A General Model for Estimating the Laminated Steel Losses under PWM Voltage Supply

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Abstract **– The new model is based on a modified Steinmetz equation and employs a hysteresis loss multiplicative coefficient and a combined coefficient for eddy-current and excess losses, both coefficients being variable with induction and frequency. The material model coefficients are firstly identified through multi-frequency tests with sine-wave excitation. The iron loss increase due to PWM supply is estimated using global waveform parameters of the non-sinusoidal voltage. The study includes three different grades of non-grain oriented electric steel. The data covers a wide range of fundamental frequency from 10 to 600Hz and induction from 0.05 to 2T. The errors of the computational model are small at relatively low fundamental frequency and increase thereafter. The main advantages of the model are its simplicity of use and minimal data requirements.**

Index terms **– Iron loss, eddy-current loss, hysteresis loss, PWM voltage, ferromagnetic steel, core loss, electric motor, electrical machine, laminated steel.**

I. INTRODUCTION

A successful electrical machine design optimization process requires the accurate prediction of iron losses. Power electronic converters, which are nowadays widely used to supply electric motors in variable speed systems, have a non-sinusoidal (PWM) voltage waveform that causes increased losses in the lamination steel. Estimation of losses under these operating conditions represents a challenging task. For this purpose, a large number of models, which are based on a physical [1, 2, 8, 12] or an engineering approach [4-7, 9, 16, 17], have been proposed by different authors and yet a definitive conclusion has not been reached.

The background of the present paper is provided by two distinct precursor research activities. One of these recent projects studied Epstein samples under sinusoidal voltage supply on a wide range of frequency and induction and achieved very good agreement between measurements and computations by employing a modified Steinmetz-type model having variable material coefficients [3, 4]. The other precursor research project was based on an engineering approach and quantified the effect of PWM harmonics on iron losses when the fundamental frequency of the voltage is relatively low, typically at 50/60 Hz [5, 6].

The new work described here combines the two theoretical models and further includes a systematic experimental study, which substantially expands the PWM fundamental frequency range previously analyzed. The research was performed in Europe and in the US using different instrumentation and three different materials, two semi-processed cold rolled motor steels and one fully-processed non-grain oriented silicon-steel, all of which are suitable for high volume production of electrical machines. Two types of samples, namely a standard Epstein pack and a wound ring core, were studied. Depending of the sample type, the data covers a wide range of fundamental frequency from 10 to 600Hz and induction from 0.05 to 2T.

These results provide insights into the applicability of a general engineering model for estimating iron losses under PWM supply by using multi-frequency sine-wave Epstein data together with global parameters calculated based on the average and rms values of the non-sinusoidal voltage waveform. The relative merits of the model, especially in terms of generality and simplicity, are discussed together with the drawbacks, such as the relatively low estimation precision at high fundamental and switching frequency. The numerical and experimental work described contributes to the on going debate and efforts in the subject of iron losses under PWM non-sinusoidal supply and can serve as a useful reference to the electric machine engineering community.

II. IRON LOSS MODELING UNDER SINUSOIDAL SUPPLY VOLTAGE

Bertotti's iron-loss model is the one mostly employed over the last decades for laminations excited with sinusoidal magnetic flux, such as in an Epstein test [1]. According to this model, the specific losses are a summation of hysteresis, classical eddy-current and excess loss:

$$w_{\mathrm{Fe}} = k_{\mathrm{h}}\, f\, B^{\alpha} + k_e\, f^2 B^2 + k_a\, f^{1.5} B^{1.5} \qquad (1)$$

The coefficients k_{h}, k_{e} k_{a} and α are assumed to be constant and are determined through the least square method from the measured data for a given frequency.

It should be noted that this paper employs the world-wide accepted terminology of iron losses and induction, while in the US preference is given to the terms of core losses and flux density, respectively.

In practice, the specific iron loss for a given grade of material varies within acceptable manufacturing tolerances in between coils and batches. A practical motor design approach, which accounts for such variations consists in building estimated curves by averaging large sets of experimental data on a per induction and frequency basis. The results obtained using the model (1) illustrated the fact that the loss coefficients k_{h}, k_{e} k_{a} need to be dependent of both induction and frequency and that the usual approach of constant coefficients can lead to unpredictable and significant numerical errors.

A new model was developed and experimental validation was performed on many materials, including three samples, which are further discussed in the paper, namely Epstein strips of a fully-processed steel (M43) and of a semi-processed steel (SPA), respectively, together with a ring core that was built from a low grade of semi-processed steel. The material main properties are provided in the Appendix.

To account for coefficient variations, the authors are using a model that extends previous research results [3-4] and allows the loss coefficients to vary with frequency and induction while the classical loss and anomalous loss are grouped into an eddy-current loss term:

$$w_{Fe} = w_{Hys} + w_{EC}$$
$$w_{Hys} = k_h(f,B) \cdot f B^2 \qquad (2)$$
$$w_{EC} = k_e(f,B) \cdot (f B)^2$$

The authors have successfully fitted the model (2) to soft magnetic materials typically employed in electric motor manufacturing, including cold-rolled laminated semi-processed and silicon-steel fully-processed steel.

