



ARE **PLANAR DESIGNS**  
THE BEST TECHNOLOGY  
FOR YOUR MAGNETICS?



# SEVEN THINGS YOU SHOULD KNOW ABOUT PLANAR SOLUTIONS

1. **Introduction**
  2. **Planar transformer design of 600W**
  3. **Impact of DC resistance increment with temperature**
  4. **Harmonics impact**
  5. **Winding resistance calculation in planar transformers**
  6. **Planar magnetic design: two-dimensional winding losses calculation**
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# Introduction

Nowadays, planar magnetic elements are commonly used in the power electronics industry due to their advantages over wound magnetic components, especially in high-frequency power converters. This technology allows for low-profile, core shapes which cover wider surface areas compared with conventional transformers, giving a better heat dissipation and larger cross-sectional areas. Other advantages are:

- Higher power density.
- AC resistance and leakage inductance minimization due to easier interleaving winding arrangements.

AC Resistance and leakage inductance minimization by easy interleaving arrangements.

With regards to the manufacturing process, the rigid structure of the printed circuit board allow for the bobbin to be removed from the component. This is necessary in wound transformers for easier winding manufacturing, thus reducing this number of necessary elements in the magnetic component manufacturing.

Number of magnetics parts and therefore cost can be reduced since the use of coil formers are no longer needed in planar transformers.

Nothing comes for free and although planar magnetics have the aforementioned benefits they also have some drawbacks. High current applications require stacking of several copper lead frames that require specific manufacturing techniques. It is well known as well that whereas leakage inductance can be reduced, planar transformer have considerable parasitic capacitance that need to be taken into account.



# PLANAR TRANSFORMER DESIGN OF 600 W



Magnetic components are the current bottleneck for improving the power density in power conversion. For that reason in SPC we have created Frenetic. Frenetic is able to provide a functional design without iterations needed in less than a week.

This document presents a FRENETIC design that could replace the transformer and resonant inductor components used in the application note "Design of a 600 W HB LLC Converter using 600 V CoolMOS P6" of INFINEON, with the aim of showing the capabilities of the optimization procedure performed by FRENETIC.

## Comparative results with the INFINEON app note magnetic components



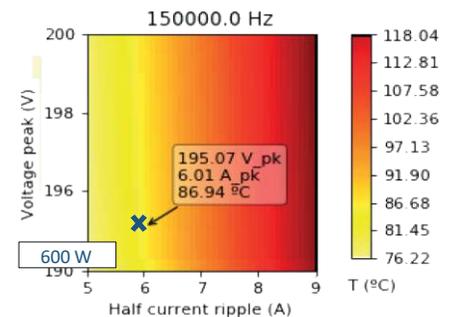
### Design comparison

INFINEON APP NOTE DESIGN

FRENETIC DESIGN



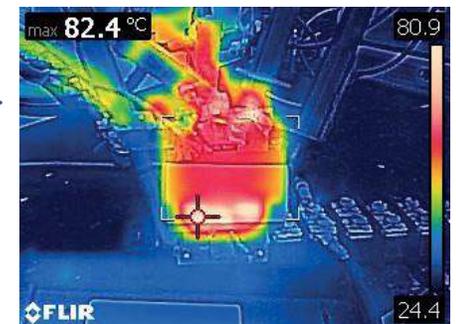
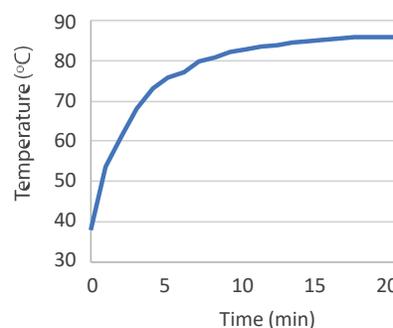
### FRENETIC temperature prediction



## Experimental results

The planar transformer was tested under full load conditions during 20 minutes, time that it required to reach thermal steady state with 84 °C. It can be therefore concluded that the design proposed by Frenetic could had an outstanding performance in the referred application.

