Predicting Core Losses based on Data-driven Physical Model

(Concept Novelty Track for 2023 MagNet Challenge)

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Abstract- Core losses are tightly related with the working conditions, such as flux densities, frequencies, temperatures, exciting waveforms and dc biases. Core losses are comprised with hysteresis losses and dynamic losses, and a core loss predicted method based on data-driven physical model is proposed. To a certain predicted point, two paths in procedure can be run automatically. First, if there exists two points having the similar working conditions with the predicted point in database, core losses can be predicted directly based on the separated equations. Second, if there are absent loss data for specified waveforms in database, hysteresis losses and dynamic losses under sinusoidal excitation can be used to predict core losses indirectly. Based on the proposed method, the effect of temperature on hysteresis losses and dynamic losses also can be fitted and analyzed individually. The proposed concepts show a good flexibility to handle various exciting waveforms in power electronics and have been verified correctly based on the loss data of 3F3 and 3C90 in MagNet database.

I. INTRODUCTION

Ferrite materials are widely used in designing high frequency magnetic components, which are one of the most important components in power converters. To design a reasonable heat sink, we need to estimate the core loss under different working conditions. Magnetic devices are often subjected to non-sinusoidal waveforms with variable duty cycles, flux densities, temperatures and dc biases. 2023 MagNet Challenge aims to upgrade the Steinmetz equation with the support of a massive amount of measurement data covering different materials across a wide range of frequencies, waveform shapes, temperatures, and dc-bias.

Two major methods stand out in quantifying power losses in soft magnetic materials, which we categorize here as the math-based approach and the physics-based approach. In the former one, the most popular method is using the modified Steinmetz equations. However, the Steinmetz coefficients varies with different temperatures and materials significantly, and they are not usually given by manufacturers and hard to measure. The model based on physical principles has the advantage of predicting the core loss in different conditions. Yet many parameters used in previous physics-based methods are not easily available [1].

In this proposal, we show how to build a predicted model based on the physical mechanisms and the massive data in MagNet database.

II. PHYSICAL MECHANISM OF FERRITE CORE LOSS

According to the modern physicist research, the ferrite core loss can be separated into three main contributions: hysteresis loss, classical eddy current loss and excess eddy current loss [2, 3]. In order to simplify the analysis, we treat that core losses are composed by hysteresis losses and dynamic losses mainly.

Hysteresis losses: hysteresis loss is introduced by the steady-state loss of the Weiss domains. A general format of the hysteresis loss power density can be written as

$$P_h \propto c_h B_p^x f \tag{1}$$

where c_h is the coefficient of the hysteresis loss. When the core is applied by low excitation, the exponent x of B_p is 3. x will change from 3 to 2 at a higher flux level for large excitation. Clearly, the coefficient x changes with the flux level and gives a trouble to model the hysteresis loss. Here, x sets as 2 since power ferrite cores are worked under large flux density normally.

Dynamic losses: The added AC voltage will produce a changing magnetic field and electric field in ferrite materials. This will generate eddy current losses, dielectric losses and other types of losses inside the core. Here, we define all losses associating with the exciting waveforms are dynamic losses. Since the main part of dynamic losses in the using ranges of ferrite materials is the eddy current loss, a general format of the dynamic loss power density can be expressed as

$$P_d \propto c_d B_p^2 f^2 \tag{2}$$

where c_d is the coefficient of the dynamic loss.

Separation equation: For the same ferrite material, c_h in (1) and c_d in (2) can be treated as constant values roughly if the flux density and frequency in two points f_A and f_B are close with each other. Therefore, based on (1) and (2), the components of hysteresis loss power density and dynamic loss power density can be separated [4].

$$\begin{cases} P_v(f_A) = P_h(f_A) + P_d(f_A) \\ P_v(f_B) = P_h(f_B) + P_d(f_B) \end{cases}$$
$$\Rightarrow \begin{bmatrix} P_v(f_A) \\ P_v(f_B) \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \dfrac{f_B}{f_A}\left(\dfrac{B_B}{B_A}\right)^2 & (\dfrac{f_B}{f_A}\dfrac{B_B}{B_A})^2 \end{bmatrix} \begin{bmatrix} P_h(f_A) \\ P_d(f_A) \end{bmatrix} \tag{3}$$

