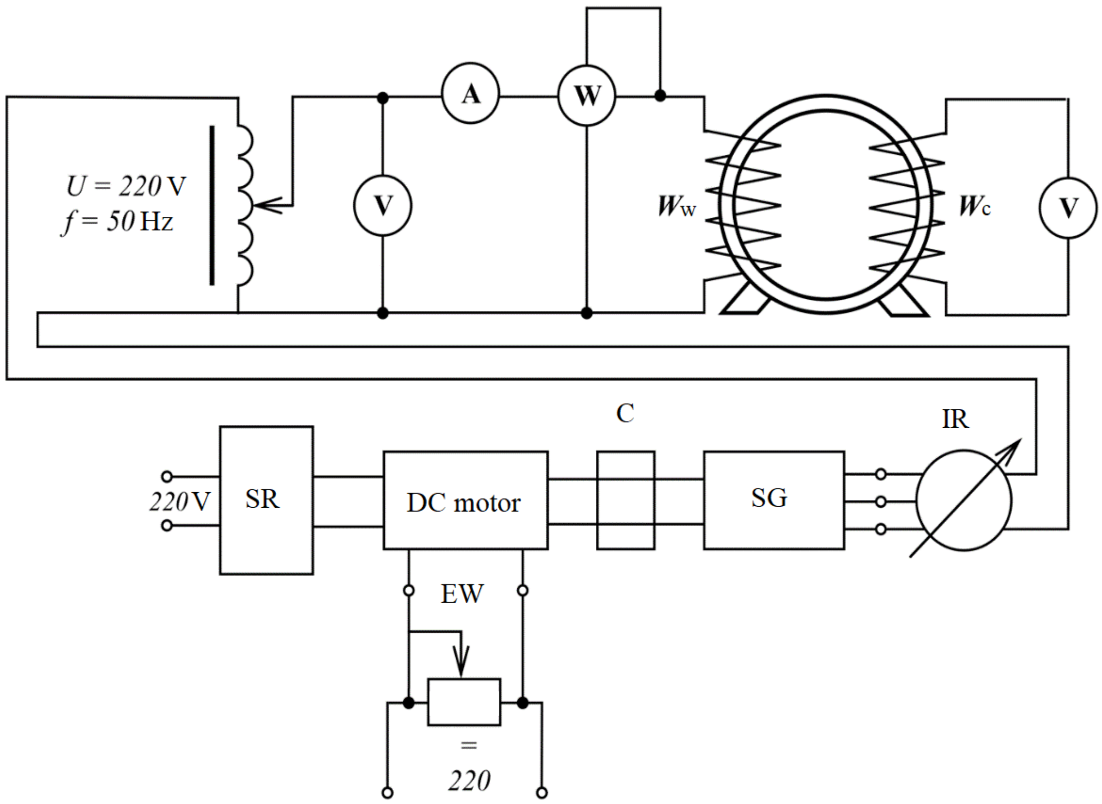

Figure 2 – Scheme of the wattmeter method for operation at a frequency other than 50 Hz

We will also conduct a similar experiment using an additional coil wound on a magnetic core in order to increase the specific losses in the steel of this magnetic core. The results of the experiments are presented in table 2.

Table 1 – Distribution of losses for the magnetic circuit without defect

f	***P***	$P_г$	$P_в$
50	47,84	34	13,84
60	60,73	40,8	19,93
70	74,73	47,6	27,13
80	89,83	54,4	35,43
90	106,05	61,2	44,84
100	123,36	68	55,36
110	141,78	74,8	66,98
120	161,32	81,6	79,72
125	171,5	85	86,5
130	181,96	88,4	93,56

Table 2 – Distribution of losses for a magnetic core with an artificial defect

f	***P***	$P_г$	$P_в$
50	56,18	34	22,18
60	72,74	40,8	31,94
70	91,07	47,6	43,47
80	111,18	54,4	56,78
90	133,06	61,2	71,86
100	156,72	68	88,72
110	182,15	74,8	107,35

Based on the obtained data, a graph of the dependence of each type of loss on the frequency value for both cases was shown, Figure 3, Figure 4.