### INFINEON APP NOTE VS FRENETIC



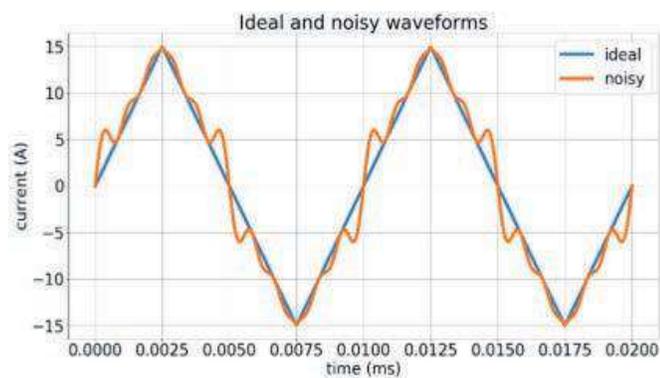
# IMPACT OF DC RESISTANCE INCREMENT WITH TEMPERATURE

Power losses in magnetic components are very frequency-dependent. For this reason, Frenetic technology analyzes the harmonics of the real current waveforms to predict high-frequency losses.

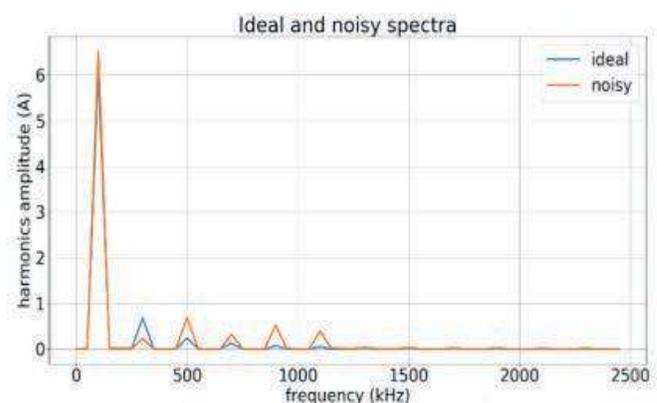
In this document, a comparison of the harmonic analysis is carried out for an ideal triangular waveform and one with noise induced by the converter. The AC resistance is the key factor for the winding losses analysis.

**In the waveform comparison, it is appreciated the noisy signal compared with the ideal one and in the spectrum, the harmonics comparison is shown.**

## WAVEFORM COMPARISON



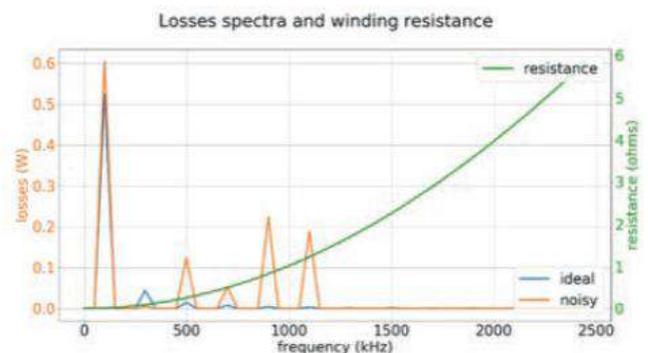
## SPECTRUM COMPARISON



## LOSSES ANALYSIS EXAMPLE

As it is shown in the picture, winding losses are induced by high-frequency harmonics, increasing the losses due to the exponential growth of the AC resistance.

Losses can be drastically reduced when the current waveform approaches its ideal behavior, in this case, the theoretical THD of 12.12% of a triangle wave.



## CONCLUSIONS

The design of a magnetic component is a very complex task to do it manually, which could produce a number of iterations due to problems found during the test stage. Noisy signals are common during first testing stages, therefore the designs should consider it. Since the technology used by Frenetic is automatized for calculating the losses due to the harmonics, the users of Frenetic can verify the maximum THD that their magnetics could manage before rising maximum temperature.

## Real Example Case

The impact of harmonics over winding losses have already been analyzed by Juan Gallego in his application note Impact of Harmonic Analysis in Magnetic Design.