If the predicted point in f_C also has the similar values of the flux density and frequency with f_A and f_B, using (4) to predict core losses will not bring obvious errors.

$$P_v(f_C) = \frac{f_C}{f_A}\left(\frac{B_C}{B_A}\right)^2 P_h(f_A) + \left(\frac{f_C}{f_A}\right)^2 \left(\frac{B_C}{B_A}\right)^2 P_d(f_A) \quad (4)$$

Waveforms: Because ferrite cores have an equivalent R_{ac}, eddy current loss is introduced by the changing magnetic fields inside the core, and their values highly depend on exciting voltage waveforms [2, 3].

$$P_e \propto \frac{1}{R_{ac}} \frac{1}{T}\int_0^T v^2(t)dt \propto \frac{1}{R_{ac}} \frac{1}{T}\int_0^T \left[\frac{dB}{dt}\right]^2 dt \quad (5)$$

where $v(t)$ is the excitation over one switching period. Since dynamic loss power density P_d are also associated with exciting waveforms, the equivalent R_{ac} of dynamic losses under different exciting voltage waveforms can be determined based on the experimental results. In [6], without calculating R_{ac}, core losses under nonsinusoidal waveforms can be predicted directly based on the mathematical relationships with sinusoidal losses.

To the excitation with extreme duty cycles or with a zero voltage period, dielectric losses increase obviously [7]. If dynamic losses are derived based on sinusoidal losses, a modified coefficient $c(D)$ can be multiplied with P_d to embody this additional effect of dielectric losses.

The effect of temperature and dc bias: The coefficients of c_h and c_d in ferrite material show the significant variations with the temperature and dc bias. Benefited from massive data in MagNet database, the change tendencies of hysteresis loss and the dynamic loss under different temperatures and dc biases can be fitted and analyzed easily.

III. Flowchart for Predicting Core Losses

From (1) to (5), the predict point under different combinations of frequencies, temperatures, dc biases and waveforms can be predicted.

Case 1: Absent sinusoidal losses under the certain combinations of f and B in database.

In most cases, predicted points may have different frequencies and flux densities with those existing points in MagNet database. So the procedure should have an ability to predict core losses from those existing points, and the demo waveforms and flowchart are shown in Fig. 1.

Step 1: Selecting suitable data from database. As mentioned before, in order to alleviate the variations of c_h and c_d, points of flux density and frequency in f_A and f_B should select the closest values with the predicted point in f_C.

Step 2: Separating hysteresis losses and dynamic losses. (3) can be used to separate hysteresis losses and dynamic losses from two points in f_A and f_B, so the loss component in f_A under certain conditions can be calculated easily.

Step 3: Calculating core losses at the predicted point. Based on (5), core losses in the predicted point f_C can be derived.

Actually, this predicted method also can be available for other types of exciting waveforms directly, such as rectangular excitations or pulse excitations when duty cycles of waveforms equal.

