Determination of Specific Losses in Stator Core of Electromechanical Energy Converter

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Abstract. The purpose of this paper is the experimental research of the magnetic losses in electrical steels, soft magnetic alloys and amorphous alloys in the wide range of the magnetization reversal frequency and magnetic induction. The comparison between different analytical calculation methods of the stator-core specific losses is presented. The article shows that the known methods with the sufficient accuracy allows the stator-core-specific-loss calculation at frequencies below 400 Hz. However, the discrepancy with the calculations of losses by the different methods at the higher frequencies (above 400 Hz) can reach 2 times. The experimental research at high frequencies showed the 2-3-time discrepancy between the calculated and experimental data.

1. Introduction

The efficiency of electromechanical energy converters (EMEC) is one of the main EMEC indicator and determines the EMEC design. For example, to improve the EMEC efficiency, the slot skewing is used; and in the high-speed EMEC, contactless bearings are used, i.e. technical solutions, which lead to the complication both in the EMEC design and in their production technology. Therefore, for economic and technical justification of these complications, it is particularly important at the EMEC design stage to determine the losses in active and constructive EMEC parts with such precision that will allow selection of the most effective EMEC design.

For the EMEC at a 50 Hz frequency, the accurately loss calculation task is solved theoretically and experimentally in [1-5].

Loss analysis for aviation EMEC with a 400 Hz frequency is presented in [6-8].

The calculation methods and experimental research of the additional and aerodynamic losses in the high-speed EMEC with 1000-3000 Hz frequencies are presented in [10-13].

However, in known works, the stator-core-loss experimental research of the high-speed EMEC with the frequencies over 400 Hz is not shown, although this loss type can reach 50 % or more of the total loss value (depending on materials properties, their thickness and stator magnetization reversal frequency).

In [2] and [3], Eq. 1 is proposed to determine the stator core specific losses in the wide frequency range:

$$P_{\text{s.c}} = k_{\text{m}} P_{\text{s.c.50/1}} \left(\frac{f}{50} \right)^{\beta} B^2 , \tag{1}$$

where $P_{s.c.}$ are the stator core specific losses, [W/kg]; $P_{s.c.50/1}$ are the specific stator core losses at a 50 Hz frequency and a 1 T induction; k_m is the steel losses factor at the technological treatment; B is the magnetic induction in the stator core; $\beta = 1.3 - 1.5$.

In [6, 7], the specific loss calculation of the high-speed EMEC (with a 400 Hz or more frequency) is performed as follows:

$$P_{s.c} = k_m P_{s.c.400/1} \left(\frac{f}{400} \right)^{1.5} B^2 , \tag{2}$$

where $P_{s.c.400/1}$ is the stator core specific losses at a 400 Hz frequency and a 1 T induction.

In [8], the k_m coefficient can be up to 4 depending on the manufacturing type. However, these recommendations are presented only for DC machines.

In [9], this coefficient is in range from 1.8 to 3.6 depending on the steel sheet thickness. These recommendations are presented for the induction AC EMEC. Also in [9], the method of the stator core specific losses calculation for the induction EMEC is proposed. To calculate the losses by this method, the magnetic flux utilization, displacement and magnification factors should be considered and determined from empirical data. They were determined for steels 1413, 1541, which are practically not used in engineering nowadays.

Therefore, for the practical use of this method, the various steel types should be experimentally investigated. However, this significantly limits the use of this method for the EMEC design.

In [14], the equation for the stator-core specific losses determination is proposed:

$$P_{s.c} = k_{hyst} B^{\beta} f + k_{eddy} B^2 f^2 , \tag{3}$$

where $\beta = 1.7 - 2.0$; k_{hyst} and k_{eddy} are respectively dimensional coefficients of hysteresis and eddy-current in the stator core.

In [12], the hysteresis and eddy-current losses are recommended to define with the same equation.

In [10], the method of the stator core specific losses determination is proposed, which uses three coefficients of stator core material properties, hysteresis-loss, eddy-current-steel-loss and excess-loss factor.

$$P_c = k_h B^2 f + k_c B^2 f^2 + k_e (Bf)^{\frac{3}{2}} , \tag{4}$$

where k_h , k_c and k_e are respectively dimensional coefficients of hysteresis-loss factor, eddy-currents-steel-loss factor and excess-loss factor.

In general, the use of the coefficients of the hysteresis-loss, eddy-current-steel-loss and excess-loss factors are typical for all foreign stator-core-specific-losses calculation methods because these coefficients are determined by foreign manufacturers of electrical steels and magnetic alloys and are indicated in the technical documentation.