Figures 1-3 show the errors between the test data and the estimations of model (2) with variable loss coefficients for all three materials. Note that the higher error values occur at low induction, while at high induction errors are typically within ±5%.

As a first step to identify the values of the coefficients, (1) is divided by the product ($f\ B^2$) resulting in:

$$\frac{w_{Fe}}{f\ B^2} = a + b\ f \qquad (3)$$

$$\text{with: } a = k_h, \quad b = k_e \qquad (4)$$

For any induction B at which measurements were taken, the coefficients of the above polynomial in f can be calculated by linear fitting, based on a minimum of two points.

In order to simplify the model (2), frequency is considered a parameter, resulting in a variation of the eddy-current coefficient k_e with induction only within a defined frequency range, as exemplified in Figs. 4-5. This variation is especially noticeable for the semi-processed material SP (Fig. 5).

Several functions have been tried to describe the k_e loss coefficients variation with the induction level. The lowest relative error values and the simplicity of implementation are provided by third order polynomials:

$$k_e(B) = k_{e3}B^3 + k_{e2}B^2 + k_{e1}B + k_{e0} \qquad (5)$$

Depending on the frequency range of the iron loss data considered for (2), different curves for k_e and k_h as a function of the induction are obtained (Figs. 4–5). The results demonstrate that the eddy-current loss coefficient k_e increases with the induction level and decreases with the frequency.

In the equation with the exponent of the induction set to be constant and equal to 2, a third order polynomial is employed for the coefficient k_h that will have an induction variation of the form (see Figs. 7-9):

$$k_h(B) = k_{h3}B^3 + k_{h2}B^2 + k_{h1}B + k_{h0} \qquad (6)$$

In the model (2), within a given frequency range, k_e and k_h are dependent only on B, which provides a more straight forward computation of the hysteresis and eddy-current loss components. Depending on the set frequency range, the polynomial functions that describe the loss coefficients k_e and k_h will have different variations. It is important to note that the higher relative error for the estimated losses at lower induction levels may be significantly reduced if a higher polynomial function, i.e. 4th order is used for the estimation of the hysteresis loss coefficient k_h.

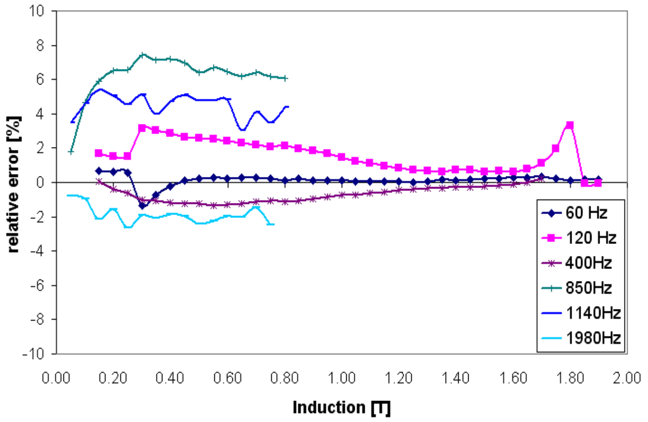

Fig. 1 Relative errors in between the losses estimated by model (2) with variable coefficients and Epstein measurements for the fully-processed steel M43.

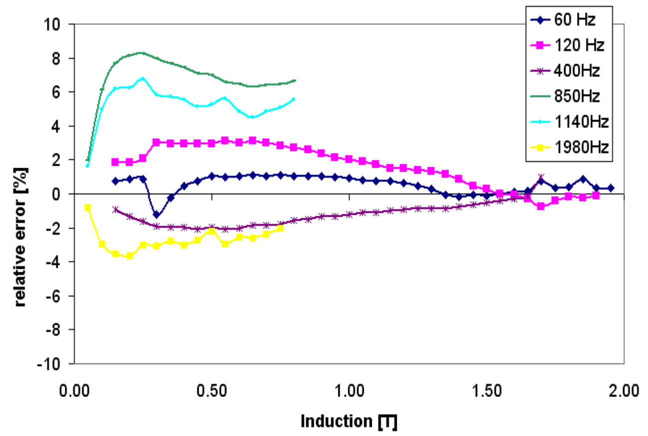

Fig. 2 Relative errors in between the losses estimated by model (2) with variable coefficients and Epstein measurements for the semi-processed steel SP.

