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Nanocristal and ferrite numerical comparison for high frequency and low power electronic converters

Comparación númerica de núcleos de nanocristal y ferrita para convertidores electrónicos de alta frecuencia y baja potencia

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Abstract

This paper presents the numerical comparison in ANSYS Maxwell between nanocrystalline, Vitroperm 500F, and ferrite, 3C90, cores to be used in power electronic converters (PECs) transformers. The converter topology used is the doubled switch Forward, due to its characteristics and its power range (<500W). The transformer model development, the characterization and the BH measure curves from the material, as well as its validation and the excitation type implemented in the numerical model are described in the methodology. The exposed results show an improvement in comparasion with the ferrite, in addition to a better flexibility in the magnetic design methodology, given by the nanocrystalline magnetic characteristics.

Nanocrystalline, ANSYS, Forward

Resumen

El articulo presenta la comparación numérica en ANSYS Maxwell entre núcleos de nanocristal, Vitroperm 500F, y ferrita, 3C90, para ser usados en transformadores para convertidores electrónicos de potencia (CEP). La topología de convertidores usada es el Forward con doble interruptor, debido a sus características y su rango de potencia (<500W). El desarrollo del modelo del transformador, la caracterización y medición de curvas BH del material, asi como su validación y el tipo de excitación implementados en el modelo númerico son descritos en la metodología. Los resultados expuestos muestran una mejora en el uso de nancristales en comparación con la ferrita, así como mayor flexibilidad en la metodología de diseño magnético dadas las características del material nanocristalino.

Nanocristal, ANSYS, Forward

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Introduction

Today, electronic power converters (PECs) have increased the operating frequency and reduced the size of the entire system [1]. This can be achieved due to the advancement in the technology of power electronic switches, such as silicon carbide (SiC). The increase in switch technology reduces switching losses [1], which is one of the major considerations by increasing the operating frequency; by increasing the working frequency, the magnetic components can be reduced in size, but the losses in the nucleus increase.

Current materials used in magnetic devices, such as ferrite, have a rather low saturation point which represents an impediment to reduce the size of magnetic devices. That is why the tendency in PECs is to find and use new magnetic materials that can work in smaller sizes and with better performance [2]. New magnetic materials with higher saturation points, wider frequency operating ranges, smaller core losses and small magnetostriction are required. The characteristics of magnetic materials with nanocrystals make this type of candidate materials to migrate from conventional materials, this has led to their potential applications being studied.

In [3] a magnetic nanocrystal stator is constructed and analyzed to reduce the losses in the stator of an electric machine. The shape of the stator core is not commercial and this configuration and special cutting was done by the Hitachi company. The results in [3] show a reduction in core losses from 64% to 75% compared to conventional silicon steel material.

Another application is shown in [4]. In this research, the authors analyzed and designed a high density transformer for a resonant converter (30 kW 200 kHz). At work it can be clearly seen a decrease in size by comparing the nanocrystalline and ferrite material, almost 50% in size. The tests performed on the transformer confirmed an improvement in the performance of the transformer by using magnetic materials with nanocrystalline structures, reducing losses, increasing power density and greater saturation of magnetic flux. While there is some research with nanocrystal magnetic cores such as those discussed in [5,6,7,8], most of the research focuses on high power.

Due to the high power, the size of the core is usually large and the cost of the nanocrystalline material is excessively high, compared to the price of ferrites. There are much smaller nanocrystalline cores that can be used in conventional low power applications with a price that can compete with that of ferrites.

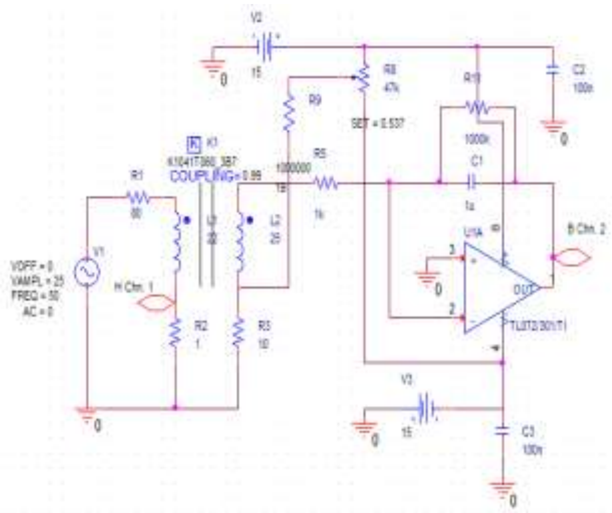

Figure 1 BH curve measuring circuit for magnetic materials

Magnetic Properties of the Cores

This section presents the circuit used to obtain the BH curves of the magnetic materials which are used in the finite element analysis in the ANSYS Maxwell software.