The objective of this paper is to show a real example case of how harmonics can considerably affect the performance of a transformer and to provide some guidelines for reducing such impact at the design stage.

### CASE OF STUDY

To evaluate the impact of the harmonics, a transformer was built and tested at Frenetic's Laboratories. Table 1 summarizes the constructive characteristics of the transformer under test (TUT) and Figure 1 shows the waveforms captured with the oscilloscope. Two cases were considered: Case 1 with a clean trapezoidal waveform and Case 2 with a distorted triangular waveform. To have a fair comparison, the same RMS current and therefore same energy content was applied in both cases. It should be noted that although there are some differences in the voltages applied, the core area and number of turns were selected to ensure negligible core losses.

Figure 2 and Table 2 show the amplitude of the harmonics measured and the theoretical power losses calculated and Figure 3 shows the temperature measured during the test (thermocouple placed between windings).

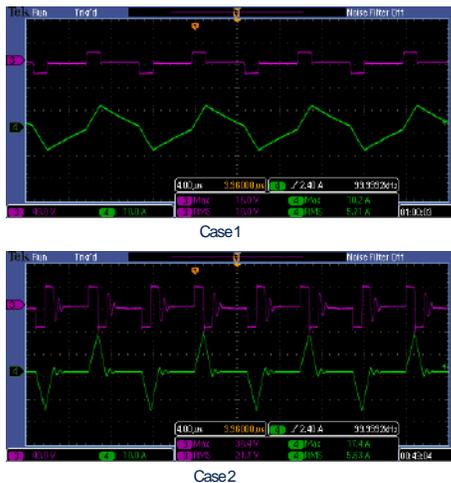


Figure 1. Voltage and current measured at the primary side of the TUT.

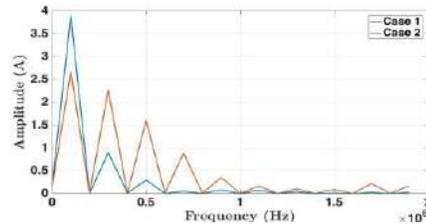


Figure 2. Harmonic content of the current waveforms.

Amplitude of Harmonics					
Case	100 kHz	300 kHz	500 kHz	700 kHz	1100 kHz
1	3,89	0,895	0,296	0,048	0,07
2	2,73	2,3	1,618	0,883	0,165

Theoretical Power Losses				
Case	Core Losses (W)	Winding Losses (W)	DC Losses (W)	AC Losses (W)
1	0,0037	1,79	0,97	0,82
2	0,0 1	5,86	0,97	4,89

Table 2. Amplitude of the harmonics and theoretical power loss analysis

Constructive Characteristics	
Core	PQ32/30 3C97
Turns	9/9
Wire	LITZ 25X0,2 mm

Table 1. Constructive characteristics of the TUT.

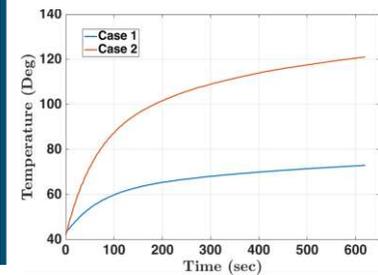


Figure 3. Winding temperature measured during the test.

As it can be seen, having almost the same amplitude at 300 kHz and at the fundamental frequency, and with 50% of the amplitude at 500 kHz, the theoretical power losses of Case 2 increases more than three times with respect to Case 1. This can be clearly seen in winding temperature measured where 120 °C are exceeded in less than 10 minutes thus leading to transformer failure.

### CASE OF STUDY WITH HARMONICS CONSIDERED AT DESIGN STAGE

The same transformer was redesigned optimizing the strand diameter for the 300-700 kHz harmonics. For a fair comparison, the conduction area was kept the same as in cases 1 and 2. The winding losses were reduced down to 1.39W, reaching thus a better performance than both previous cases.