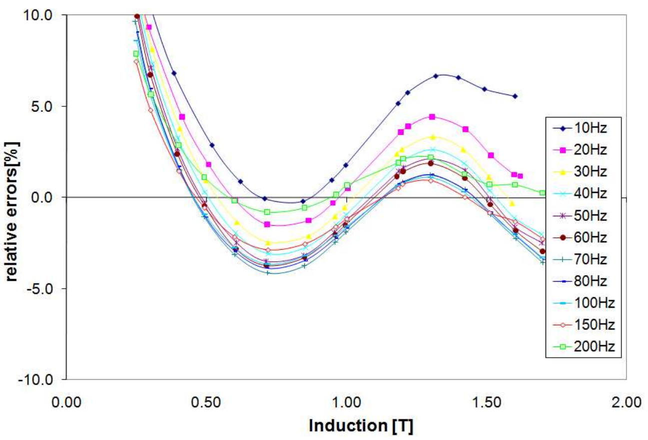

Fig. 3 Relative errors in between the losses estimated by model (2) with variable coefficients and Epstein measurements for the ring core of semi-processed steel.

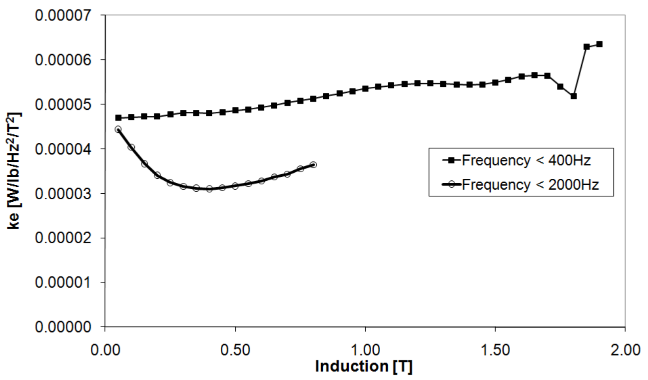

Fig. 4 Variation of the eddy-current loss coefficient k_e with induction within different frequency ranges for the fully-processed steel M43.

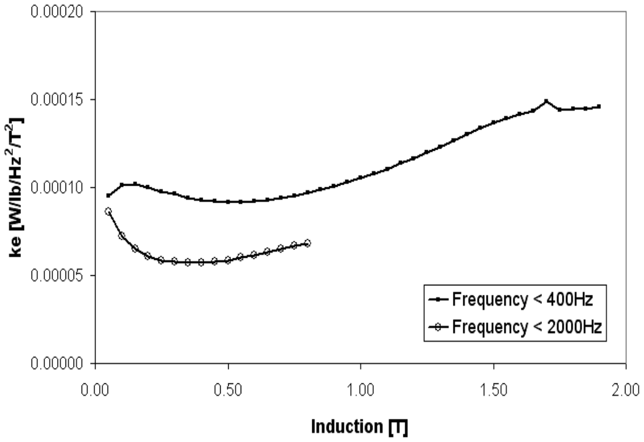

Fig. 5 Variation of the eddy-current loss coefficient k_e with induction within different frequency ranges for the semi-processed material SP.

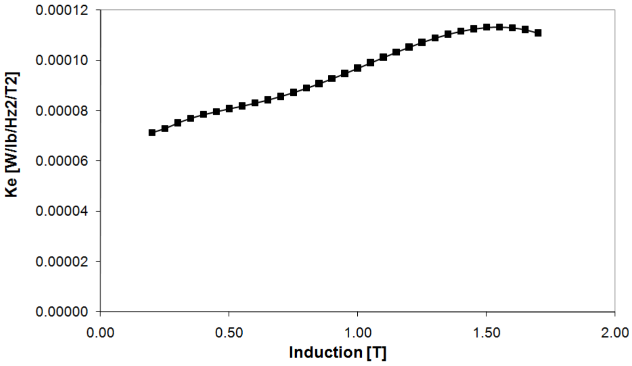

Fig. 6. Variation of the eddy-current loss coefficient k_e with induction within 10—200Hz for the ring core of semi-processed steel.

In Figs. 7–8 the lower curves correspond to test data in a frequency range up to 400Hz, while the upper curves correspond to test data in a frequency range of up to 2000Hz. These results suggest that the hysteresis loss coefficient k_h will decrease with the induction level and increase with the frequency.

As demonstrated in [3], because at very low frequency the hysteresis loss component is dominant, the coefficient k_h can be experimentally determined as:

$$k_h = \frac{\pi}{\rho_V} \cdot \frac{H_{irr}}{B_P} \tag{7}$$

where, the irreversible peak field H_{irr} equals the positive field value at zero induction (i.e. the intersection of the hysteresis loop with the field axis), B_P is the maximum (peak) value of induction in the hysteresis cycle and ρ_V is the volumetric mass density.