Figure 1 shows the circuit used for the measurement of magnetic parameters, magnetic flux density (B) and magnetic field (H). The magnetic field strength is directly proportional to the field generating current (1) and this passes through the primary of the transformer; therefore, a shunt resistor is necessary to measure the magnetic flux intensity in the core. The magnetic flux is given by the integral of the voltage induced in the secondary, which is why the operational amplifier is configured to function as an integrator and thus the magnetic flux is directly proportional to the output voltage of the operational amplifier (2).

$$H=\frac{Np*I}{Lc} \quad (1)$$

Where H is the magnetic field strength, Np is the number of turns in the primary and Lc is the length of the magnetic path of the core.

$$B=\frac{\Phi}{Ac}=-\frac{Vo*C1*R6}{Ns} \quad (2)$$

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Where B is the magnetic field density, Ac is the cross-sectional area of the core, Φ is the magnetic flux, Vo is the output voltage of the operational amplifier, C1 and R6 are the elements of the integrated and Ns is the number of turns in the secondary.

An oscilloscope is necessary where the channels can be used as axes, since channel one will be connected to the shunt resistor and channel two to the output of the operational amplifier. Figures 2 and 3 show the BH curves of the Vitroperm 500F material and 3C90 ferrite respectively, which were measured at 500 Hz and at 28.5 ° C.

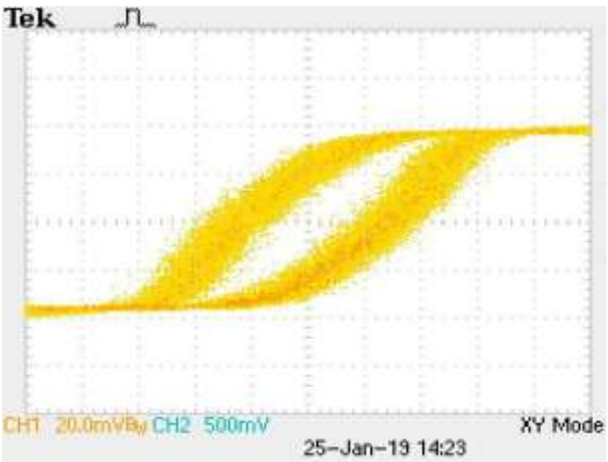

Figure 2 BH curve of the Vitroperm 500F material at 500Hz and 28.5 ° C

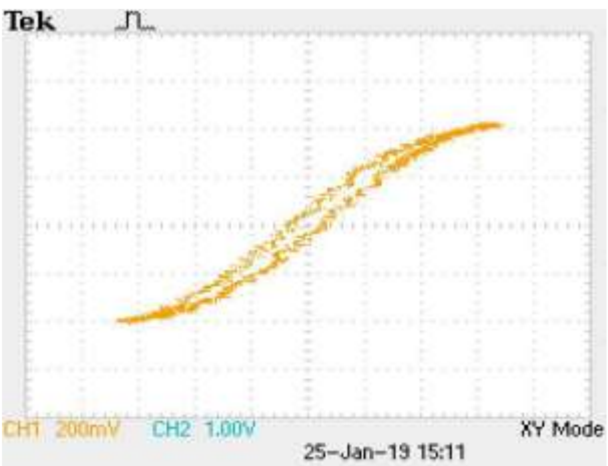

Figure 3 BH curve of the 3C90 ferrite at 500Hz and 28.5 ° C

Finite Element Analysis (FEA)

In this section all the details for the numerical simulation are described. The main design parameters are shown and how the model will be analyzed is created. It is important to present the considerations to simulate a numerical model in the most optimal way.