Case	Nº Strands	Strand Diameter (mm)	Outer Diameter (mm)	Conduction Area (mm <sup>2</sup> )	Turns	DC Resistance (Pri/Sec)(mΩ)
1-2	25	0,2	1,42	0,785	9/9	17/18,3
3	420	0,05	1,46	0,82	9/9	17,7/19,9

Table 3. Case 3 constructive characteristics.

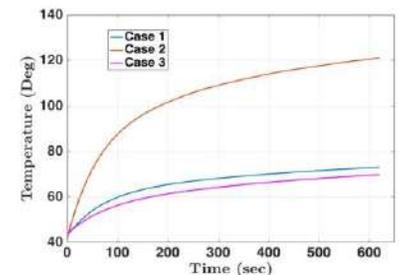


Figure 4. Winding temperature measured during the test.

### CONCLUSIONS

Harmonics have a significant impact on magnetic components performance. This paper has presented a simple example of three cases where the same transformer operates completely different under the same input specifications.

The objective of this paper is not to think of litz wire optimization but rather on how the complete system can be optimized by considering the harmonics at the design stage.

# WINDING RESISTANCE CALCULATION IN PLANAR TRANSFORMERS

Nowadays, planar transformers are commonly used in the design of high-frequency power converters due to its advantages, like low profile, excellent thermal characteristics or power density. In the design of the transformer, an important step is the calculation of the winding losses, which depend on the winding AC and DC resistances.

The objective of this App Note is to show how to calculate the winding resistances and to compare the value of the AC resistance using an interleaved and non-interleaved winding arrangement for the study its influence in the winding resistance calculation.

## WINDING DC RESISTANCE CALCULATION:

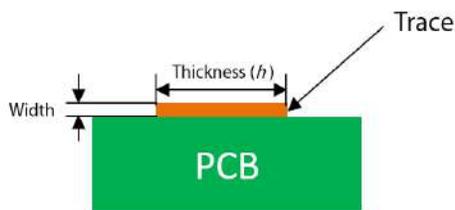
$$R_{dc} = \rho \cdot \frac{l}{A}$$

Where:

$\rho$  is the resistivity.

$l$  is the tracelength.

$A$  is the trace section:  $A = \text{Thickness} \cdot \text{Width}$



## WINDING AC RESISTANCE CALCULATION:

$$\frac{R_{ac,m}}{R_{dc,m}} = \frac{\xi}{2} \left[ \frac{\sinh \xi + \sin \xi}{\cosh \xi - \cos \xi} + (2m - 1)^2 \cdot \frac{\sinh \xi - \sin \xi}{\cosh \xi + \cos \xi} \right]$$

Where:

$\xi$  is the ratio of the layer thickness:  $\xi = h/\delta$

$h$  is the trace thickness.

$\delta$  is the skin depth.

$m$  is the ratio of the proximity effect influence:

$$m = \frac{F(h)}{F(h) - F(0)}$$

\* This calculation gives an approximated AC resistance, and does not consider the porosity factor and high frequency effects related to the currents distribution that cause an extra winding loss.

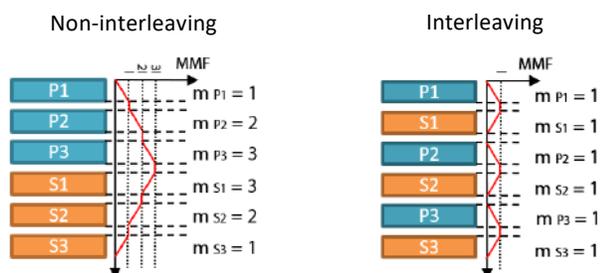
## AC RESISTANCE CALCULATION USING AN INTERLEAVED AND NON-INTERLEAVED WINDING ARRANGEMENTS:

### Transformer specifications

Parameters	Values
Operating frequency	100 kHz
Trace material	Copper
Trace thickness (primary)	6 oz
Trace thickness (secondary)	6 oz
DC resistance	4.1 mΩ
Number of turns (Pri :Sec)	3 : 3

\*One turn per layer

### AC resistance comparison



RAC = 8.9 mΩ

RAC = 4.5 mΩ (50% lower)

## CONCLUSIONS

The winding AC and DC resistance calculation is a very important part of the magnetic design procedure for determining the total power losses. In order to obtain the optimum AC and DC resistances value, a lot of iterations are needed, covering, among other things, all the possible layers distributions or the trace thickness values in planar transformers. Frenetic, thanks to its AI technology, is able to determine the optimum design faster than classical methods.