In summary, a practical minimum-effort approach for the determination of k_h and k_e according to the model (5)-(6) is described as follows:

(a) measure the iron losses corresponding to at least four induction values, i.e. 0.1T, 0.5T, 1T, 1.5T for a low frequency, i.e. 5Hz;
(b) determine experimental k_h with (7) for all four points;
(c) compute the terms k_{h0}, k_{h1}, k_{h2}, k_{h3} from (6);
(d) measure the iron losses corresponding to four induction values, i.e. 0.5T, 1T, 1.5T, 1.9T for the mean frequency of the range of interest, e.g. 200Hz for a range up to 400Hz;
(e) determine experimental k_e for all four points with the expression:

$$k_e = \frac{1}{f^2 B_p^{\,2}} \left(w_{Fe} - f\ B_P \frac{\pi H_{irr}}{\rho_V} \right) \tag{8}$$

where H_{irr} is the irreversible field-strength measured at step (a) for low frequency (5-15Hz) and for the same induction values;
(f) compute the terms k_{e0}, k_{e1}, k_{e2}, k_{e3} from (5);
(g) the loss coefficients are estimated with (5), (6) for any other induction level and may be easily applied to any further numerical method of computing the iron losses in electrical motors.
(h) the total iron losses are computed with (2).

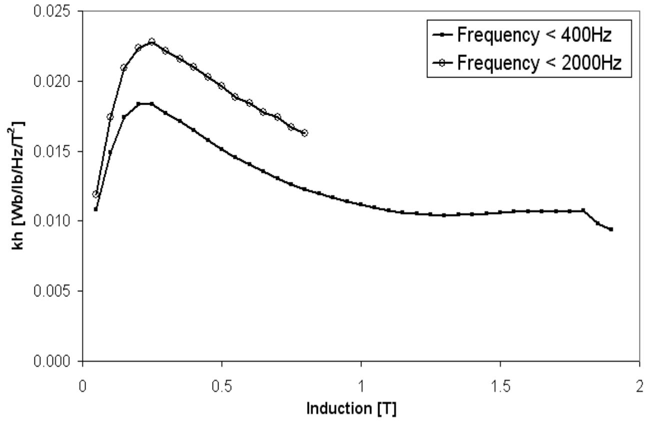

Fig. 7. Variation of the hysteresis loss coefficient k_h with induction within different frequency ranges for the fully-processed steel M43.

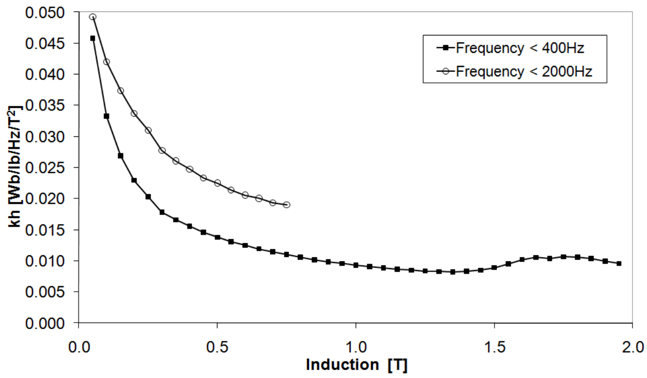

Fig. 8. Variation of the hysteresis loss coefficient k_h with induction within different frequency ranges for the semi-processed steel SP.

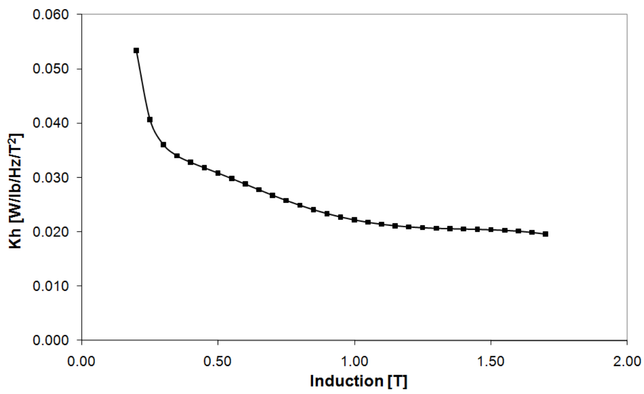

Fig. 9 Variation of the hysteresis loss coefficient k_h with induction within 10—200Hz for the ring core of semi-processed steel.

The procedure described requires for the measurement of parameters of (7)-(8) the use of a hysteresisgraph coupled to an Epstein frame or wound ring core. For the experimental study, the authors have employed such a stateof-the-art instrument and performed measurements with sinusoidal induction waveforms.

Figs. 10 – 13 show the variation of k_e when both the induction and frequency vary and the algorithm previously described is employed. Note that the variation with frequency of the eddy-current loss coefficient, k_e., is less significant, while the variation with induction is steeper. We also observe that a fully-processed material will exhibit a relatively lower degree of variation with induction and frequency as compared to the semi-processed material. The results for up to 200Hz for the ring sample of semi-processed are similar and are not displayed here.

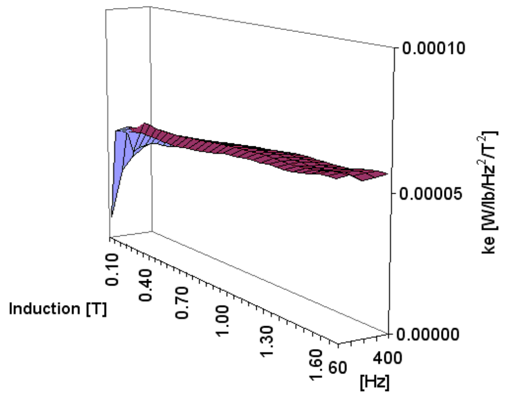

Fig. 10 Variation of the eddy-currents loss coefficient k_e for the fully-processed steel M43.