Therefore, a 2D model is presented in this section. The materials used in the 2D model, as well as the validation to use it are described. It is necessary to validate all material used in an analysis with reference values, usually they can be found in the manufacturer's data sheets. In the corresponding section, the values taken to validate the nanocrystal material are mentioned. Finally, the transitory design of the Forward converter is exposed; this model is created to analyze the transformer. This analysis serves to know the distribution of the magnetic flux and saturation of the nucleus. Core losses are obtained from this analysis because the power of the transformer into a Forward converter is not sinusoidal.

The design of the converter is beyond the scope of this paper, however, the methodology and analysis of the Forward topology with double switch (Figure 4) can be found in [10].

Parameter Name	Design parameters *Value*	*Unit*
Input voltage	200	V
Output voltage	50	V
Output current	10	A
Work cycle	0.25	-
Operating frequency	100	kHz
Inductor value	192	uH
Capacitor value	22	uF

Table 1 Design parameters for the Forward converter

Parameter Name	Design parameters *Nanocrystalline core*		Design parameters *Ferrite core (ETD34)*	
	Value	**Unit**	**Value**	**Unit**
Operating frequency	100	kHz	100	kHz
Security Saturation Point	0.8	T	0.33	T
Number of turns ratio	1	-	1	-
Area product (calculated)	0.3411	4	1.11	cm4
Area product (core)	0.4755	cm4	11.931	cm4
Number of turns in the primary and secondary coil	23	-	23	-

Table 2 Design parameters for the transformer

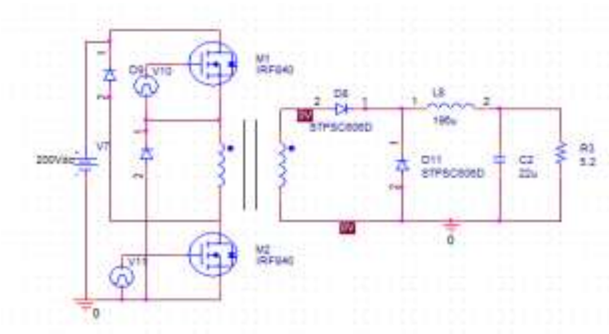

Figure 4 Forward converter with double switch

The parameters for the Forward converter are shown in Table 1. The design parameters of the nanocrystalline and ferrite transformers can be observed in Table 2. The methodology for transformer design can be found in [11] and it shows that the more magnetic flux density can be induced in a material, the smaller the cross-sectional area is needed and the smaller the size of the magnetic device.

The methodology to design an electronic power transformer and analyze it in ANSYS consists of:

1. Design the 3D or 2D model in a computer-aided design software.

2. The next step is to characterize all the materials to be used in the model.

3. Perform a frequency analysis and calculate the losses in the core to compare them with those of the manufacturer.

4. Finally, the transitional analysis model is created. With external power due to the non-sinusoidal power signals that can be observed in the converters.

2D Core and Winding Design

The geometry for nano-crystal numbers, competitive in price to ferrite, which satisfies the design requirements, is a toroidal shape. For a 500W Forward converter, the specific core of the manufacturer Vacuumschmelze is the model T6006-L2025- W523. For the ferrite, the smallest core that satisfies the requirements is the ETD34. These design features to select the cores are those shown in Table 2.

The nominal values of each core, used for the creation of the 2D and 3D model are shown in [12] and [13], for the nanocrystal core and the ferrite, respectively. Because the coating material of the nanocrystal core is considered to be permeable equivalent to that of vacuum, the plastic is created as a non-model element in ANSYS Maxwell to improve the computing speed.

The toroidal model is performed in 2D simulation because simulating the complete 3D model as shown in Figure 5 requires a large amount of computational memory, due to the small cable length. To simulate this model, the first iteration consists of approximately 1,700,000 elements. So the 2D model is recommended when the geometries prevent simplifying winding due to changes in the cross-section of the cable. In the 2D model (Figure 6) we consider that each conductor that is observed is litz cable and there is no induced skin effect on them.