In the Russian standards for the electrical steels and soft magnetic alloys, these coefficients are absent (for example, in the GOST 21427.1-83, etc.), which complicates the use of the foreign methods.

In [11], the empirical equation for the stator-core-specific-loss calculation is presented:

$$P_{s.c} = \left(7 \cdot 10^{-4} B^{1.75} f^{1.5} + 4.7 \cdot 10^{-4} B^{1.86} f^{1.53} \right). \tag{5}$$

Eq. 5 is the approximation of the stator-core-specific-loss dependence of the current frequency for the 10JNEX900 electrical steel alloyed with the silicon.

2. Problem statement

As can be seen from the above overview, many different equations to determine the stator-core-specific losses are presented. Therefore, it seems appropriate to make the calculations for these equations in order to assess their convergence. The calculations were made for the 2421 isotropic steel with a 0.18 mm thickness (GOST 21427.2-83) in a frequency range from 50 Hz to 2000 Hz at an induction of 0.5 and 1 T. The electrical steel was chosen for the preliminary calculation because it is most applicable for the high-speed EMEC developed in Russia [15-18]. Calculation results are presented in Table 1. Since a large part of the considered equations is derived from Eq. 2 and Eq. 3, the calculations were made for Eq. 2, Eq. 3 and Eq. 5. When calculating Eq. 3, approximation coefficients k_{hyst} and k_{eddy} are equal to $2{\cdot}10^{-4}$ and $0.78{\cdot}10^{-4}$ respectively.

Table 1. Calculation of the specific losses in the stator core made of a 2421 steel (a 0.18 mm thickness, specific losses is 12.5 W/kg at a 400 Hz frequency and 1 T magnetic induction [21]) by different methods

Induction B [T], frequency [Hz]	0.5 T, 50 Hz	1.0 T, 50 Hz	0.5 T, 400 Hz	1.0 T, 400 Hz	0.5 T, 1000 Hz	1.0 T, 1000 Hz	0.5 T, 2000 Hz	1.0 T, 2000 Hz
Specific losses using Eq. 2	0.138	0.55	3.125	12.5	12.35	49.41	34.93	139.75
Specific losses using Eq. 3	0.0488	0.19	3.125	12.5	19.5	78.002	78	312
Specific losses using Eq. 5	0.12	0.43	2.9	10.1	11.61	40.42	33.16	115

The result analysis of Table 1 shows that the considered methods give the close results at a 50 Hz and 400 Hz frequencies. At a frequency of over 400 Hz, the discrepancy between results obtained by different methods can reach two times.

This discrepancy can lead to very negative consequences for all EMECs in general and for the high-speed EMECs in particular. Because the incorrect definition of the stator-core-specific losses for these EMEC types can reach 50% of the total loss value, and it may lead either to the EMEC overheating or to the unjustified overstatement of its weight and size.

In addition, the different methods uncertainty of stator-core-specific-loss calculation limits the EMEC design general theory. Therefore, the stator-core-specific loss research has both a great practical and theoretical significances.

In this paper, the stator-core-specific-loss experimental research at various frequencies and inductions was made, the acceptable usage limit of the varying methods was determined. It is shown that known methods with the sufficient accuracy allows the stator-core-specific-loss calculation at frequencies below 400 Hz.

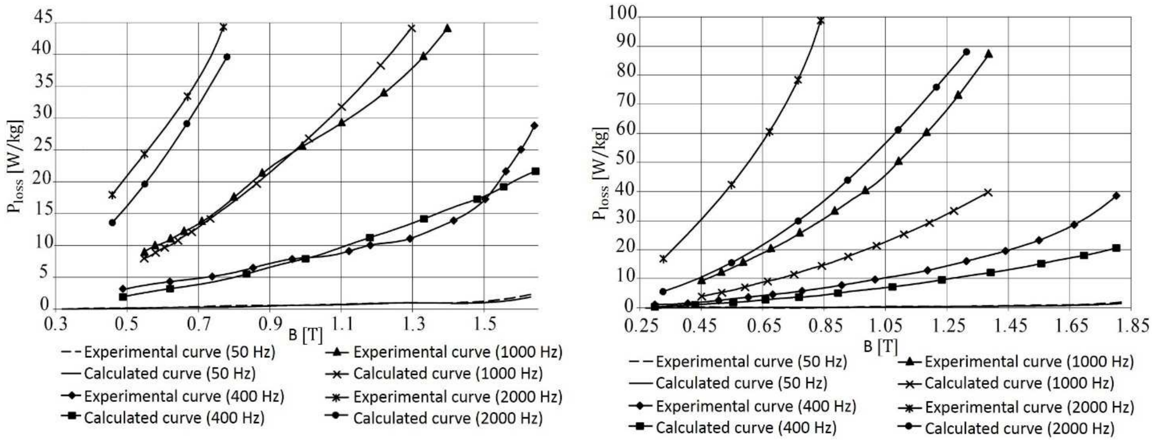
3. Stator-core-specific-loss experimental research

For the stator-core-specific-loss experimental research, the deep modernization of the series-produced magnetic measuring unit MK-4E was produced. The result of this modernization is the ability to measure the specific losses in the steel at frequencies up to 3000 Hz (previously at a frequency range up to 400 Hz).