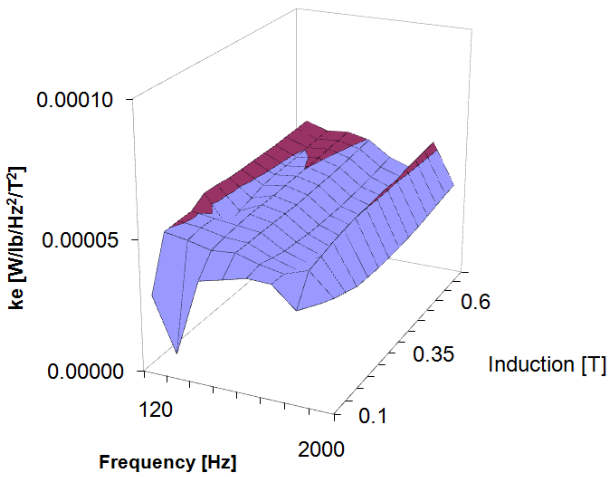

Fig. 11 Variation of the eddy-currents loss coefficient k_e for the fully-processed steel M43.

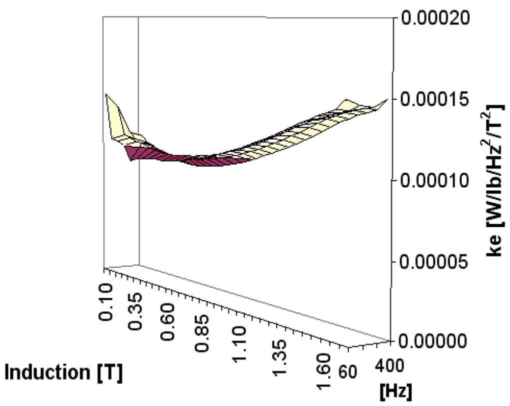

Fig. 12 Variation of the eddy-currents loss coefficient k_e for the semi-processed steel SP.

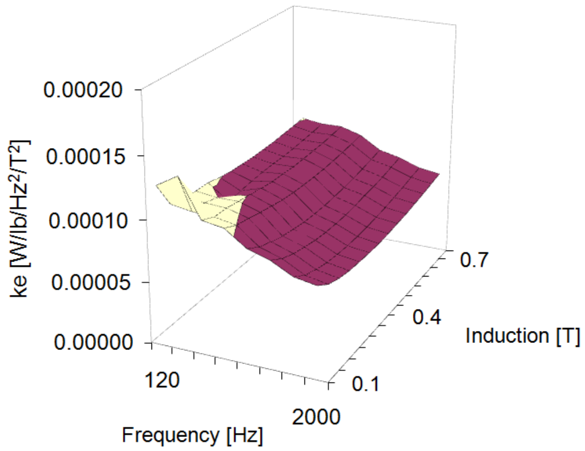

Fig. 13 Variation of the eddy-currents loss coefficient k_e for the semi-processed steel SP.

III. IRON LOSSES MODELING UNDER PWM SUPPLY VOLTAGE

In a wide range of electric motor applications, the supply voltage is non-sinusoidal. Consequently, both the static (hysteresis) and the rate-dependent (eddy-currents) effects in the lamination steel will produce an increased amount of losses.

Several models for the iron losses with arbitrary supply voltage have been published in recent decades following the introduction of static converters, such as inverters or choppers [5-7, 12-14]. Most of these models, such as [12-14], require very detailed knowledge of the material physical properties and laborious mathematical formulations for the minor hysteresis loops.

A simple and efficient engineering approach was proposed by the co-authors in [5-6], showing that it is possible to model the variation of the iron losses with the supply voltage provided that voltage characteristics are known. By neglecting the effect of the minor loops, it was demonstrated that the peak value of induction is proportional to the average value of the rectified supply voltage, V_{avg}, and, consequently, the hysteresis loss component varies with V_{avg}. Similarly, as the eddy-current loss depends on the rate of time variation of induction (dB/dt), this loss component was associated with the rms value of the supply voltage, V_{rms}.

Thus, the iron losses with an arbitrary voltage waveform may be estimated as:

$$w_{\mathrm{Fe}} = \eta^2 w_{\mathrm{Hys}} + \chi^2 w_{\mathrm{EC}} \quad (9)$$

where the parameters η and χ are defined as:

$$\eta = \frac{V_{avg}}{V_{1avg}} \qquad \chi = \frac{V_{rms}}{V_{1,rms}} \quad (10)$$

In the above equations, the subscripts stand for:

avg – average rectified value,
rms – root means square value,
1 – fundamental.

Two sets of experiments were performed for validating the iron loss model (9) - (10) under PWM supply, as described in the following.