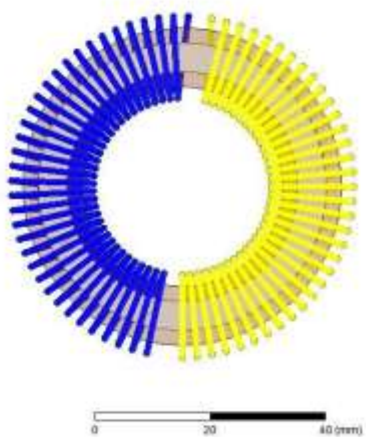

Figure 5 3D model of the toroidal transformer

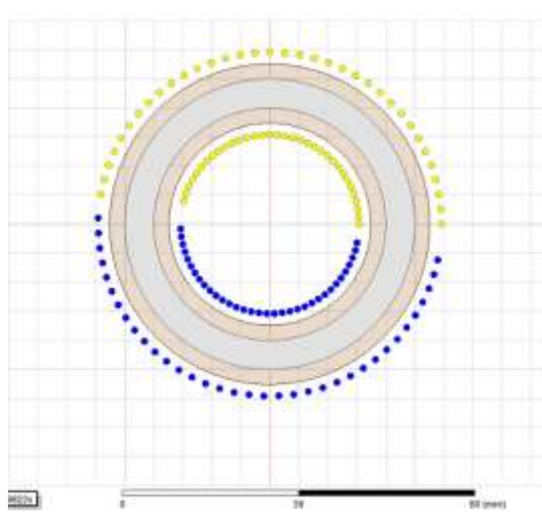

Figure 6 2D model of the toroidal transformer

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In the case of the ferrite core, the winding maintains an equal cross-sectional area in all parts because it is designed as a cylinder. Therefore, this model can be simplified as a solid conductor, where the width of the conductor is given by (3).

$$h = \sqrt{(\pi / 4)} * D \quad (3)$$

Moreover, due to the symmetry stored by the ETD34 core, it is possible to cut the model and simulate only 1/4 of the complete geometry without compromising the system response. The final simulation model for the ferrite core can be seen in Figure 7.

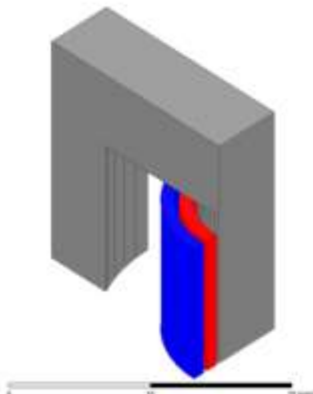
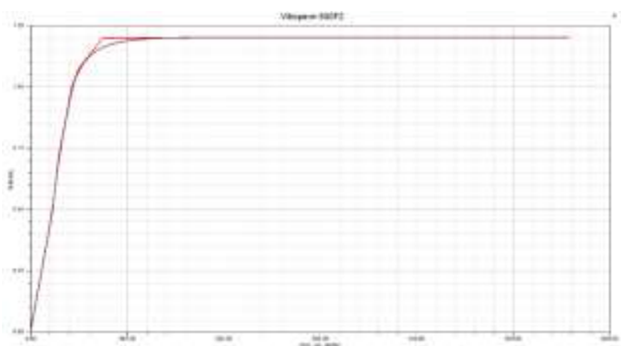


Figure 7 3D model of the transformer, ETD34 core

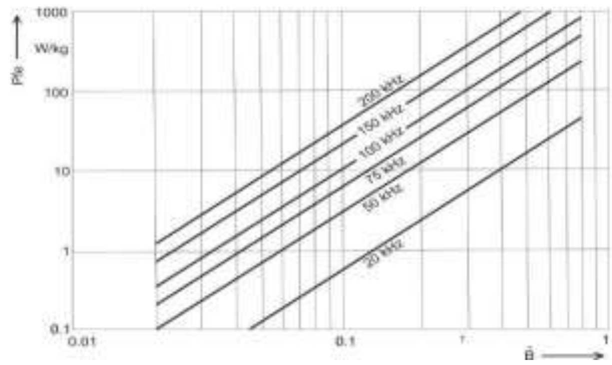


Graph 1 BH curve of the DC of the Vitroperm 500F material

Nanocrystalline Material Characterization

The characterization of ANSYS Maxwell requires giving the BH curve in DC. The BH curve of DC does not contain hysteresis to obtain said curve of the values of Figure 2; the values can be interpolated and checked with the curve given in [9]. The BH curve for the characterization of the material can be seen in Graph 1.