The experimental research was carried out according to the measurement method contained in the RE 4276.020.20872624.2009 [19] in the normal climatic conditions at a samples' temperature of not more than 23ºC and 25% relative humidity. The mass measure of analyzed samples was carried out on the electronic scales with accuracy of at least 0.01 g.

The specific loss measurements in ring samples of the electrical anisotropic steel strip (GOST 21427.1-83), three types of 5BDSR amorphous alloys (type B, type E and type T, TU 14-123-149-2009, manufactured by the Asha metallurgical factory [20]) and 79 NM soft magnetic alloys (GOST 10994-74, the laminated magnetic core and the wound magnetic core) were made.

Experimental research results and the comparison with calculations by using Eq. 1 are presented in Fig. 1-3. To verify results, the obtained values of the specific losses were compared with the standard values for tested materials (Table 2).



a b

Figure 1. Experimental research results and comparison with calculations using Eq. 1: a – the 3424 steel; b – the 3406 steel

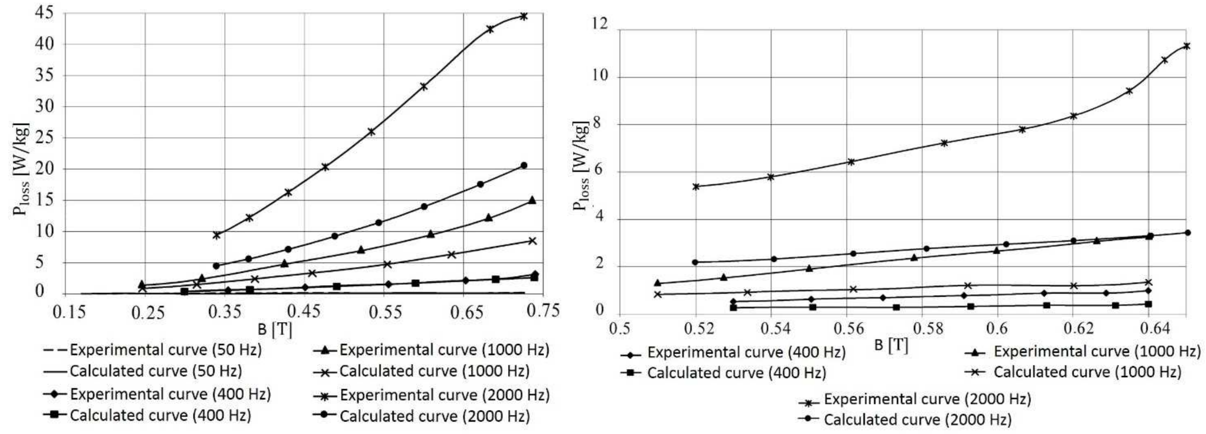


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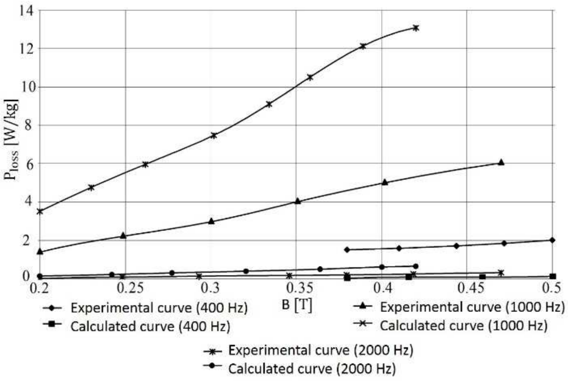
Figure 2. Experimental research results and comparison with calculations using Eq. 1 for the 79NM soft magnetic alloy: a – laminated magnetic core; b – wound magnetic core

Table 2. The comparison of the specific-loss standard values with the specific-loss experimental values for different materials

Material	Standard	Specific-loss standard values, [W/kg]	Specific-loss experimental values, [W/kg]
Electrical steel 3424, a 0.15 mm thickness	GOST 21427.4-78	$P_{1.5/400} = 16$	$P_{1.5/400} = 16$
Electrical steel 3406, a 0.35 mm thickness	GOST 21427.1-83	$P_{1.7/50} = 1.43$	$P_{1.7/50} = 1.42$
79NM soft magnetic alloy, a 0.2 mm thickness (laminated magnetic core)	GOST 10160-75	$P_{0.5/400}=1.2$	$P_{0.5/400}=1.26$