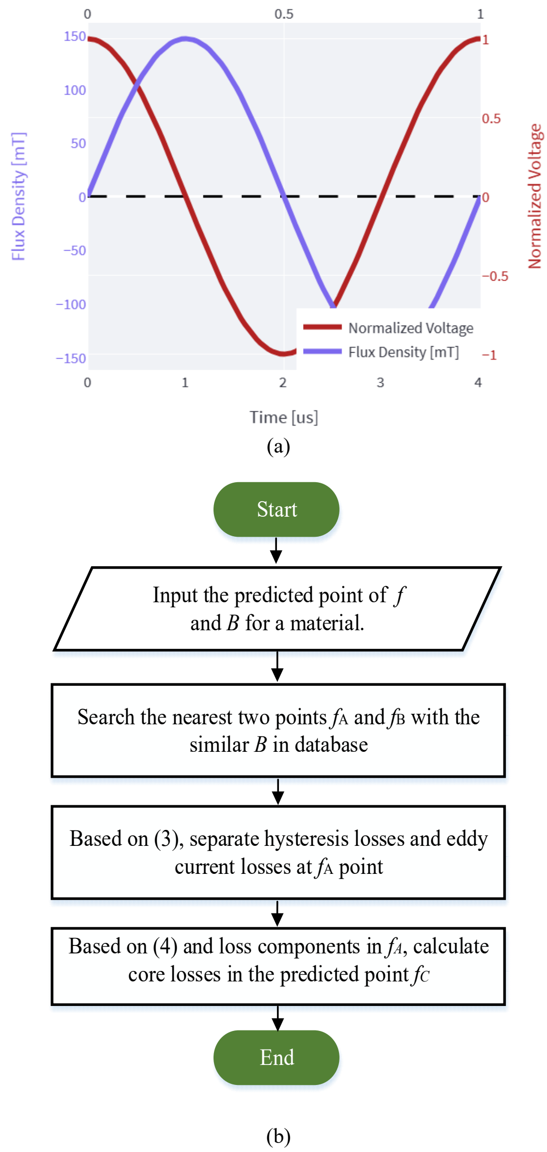


Fig. 1 Calculation sinusoidal losses under a random combination of *f* and *B*

Case 2: Absent sinusoidal losses under the certain temperature in database.

In this case, the predicted point has a temperature that does not exist in database, and the flowchart is shown in Fig. 2.

Step 1: Calculating hysteresis losses and dynamic losses under the frequency and flux density of the predicted point for typical temperatures in database, as listed in (1).

Step 2: Fitting the changing curves of hysteresis losses and eddy current losses under the typical temperature individually.

Step 3: Calculating the losses components of P_h and P_d under the certain temperature, and the total core loss power density can be derived.

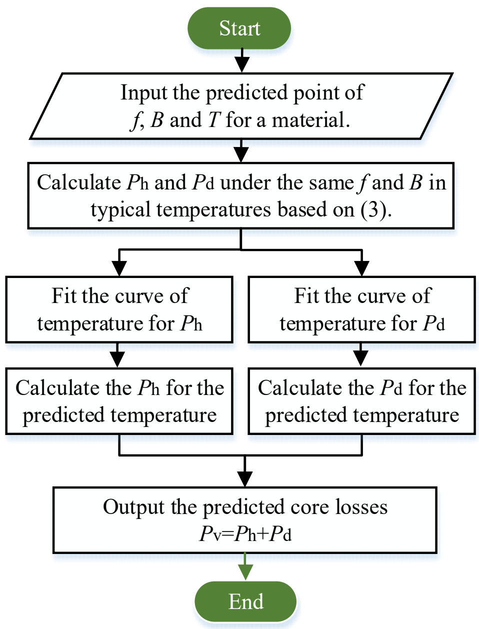


Fig. 2 Calculation sinusoidal losses under a specified temperature

***Case 3**: Absent rectangular losses under the certain combinations of f and B in database.*

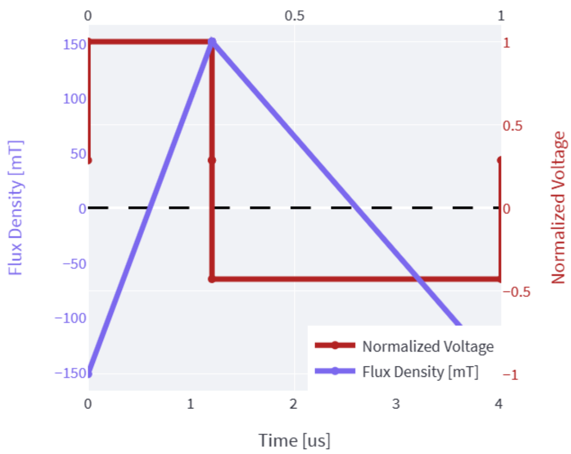
If the flux density and frequency are the same, different voltage waveforms only effect the component of dynamic losses, and will not effect hysteresis losses. In this case, it shows that core losses under rectangular excitations can be derived from sinusoidal losses directly. The demo waveforms and flowchart are shown in Fig. 3.