# PLANAR MAGNETICS DESIGN: TWO-DIMENSIONAL WINDING LOSSES CALCULATION

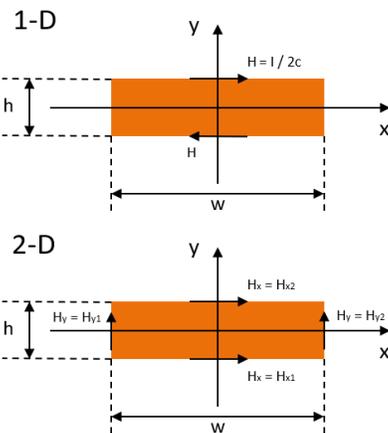
Planar magnetics are increasingly used in switch mode power supplies (SMPs) due to its unique advantages, so accurate losses models are needed to avoid using finite element methods (FEM) in the magnetic elements design procedure, due to the fact that a lot of computing time is required.

The objective of this App Note is to compare two winding losses calculation models: the classical Dowell one-dimensional (1-D) model and a two-dimensional (2-D) model, that takes the edge effect into consideration.

## CONDUCTOR LOSSES PER METER CALCULATION WHEN A SINUSOIDAL WAVEFORM IS APPLIED :

### 1-D conductor losses model:

$$P_{loss} = \frac{I^2}{4\sigma\delta w} \frac{\sinh\left(\frac{h}{\delta}\right) + \sin\left(\frac{h}{\delta}\right)}{\cosh\left(\frac{h}{\delta}\right) - \cos\left(\frac{h}{\delta}\right)}$$



**2-D conductor losses model:** unlike the 1-D model, it considers the conductor thickness, so the two longitudinal components of the magnetic field strength affect the winding losses value and a more accurate result is obtained.

$$P_{loss} = \frac{w}{\sigma\delta} \left(\frac{H_{x2} - H_{x1}}{2}\right)^2 \frac{\sinh\left(\frac{h}{\delta}\right) + \sin\left(\frac{h}{\delta}\right)}{\cosh\left(\frac{h}{\delta}\right) - \cos\left(\frac{h}{\delta}\right)} + \frac{w}{\sigma\delta} \left(\frac{H_{x2} + H_{x1}}{2}\right)^2 \frac{\sinh\left(\frac{h}{\delta}\right) - \sin\left(\frac{h}{\delta}\right)}{\cosh\left(\frac{h}{\delta}\right) + \cos\left(\frac{h}{\delta}\right)} + \frac{h}{\sigma\delta} \left(\frac{H_{y2} - H_{y1}}{2}\right)^2 \frac{\sinh\left(\frac{w}{\delta}\right) + \sin\left(\frac{w}{\delta}\right)}{\cosh\left(\frac{w}{\delta}\right) - \cos\left(\frac{w}{\delta}\right)} + \frac{h}{\sigma\delta} \left(\frac{H_{y2} + H_{y1}}{2}\right)^2 \frac{\sinh\left(\frac{w}{\delta}\right) - \sin\left(\frac{w}{\delta}\right)}{\cosh\left(\frac{w}{\delta}\right) + \cos\left(\frac{w}{\delta}\right)} + \frac{(H_{x2} - H_{x1})(H_{y2} - H_{y1})}{\sigma}$$

Where:

I is the sinusoidal current amplitude.

w is the conductor width.

h is the conductor thickness.

δ is the skin depth:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

σ is the conductor conductivity.

H is the magnetic field strength.

f is the operating frequency.