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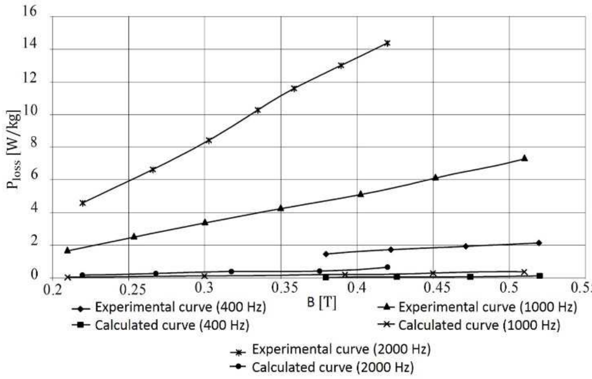

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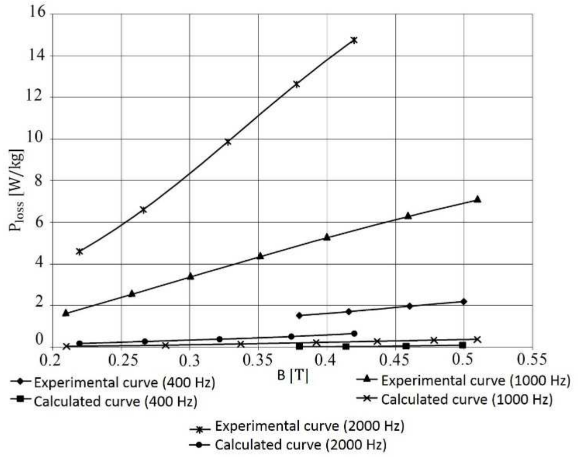

c

Figure 3. Experimental research results and comparison with calculations using Eq. 1 for the 5BDSR amorphous alloy: a – B-type; b – T-type; c – E-type

The result analysis shows that analytical calculations give a reasonable correlation with experimental data at 50 and 400 Hz frequencies for anisotropic steels and inductions lower than the saturation induction. Thus, at high frequencies, the discrepancy between calculated and experimental data may reach 2-3 times.

Herewith, this discrepancy increases with the magnetic induction increasing, which proves the impossibility of the accounting for this discrepancy by the constant coefficient introduction, as is done in [2-7]. For soft magnetic alloys, the significant discrepancy between experimental and analytical data occurs at a 400 Hz or more frequency. The specific losses in the laminated magnetic core made of the magnetic alloy are by 30-60 % more than those of a wound magnetic core.

This is because the laminated sheet thickness was 2.5 times greater than the band thickness. For amorphous alloys, the estimated losses are significantly different from the experimental results. Herewith, the amorphous alloy type (the hysteresis loop type) significantly influences to the loss value. Thus, using the known methods for the stator-core-loss calculation is acceptable for frequencies not exceeding 400 Hz, and the induction below the saturation induction.

For stator cores operated at higher magnetization reversal frequencies, specific-loss-approximation functions should be developed. For each material type (anisotropic, isotropic, magnetic, etc.), the coefficients in these functions should be unique. Some steel manufacturers, for example, the VACUUMSCHMELZE GmbH & Co. KG (Germany) took this path, which for the produced steel types provides the variation curves of the specific losses at 50, 60, 400, 1000 and 2000 Hz frequencies [21].

It is also important to notice that the experimental research of the stator-core-specific losses was produced with the sinusoidal magnetic flux, and the magnetic-flux-shape change (e.g. to the trapezoidal shape, which is typical for the EMEC with permanent magnets) can lead to the increase in the specific losses for another 10-15 %.

4. Results and conclusion

The research results established that equations presented in literature are valid for the frequency from 50 Hz to 400 Hz at the inductions below the saturation induction. At higher frequencies, calculations according to these equations lead to a large error, the amount of which varies from 2 to 3 times depending on the frequency. The large frequency corresponds to a large error. For stator cores operated at the higher magnetization reversal frequencies, it is necessary to develop functions approximating specific losses. For each material type (anisotropic, isotropic, magnetic, etc.), the coefficients in these functions should be unique.

In addition, at inductions below the saturation induction, the loss dependence of the frequency is linear. In case of the induction, close to the saturation induction, the significant nonlinearity should be taken into account to calculate the EMEC efficiency.

5. Acknowledgements

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