Step 1: According to the f and B at the predicted point under rectangular excitation, P_h and P_d with the same f and B under sinusoidal excitations are separated.

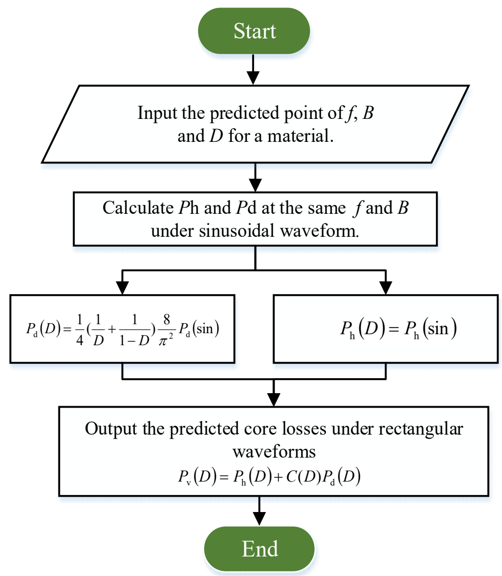
Step 2: Building the mathematical relationships of dynamic losses between the sinusoidal waveform and the rectangular waveform. P_d under different duty cycles can be calculated, as listed in (6).

$$P_d(D)=\frac{1}{4}\left(\frac{1}{D}+\frac{1}{1-D}\right)\frac{8}{\pi^2}P_d(\sin) \tag{6}$$

Step 3: Calculating the total core losses power density P_v based on P_h and P_d.



(a)



(b)

Fig. 3 Calculation rectangular losses from sinusoidal losses

***Case 4**: Absent pulse losses under the certain combinations of f and B in database.*

Similar to the case 3, core losses under pulse excitations also can be derived from sinusoidal losses. In MagNet challenge database, the arbitrary pulse waveforms have four periods which are D_1, D_2, D_3 and D_4, as shown in Fig. 4 (a). The typical amplitudes of voltage in each period are listed in Table I. The flowchart is shown in Fig. 4 (b).

Step 1: According to the f and B at the predicted point under pulse excitations, P_h and P_d at the same f and B under sinusoidal excitations are separated.

Step 2: Building the mathematical relationships of dynamic losses between the sinusoidal waveform and the pulse waveform. P_d under different duty cycles can be calculated. Although pulse waveforms in MagNet challenge show various voltage levels under different duty cycles, the volt-second balance is met. We build the mathematical relationships of dynamic losses between the sinusoidal waveform and the square waveform with D=0.5 at first, then $P_d(D)$ under symmetrical pulse waveform with D=0.4 can be predicted [7].

$$P_d(D_1=0.4)=1.25\frac{8}{\pi^2}P_d(\sin) \tag{7}$$

Step 3: Calculating the total core loss power density P_v based on P_h and P_d.

Table I The features of pulse waveforms with positive D_1

D_1	D_2	D_3	D_4	V_{D1}^*	V_{D2}^*	V_{D3}^*	V_{D4}^*
0.1	0.4	0.1	0.4	1	0	-1	0
0.2	0.3	0.2	0.3	1	0	-1	0
0.3	0.3	0.1	0.3	0.667	-0.167	-1	-0.167
0.3	0.2	0.3	0.2	1	0	-1	0
0.4	0.2	0.2	0.2	0.667	-0.167	-1	-0.167
0.4	0.1	0.4	0.1	1	0	-1	0
0.5	0.2	0.1	0.2	0.429	-0.286	-1	-0.286
0.5	0.1	0.3	0.1	0.667	-0.167	-1	-0.167
0.6	0.1	0.2	0.1	0.429	-0.286	-1	-0.286
0.7	0.1	0.1	0.1	0.25	-0.375	-1	-0.375