## WINDING LOSSES CALCULATION USING BOTH 1-D AND 2-D MODELS IN A 1 LAYER AND 3 LAYERS INDUCTOR:

### Conductor specification

Parameters	Values
Operating frequency	250 kHz
Trace material	Copper
Trace thickness	1 oz
Trace width	5 mm
Current amplitude	4 A

### Comparison

	Model	Winding losses
1 layer	1-D	0.7881 W/m
	2-D	0.8743 W/m (11% Higher)
3 layers	1-D	0.7969 W/m
	2-D	0.9514 W/m (20% Higher)

It can be seen how the conductor thickness influence in the winding losses is not negligible and the losses difference between both models increase with the number of layers.

## CONCLUSIONS

The winding losses calculation is an important step in the magnetic design procedure, and a high difference between theoretical and real results can be shown if a low accurate model is used. Frenetic, thanks to its AI technology, is able to use real measurements during the magnetic elements design, for having more accurate results without using FEM.

# PARASITIC CAPACITANCE IN PLANAR TRANSFORMERS

The use of planar transformers throughout the industry is growing fast due to their advantages as low profile, higher efficiency, manufacturing repeatability and reduced electromagnetic interferences. One of the characteristics of planar transformers is the possibility of obtaining a very good coupling between windings, but the drawback is the increment of the parasitic capacitance. Consequently, obtaining the value before manufacturing the transformer is crucial for avoiding potential problems.

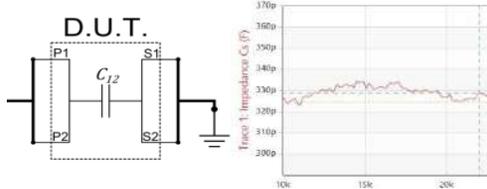
## EXAMPLE OF HOW FRENETIC AI HANDLES THIS PARASITIC CAPACITANCE

In this app note we are going to prove the effectiveness of Frenetic AI calculating the parasitic capacitance comparing Frenetic estimation with the theoretically calculated using different models and real measurements. As an example, we will use a 2 layers PCB on primary and two layers PCB on secondary transformer.

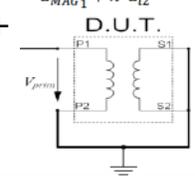
### Laboratory measurements:

The values needed are obtained, with a measurement from the equipment Bode 100 and processing this data with the equations that follow.

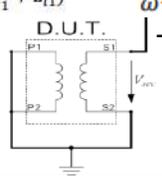
#### Interwinding capacitance



#### Primary Interwinding Capacitance

$$L_{C1} = L_{l1} + \frac{L_{MAG1} \cdot n^2 L_{l2}}{L_{MAG1} + n^2 L_{l2}} \quad C1 = \frac{1}{\omega^2 L_{C1}}$$


#### Secondary Interwinding Capacitance

$$L_{C2} = L_{l2} + \frac{L_{MAG1} \cdot L_{l1}}{n^2 \cdot (L_{MAG1} + L_{l1})} \quad C2 = \frac{1}{\omega^2 L_{C2}}$$


Where:  
 $L_{MAG}$ : Magnetizing inductance  
 $L$ : Leakage inductance  
 $n$ : Number of turns  
 $\omega$ : Angular frequency

### Classic models:

The theoretical models from (Ziwei Ouyang, Ole C.Thomsen, Majid Pahlevaninezhad, Djilali Hamza, Amish Servansing) are used for a theoretical estimation of the parasitic capacitance.

$$C_0 = \epsilon_r \cdot \epsilon_0 \cdot \frac{S}{h_{\Delta}} \quad C_d = \frac{(n+1)(2n+1)}{6n} C_0$$

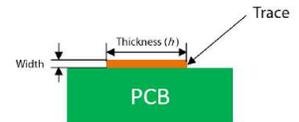
Parallel connection

$$C'_d = \frac{4(m-1)}{m^2} C_d \quad C_d = (n/4) \cdot C_0$$

Series connection

Where:  
 $S$ : overlapping surface area of the layers  
 $\epsilon_0$ : permittivity of free air space  
 $\epsilon_r$ : permittivity of the material  
 $h_{\Delta}$ : distances between the layers