(I) The ring core sample of semi-processed steel was supplied from a power electronics inverter with a fundamental frequency of the 50Hz, a switching frequency of 2kHz and a DC bus voltage of 30V. The electrical quantities have been recorded using a power analyser with a bandwidth of 800kHz.

Table I summarizes the relative errors for the estimated iron losses with the model (9)-(10) and with the models proposed in other references [13-15]. The present paper and the method of reference [15] employ the same set of measured data, i.e. voltage, current and power. On the other hand, the methods described in [13-14] are based on the use of a hysteresisgraph, require knowledge of the material electrical conductivity and entail significant computational efforts. For this study with relatively low fundamental and switching frequencies, the errors of all the methods are comparable and the highest errors are recorded at low values of induction.

TABLE I
RELATIVE ERRORS IN THE ESTIMATION OF IRON LOSSES UNDER PWM SUPPLY AT 50 HZ FUNDAMENTAL FREQUENCY AND 2 KHZ SWITCHING FREQUENCY [15]

INDUCTION [T]	RELATIVE ERRORS [%]			
	REF [13]	REF [14]	REF [15]	EQ. (9)
0.311	20.91	-12.42	-5.18	-10.73
0.492	5.15	-11.91	-2.83	-6.45
0.716	0.91	-6.51	-3.90	-2.82
0.951	-2.34	-6.09	-5.88	-3.05
1.185	-2.69	-3.53	-6.98	-2.51
1.414	-3.97	-3.41	-3.70	-3.28
1.506	-3.06	-3.06	-2.58	-1.45

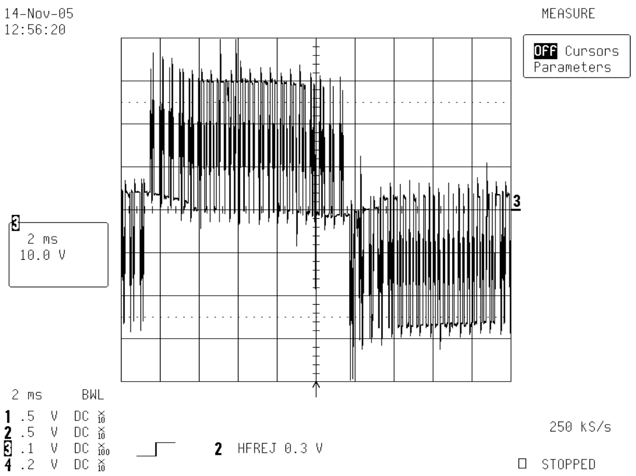

Fig. 14 Secondary induced PWM voltage waveform (fundamental induction = 1.414T, 50Hz)

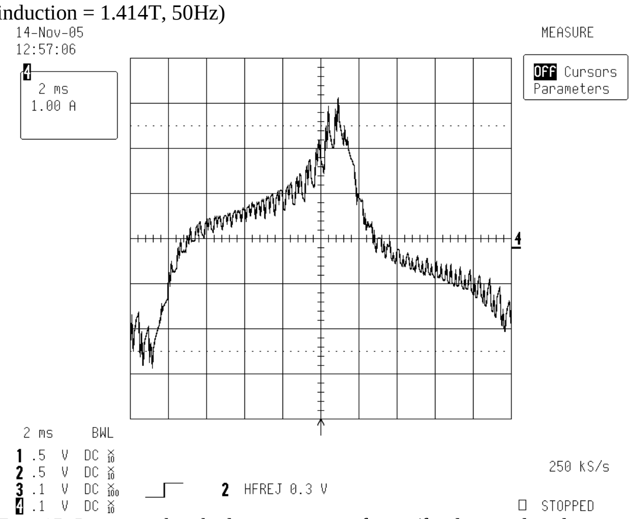

Fig. 15 Primary absorbed current waveform (fundamental induction = 1.414T, 50Hz).

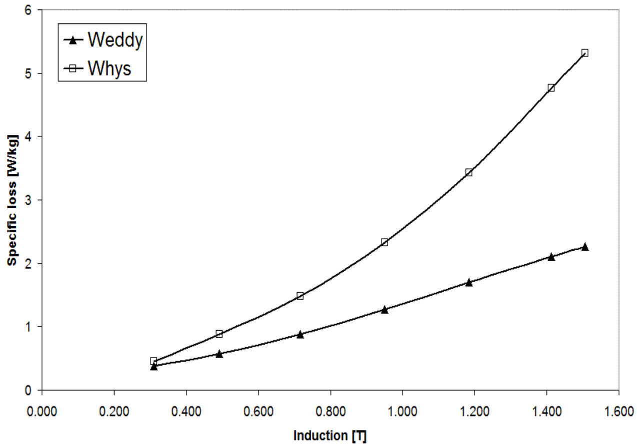

Fig. 16 Estimated loss components for the ring core of semi-processed steel with PWM voltage at 50Hz fundamental frequency.