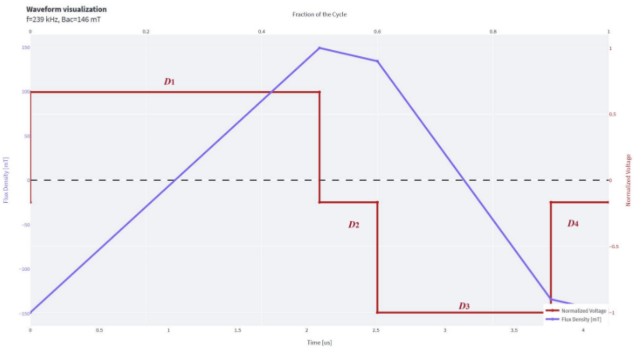
Taken the amplitude of symmetrical voltage at D_1 = 0.4 as a reference. According to the principle of vol-second balance, the voltage relationships meet (8) .

$$\begin{cases} V_{D1} = V_{D=0.4} \times \dfrac{0.4}{D_1}, & V_{D2} = V_{D1} \times \dfrac{V_{D2}^*}{V_{D1}^*} \\ V_{D3} = V_{D1} \times \dfrac{V_{D3}^*}{V_{D1}^*}, & V_{D4} = V_{D1} \times \dfrac{V_{D4}^*}{V_{D1}^*} \end{cases} \tag{8}$$

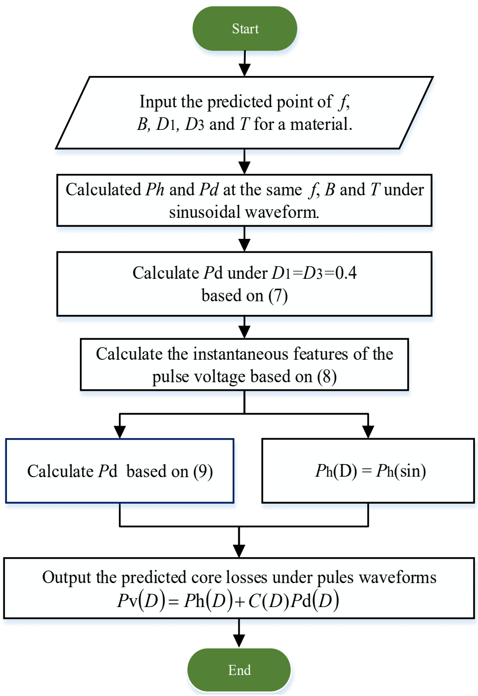
When duty cycles change, dynamic loss power density can be determined based on the features of pulse waveforms, and their relationships meet (9).

$$\begin{cases} P_d(D_1 = 0.4) = \dfrac{0.8 V_{D=0.4}{}^2}{R_e} \\ P_d(D) = \dfrac{V_{D1}^2 D_1 + V_{D2}^2 D_2 + V_{D3}^2 D_3 + V_{D4}^2 D_4}{R_e} \end{cases} \tag{9}$$

Based on (7), (8) and (9), dynamic loss power density under various duty cycles can be calculated.



(a)



(b)

Fig. 4 Calculation pulse losses from sinusoidal losses

IV. RESULTS ANALYSIS

For sinusoidal losses in case 1, Fig. 5 shows the errors between the predicted values and the actual values for N87 @25℃ under sinusoidal excitations. The hollow circle represents the actual losses, the star symbol represents the predicted losses, and the solid square represents the errors between the actual losses and the predicted values. Although the actual points have different combinations of flux density and frequency, the predicted values based on (3) and (4) show a good accuracy and the maximum error in the selected points is 1.5% only.