$n$ : number of turns  
 $m$ : number of layers  
 $C_0$ : capacitance between two plates  
 $C_d$ : capacitance of the same winding  
 $C'_d$ : capacitance in all layers



## SOLUTIONS OBTAINED

### Case of study:

-Primary:(type A)    -Secondary:(type B)  
 Turns = 8                Turns = 1  
 Layers = 2                Layers = 2  
 Thickness = 2oz        Thickness = 2oz  
 Area = 0.0064            Area = 0.0064  
 Material = FR4



Results	Measured	Classic	Frenetic AI
Operating frequency	200 kHz	200 kHz	200 kHz
Interwinding capacitance	324 pF	465 pF $\pm 30\%$	320 pF $\pm 2.3\%$
Primary capacitance	437 pF	581 pF $\pm 24\%$	414 pF $\pm 4.3\%$
Secondary capacitance	445 pF	611 pF $\pm 27\%$	439 pF $\pm 2.5\%$
Total Capacitance	1206 pF	1657 pF $\pm 27\%$	1173 pF $\pm 3.8\%$

% of error

Frenetic AI found variables that were not considered in other models that affect in the calculation of the capacitance, and use them to obtain a solution really close to the reality and also in a short time.

### CONCLUSIONS

In planar technology the PCB windings implementation causes higher parasitic capacitance than other technologies. The capacitance affects to the resonance frequency and operation of the transformer, limiting the operating region of the transformer, therefore, obtaining a very accurate estimation will avoid future problems.

# CORE LOSSES CALCULATION PROBLEMS

## COMPENDIUM OF DIFFERENT APPROACHES INCLUDING NEW AI-BASED SOLUTION

At Frenetic we propose a new method for predicting ferrite properties. In this app note we will compare this new method with three other classical models for calculating hysteresis losses. These models have good accuracy in the frequency range from 50 kHz to 300 kHz, but have poor performance outside, mainly because of harmonics or closeness to saturation zone. In this application note, the results are shown.

### Steinmetz

Improved General Steinmetz's Equation.

\*Accurate Prediction of Ferrite Core Loss with Nonsinusoidal Waveforms Using Only Steinmetz Parameters.

K. Venkatachalam C. R. Sullivan T. Abdallah H. Tacca

$$\overline{P}_v = \frac{1}{T} \int_0^T k_1 \left| \frac{dB}{dt} \right|^\alpha |B(t)|^{\beta-\alpha} dt$$

$$k_1 = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos \theta|^\alpha |\sin \theta|^{\beta-\alpha} d\theta}$$

**Pros:** Coefficients provided by the manufacturers.  
Easy implementation.

**Cons:** Inaccurate for waveforms with high harmonic content.  
DC magnetization is not taken into account.

### Jiles-Atherton

Isotropic material model.

\*Jiles D. C., Atherton D. "Theory of ferromagnetic hysteresis Journal of Magnetism and Magnetic Materials 61 (1986)48.

$$M_{an} = (1-t)M_{an}^{iso} + tM_{an}^{aniso} \quad M_{an}^{iso} = M_s \left( \coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e} \right)$$

$$\frac{dM}{dH} = \frac{1}{1+c} \frac{M_{an} - M}{\delta k - \alpha(M_{an} - M)} + \frac{c}{1+c} \frac{dM_{an}}{dH}$$

**Pros:** Easy implementation and quick computing.  
Better than Steinmetz's with harmonics.

**Cons:** Not all manufacturers give the parameters.  
Poor accuracy near saturation.

### Preisach-Everett

Dynamic Preisach model.