Figs. 14 and 15 show examples of the recorded waveforms for the absorbed primary current and for the secondary induced PWM voltage in the windings of the ring core sample, respectively. The estimated specific iron loss components for the same conditions, i.e. 50Hz fundamental and a 2kHz switching PWM supply voltage, are plotted in Fig. 16, showing that in this study the hysteresis loss is the dominant component.

(II) The Epstein frame samples of the fully-processed steel M43 and of the semi-processed steel SPA were studied as supplied from a PWM inverter with a fundamental frequency set in between 200Hz and 600Hz, switching frequencies of 10kHz to 20kHz and a variable DC bus voltage of up to 365V. The electrical quantities have been recorded using a power analyser with a bandwidth of 800kHz.

Experiments were also performed at the higher fundamental frequencies of 800Hz and 1000Hz, respectively. However, in these cases satisfactory repeatability of the measurements could not be achieved due to the limitations of the experimental set-up.

If the ratio between the carrier frequency and the modulation frequency is high, the η coefficient is typically equal to unity, as verified in a high number of measurements on the three phase PWM inverter. As a consequence, in this case, the increase in iron loss with a PWM supply is solely due to an increase in dynamic hysteresis (eddy-currents) loss.

In an initial set of experiments the inverter PWM modulation index m was maintained constant to a value of 1. The computed value of the parameters χ and η varied around the values of 1.20 and 1 respectively. In this case, the estimated iron losses under PWM supply are actually scaled from those obtained with sinusoidal supply, by using constant factors for the modelling of the increase in the dynamic (eddy-currents) and static (hysteresis) iron loss components.

A second round of experiments was performed with a variable modulation index in between 0.3 and 1. The parameter χ, which accounts for the dynamic iron loss increase under PWM supply, varied as shown in Fig. 17. As expected, the parameter η, which models the static iron loss increase, was practically unchanged and a constant value of 1 was used in the calculations.

The relative errors between the test data and the computational estimations for a constant modulation index m =1 are shown in Figs.18-19. For the fully processed steel studied, the errors could be considered satisfactory, with the exception of the highest-flux density condition. In this case, the sudden increase in error can be attributed, at least in part, to the inherent limitations of the measurement system. For the semi-processed steel sample, the errors of Fig. 19 are oscillating with some of the larger values being noted at the high induction and high frequency field.

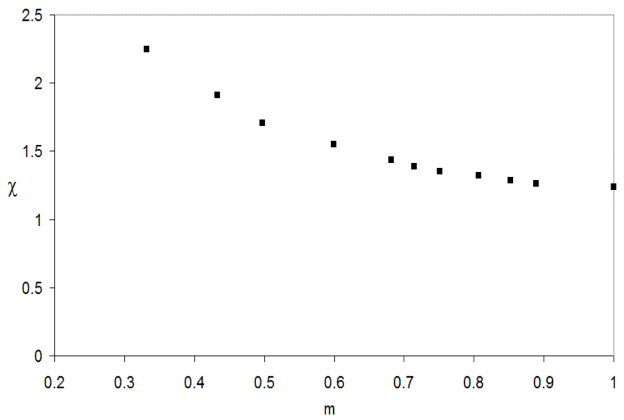

Fig. 17. Variation of parameter χ with inverter PWM modulation index *m*.

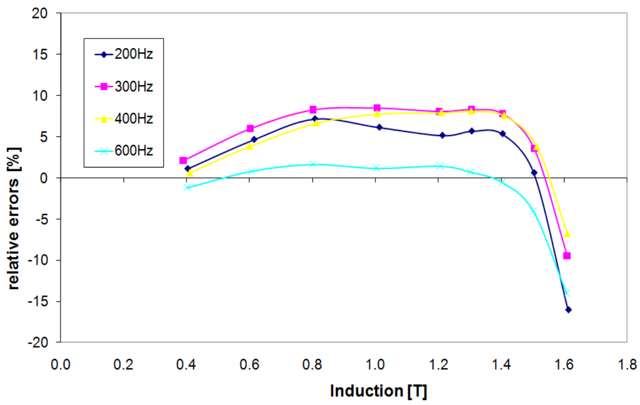

Fig. 18 Relative errors between losses estimated by the model (9)-(10) with variable coefficients and Epstein measurements under PWM voltage supply with constant modulation index *m* = 1 for fully-processed steel M43.

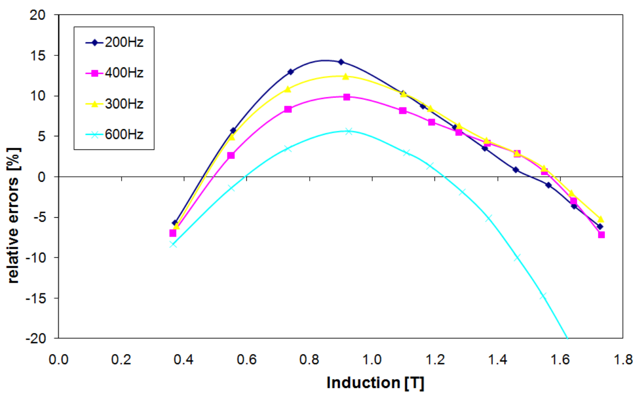

Fig. 19 Relative errors between losses estimated by the model (9)-(10) with variable coefficients and Epstein measurements under PWM voltage supply with constant modulation index *m* = 1 for semi-processed steel SPA.