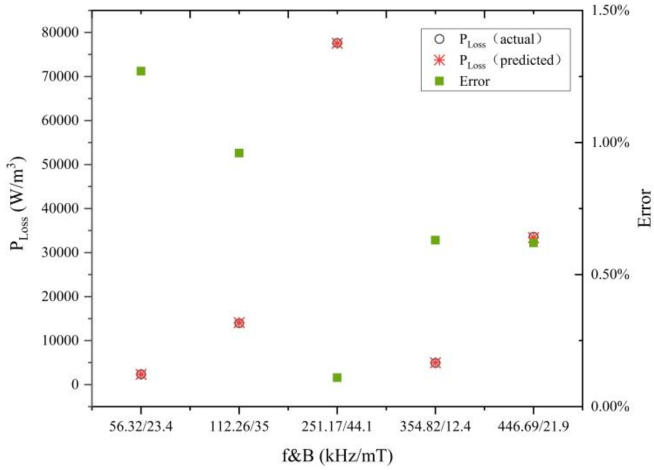


Fig. 5 The predicted values for N87@25°

For the effect of temperature in case 2, N49 is selected as an example. Fig. 6 show the changing tendency of core loss power density, hysteresis loss power density and dynamic loss power density under typical temperatures respectively. Under different combinations of flux density, core loss power density changes nonlinear greatly with temperature, as shown in Fig. 6 (a). This will bring a significant difficulty to predict core losses. Based on (3), hysteresis losses and dynamic losses under typical temperature can be separated individually and used to fit curves, as shown in Fig. 6 (b) and Fig. 6 (c). Therefore, to those points do not exist in database, core loss power density under various temperatures can be predicted simply.

For predicting rectangular losses from sinusoidal losses in case 3, three combinations of flux density and frequency in N87 are selected to predict core loss power density under duty cycles from 0.1 to 0.9, as shown in Fig. 7. Lines are the fitting curves based on rectangular losses in MagNet database, and solid points are predicted values from sinusoidal losses. As mentioned above, dielectric losses can not be neglected under rectangular excitations with extreme duty cycle. Therefore, we select the modified coefficient $c(D)$ = 1.3 to multiple the original P_d under D=0.1 or D=0.9.

For predicting pulse losses from sinusoidal losses in case 3, three combinations of flux density and frequency for N49 are selected to predict core losses under different duty cycles, as shown in Fig. 8. Lines are the fitting curves based on pulse losses in MagNet database, and solid points are predicted values from sinusoidal losses. Again, dielectric losses can not be neglected when pulse waveforms contain zero voltage periods. Therefore, we select the modified coefficient $c(D)$=1.48@D=0.1, $c(D)$= 1.38@D=0.2, $c(D)$=1.26@D=0.3 to multiple the original P_d for symmetrical pulse waveforms respectively.

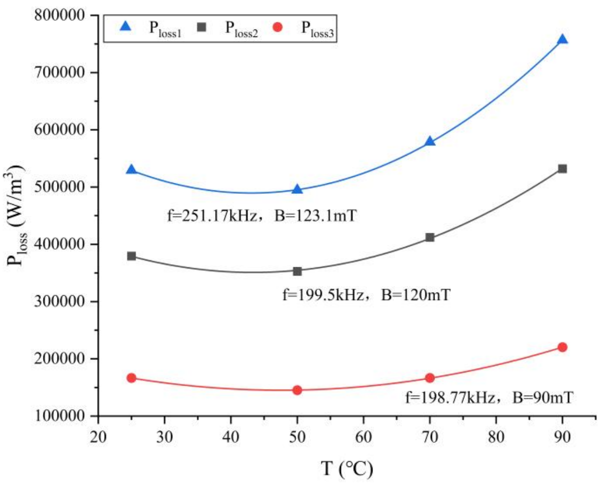
In Table II, the total number of model parameters and model size are listed for the final five unknown materials.

Table II The features of pulse waveforms

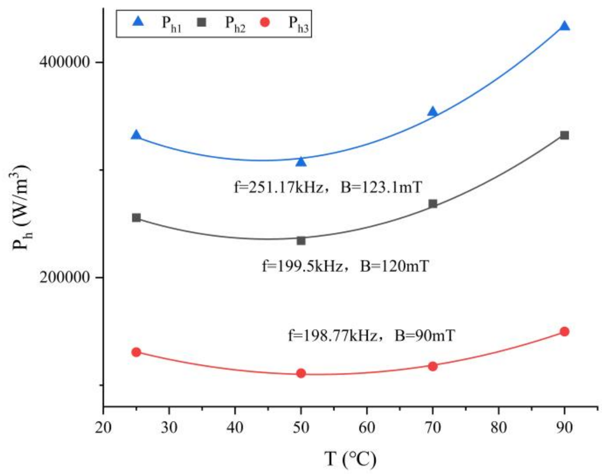
Sample	Numbers of parameter	Size (KB)
1	3 (*f*, *B*, *T*)	51
2	3 (*f*, *B*, *T*)	40
3	3 (*f*, *B*, *T*)	49
4	3 (*f*, *B*, *T*)	60
5	3 (*f*, *B*, *T*)	49