\*Preisach Type Hysteresis Models with Everett Function in Closed Form ZsoltV Szabó János Füzí

$$B_i = \sum_{l=1}^n \frac{\alpha_l^2}{\beta_l^2} \frac{(1-e^{-2\beta_l H_i})(\gamma_l^2 - 1) - (1+\gamma_l e^{-\beta_l H_i})^2 \log \frac{(1+\gamma_l e^{\beta_l H_i})(\gamma_l + e^{-\beta_l H_i})}{(1+\gamma_l e^{-\beta_l H_i})(\gamma_l + e^{\beta_l H_i})}}{(\gamma_l^2 - 1)^2 (1+\gamma_l e^{-\beta_l H_i})^2} \frac{dH_i}{dt} = a_n(H-H_n) - b_n \frac{dB}{dt} + c_n \frac{dH}{dt}$$

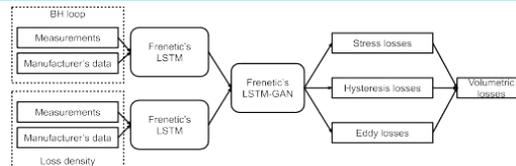
$$E(x,y) = \sum_{l=1}^n \frac{\alpha_l^2}{\beta_l^2} \frac{(e^{\beta_l x} - e^{\beta_l y}) + \frac{(\gamma_l + e^{\beta_l y})(1+\gamma_l e^{\beta_l x})}{1-\gamma_l^2} \log \frac{(1+\gamma_l e^{\beta_l y})(\gamma_l + e^{\beta_l x})}{(1+\gamma_l e^{\beta_l x})(\gamma_l + e^{\beta_l y})}}{(1-\gamma_l^2)(\gamma_l + e^{\beta_l y})(1+\gamma_l e^{\beta_l x})} \frac{dB}{dt} = \mu_0 \left( \frac{dH_n}{dt} + \frac{dM}{dt} \right) = \mu_0 \left( 1 + \frac{dM}{dH_n} \right) \frac{dH_n}{dt}$$

**Pros:** Good accuracy over a wide frequency range.  
Works well with non-sinusoidal waveforms.

**Cons:** Need to calculate the Preisach coefficients and material parameters.  
Heavy computing.

### Frenetic

Deep Learning Model.

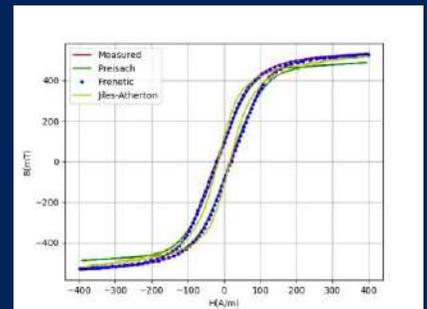


**Pros:** Good accuracy over a wide frequency range.  
Works well with non-sinusoidal waveforms.

**Cons:** Few data points given by manufacturers.

## Experimental results

Model	Hysteresis losses (kW/m <sup>3</sup> )	B-H loop
Steinmetz	16.01	No
Jiles-Atherton	61.841	Yes
Preisach-Everett	72.96	Yes
Frenetic	65.446	Yes
Measurement <small>Driver: BST-PortA</small>	66.805	Yes



### Case of study:

$A_L = 2500$  nH  $l_e = 62.83$  mm  $R_w = 16.5$  mΩ Material= 3F36<sub>FXC</sub> Turns= 10 Freq= 10 kHz  
 $V_e = 3141.59$  mm<sup>3</sup>  $L = 250$  μH Shape= T25/15/10 Wire= Round 18 AWG Temp= 25 °C

## CONCLUSIONS

The results given by the Artificial Intelligence keep the error rate low (~2%, much lower than the other models) due to its intrinsic understanding of the non-linearities existing in the materials (in this case in a low-frequency range), in addition to the blending of measurements and analytical models from which it learns. Predicting power losses with such high accuracy enables engineers to optimize the design of magnetic components by letting them get closer to the working limits of the materials, resulting in more compact and efficient power systems.

## We hope you liked it!

Our team is continually writing new app-notes and articles, we know our customers appreciate all the knowledge we are delivering and we are willing to grow hand-in-hand with our clients and partners.

Join our magnetics learning center, get Frenetic by your side.

Click below, register on our platform and our team will contact you and schedule a demo for you to understand our technology!

Frenetic team.