The relative errors between the test data and the computation for variable modulation index are shown in Figs. 20-21 within the same band of +/-20%. The largest errors are noted at relatively low values of induction, below 0.8T. This could be caused, at least in part, by the minor loop effects on the static hysteresis loss component.

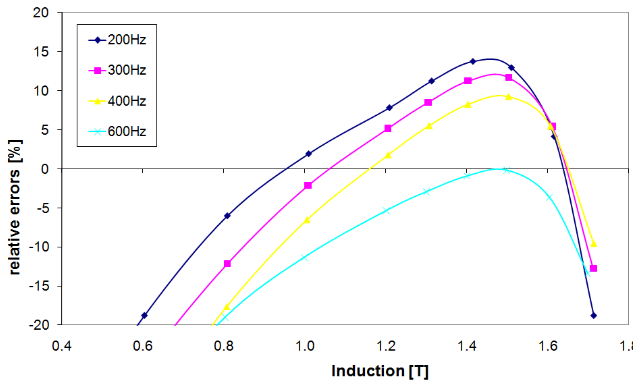

Fig. 20 Relative errors between losses estimated by the model (9)-(10) with variable coefficients and Epstein measurements under PWM voltage supply with variable modulation index *m* for fully-processed steel M43.

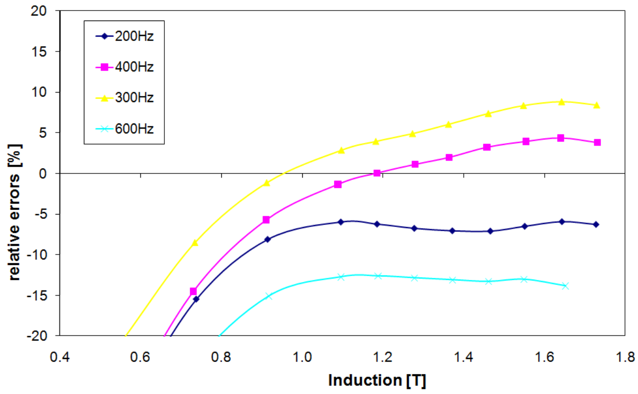

Fig. 21 Relative errors between losses estimated by the model (9)-(10) with variable coefficients and Epstein measurements under PWM voltage supply with variable modulation index *m* for semi-processed steel SP.

In this case, another source of errors could be introduced by the inherent measurement challenges. The low induction values correspond to a low fundamental voltage, which has to be obtained through a low value of the modulation index *m* from a DC bus voltage that is fixed at its maximum value. On the digital power-meter, such low-voltage measurements have to be performed in the lowest range of a very wide voltage scale, the top of which is determined by the peak values of the PWM voltage.

In summary, the PWM study provides some very interesting insights into the new iron loss model. At the low fundamental frequency of 50Hz the errors are lower than 5% in a range of induction between 0.7T and 1.5T. At higher fundamental frequency, in between 200Hz and 600Hz, the errors are larger, but still within a +/-20% range for inductions between 0.8T and 1.5T. While such errors maybe too high for detailed optimization studies, they are typically acceptable for the initial design sizing, when simplicity and speed of computation are of the essence.

IV. Conclusions

A practical engineering model is proposed for estimating the power losses in steel laminations under PWM voltage supply. The model segregates the iron losses in dynamic (eddy-current) and static hysteresis losses, both of which have coefficients that vary with induction and frequency. The loss increase due to the PWM supply is computed based on the data for sine-wave excitation and the PWM waveform global parameters, namely the average rectified and the root mean square values of the non-sinusoidal voltage and of its fundamental.

The main advantages of the new iron loss model are its simplicity of use and minimal requirements in terms of experimental multi-frequency sine-wave data collected from a standard Epstein sample or from a ring core. At relatively low fundamental and switching frequency the PWM estimation errors are low. The errors increase at higher frequency and further work is currently being pursued for improving the model, especially when the PWM inverter modulation index is variable. Based on its particular merits, the model is especially suitable for tasks such as preliminary electrical machine design and analysis or evaluation of possible power de-rating for PWM supply of a motor originally designed for line-fed operation.

APPENDIX

MAIN CHARACTERISTICS OF SAMPLE MATERIALS

Material type	Thickness	Permeability at 1.5T and 60Hz	Loss @ 1.5T and 60Hz	Density
	[in]	[–]	[W/lb]	[kg/m^3]
M43	0.018	1387	1.88	7700
SP	0.022	3071	3.16	7850
Ring core	0.019	1180	3.81	7800

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