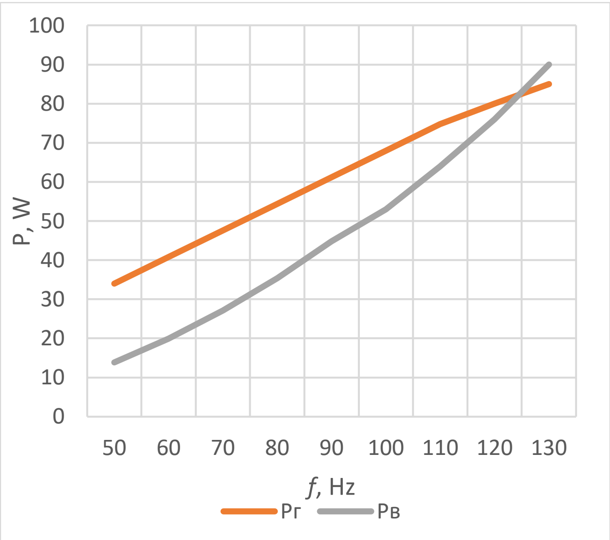

Figure 3 – Graph of the dependence of component losses in steel on the frequency change at induction B = 1T

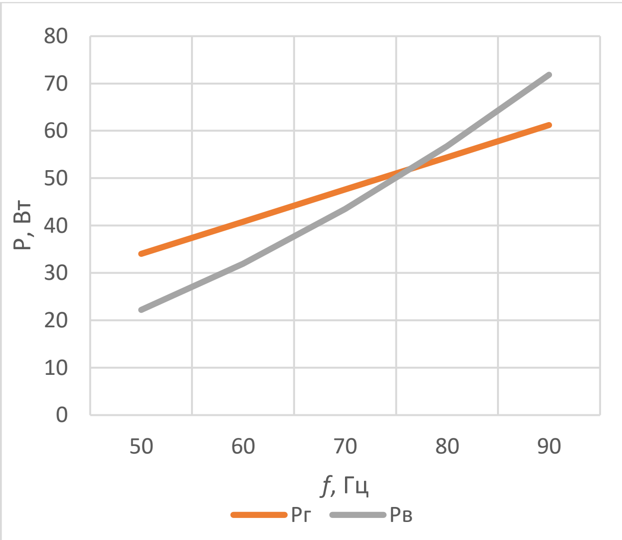

Figure 4 – Graph of the dependence of component losses in steel on the frequency change at induction B = 1T for the case of an artificial defect

A comparison of the two graphs shows that with the appearance of the defect, the dependence of eddy current losses with increasing power supply frequency is parabolic in contrast to the almost linear increase in hysteresis losses, which indicates an increase in this component of losses.

As can be seen from the presented graphs, the artificial defect of the intersheet insulation significantly shifts the equality of losses on hysteresis and eddy currents in the region of lower frequencies, which can be a physical basis for creating a method of quality control of laminated magnetic cores of electric machines.

Conclusions. The specific losses in the studied magnetic cores were determined experimentally. Experiments are also conducted in modeling the deterioration of the magnetic core, which is performed by winding the coil on the back of the magnetic core and connecting its ends on a voltmeter. This allows you to get twice as much input information for further research and simulates the case where there are two magnetic cores of the same series, but different degrees of defect.

The losses received during the implementation of the wattmeter method were divided into components of hysteresis and eddy currents. These calculations assume that the loss of hysteresis is almost unchanged with the deterioration of the sheet insulation of the magnetic circuit. This distribution shows that the deterioration of the magnetic circuit increases the loss of eddy currents and thus it was decided to build a new research methodology based on the action of eddy currents and their characteristic phenomena.

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