V. CONCLUSION

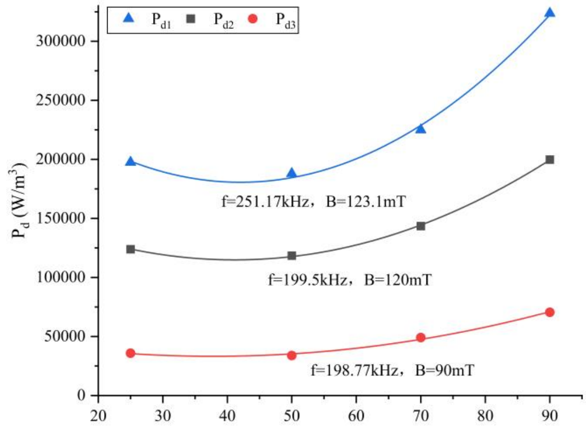
In this paper, core losses are separated into hysteresis losses and dynamic losses, and a data-driven physical prediction model of core losses is proposed. Based on losses in MagNet database, core losses under arbitrary excitations can be predicted directly. At the same time, the effect of temperature on hysteresis losses and dynamic losses also can be fitted and analyzed individually. The proposed concepts show a good flexibility to predict core losses under various exciting waveforms in power electronics.



(a) The changing curves of P_v



(b) The changing curves of P_h



(c) The changing curves of P_d

Fig. 6 The changing tendency under different temperatures for N49

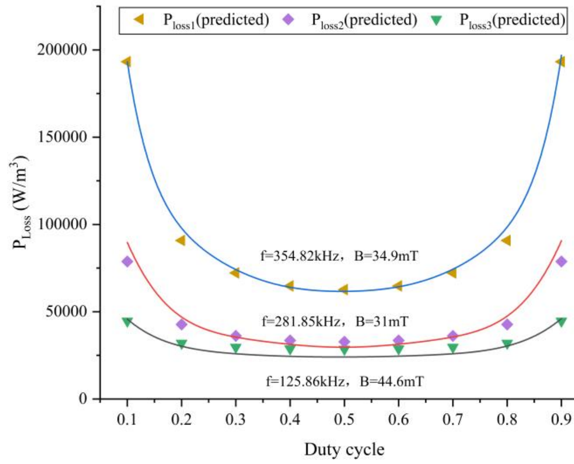


Fig. 7 The predicted values under rectangular excitation for N87@25°

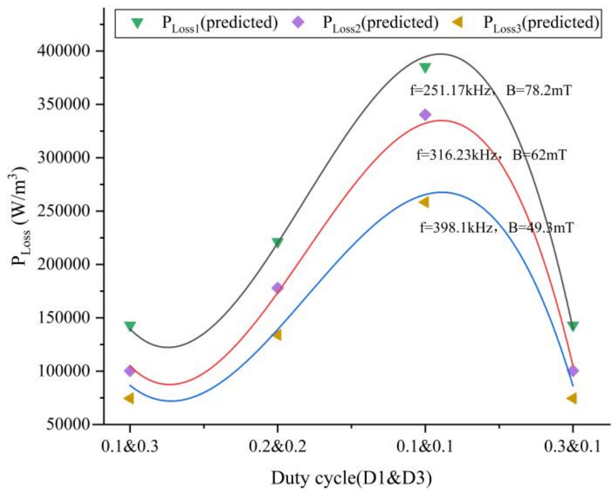


Fig. 8 The changing tendency under pulse waveform for N49

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