Given the extensive study in the field of ferrites, the ANSYS Maxwell software has in its libraries the magnetic properties of the Ferroxcube 3C90 ferrite, as well as the coefficients of the mathematical loss model, Steinmetz; therefore, it is not necessary to inquire about obtaining the parameters. However, the BH curve obtained in the measurements can be interpolated in the same way as the nanocrystal curve to check the model of the library with the physicist.



Graph 2 Loss curves vs. frequency of the Vitroperm 500F material

The loss model of Steinmetz (4) [14] is the one used in ANSYS to calculate the losses of the magnetic components. The coefficients of the Steinmetz mathematical model are obtained with the loss curves at various frequencies shown in Graph 2 and given in [15].

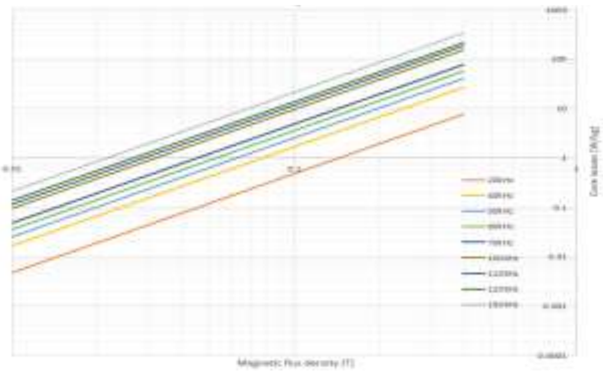
$$P_c = K_h * f * B_p^n + K_e * (f * B_p)^2 + K_\alpha * (f * B_p)^{1.5} \quad (4)$$

Where Kh, n, Ke and Ka are the loss coefficients, f is the operating frequency and Bp is the average magnetic flux density flowing through the core cross section.

The mathematical model of losses already considers hysteresis losses with the corresponding coefficient Kh. Density and stacking factor for laminated materials are other characteristics that are required by the software. The stacking factor can be obtained with (5). The density for the nanocrystal is 7100 kg/m^3 and the stacking factor is 0.4 and must be oriented in cylindrical coordinates on the radial axis, by toroidal geometry.

$$S_F = A_N / A_{Fe} \quad (5)$$

Where A_{Fe} is the effective cross-sectional area of the nanocrystalline material and A_N is the nominal cross-sectional area of the core.



Graph 3 Loss vs. frequency curves of the Vitroperm 500F material obtained in ASYS Maxwell

Nanocrystalline material validation

To validate the material model, it is necessary to perform a frequency analysis with ANSYS Maxwell. The geometry for this simulation is the same one designed in the previous section and only one coil is used to simplify the simulation model. With this analysis, a variation is made in the input power, which is a sine wave, to vary the magnetic flux density induced in the core. To obtain the losses in the core in ANSYS Maxwell (Graph 3) it is necessary to create a line in the core cross section. To obtain a value of the magnetic flux density is used (6).

$$B=\int|\vec{B}|.ds/s \quad (6)$$

Where $\vec{B}$ is the magnetic flux density vector and s is the area of the core cross section.

Losses can be plotted for losses in the core against frequency. Comparing the graph obtained in ANSYS and the one given by the manufacturer, it can be seen how each of the curves of both graphs corresponds, so that the material has been validated with real values and can be used in the following analyzes.

Transitional Analysis Design

The Forward topology comprises a transformer used to isolate the input and output stages of one another and to increase or decrease the output voltage. The transient analysis shows the losses in the nuclei of both transformers: nanocrystal and ferrite.

In this design the excitation of the transformers is the topology of the Forward converter (Figure 4), the parameters are extracted in the circuit editor of ANSYS Maxwell. These parameters determine the amplitude and waveform of the current in the primary. Thus, the transformer can be analyzed for the application that was designed and the other elements of the converter are simulated as ideals.

Numerical Results and Performance Comparison

This section shows the results of the transitional analysis. The analysis is considered from the start of the circuit and is simulated until it reaches the steady state in order to compare the cores correctly. The time range for the simulation is from 0us to 900us, with a time step of 0.1us to ensure quality results; 9000 iterations are performed per transformer. Due to the analysis requirements, parallel processing is used in ANSYS using 9 of 10 available processor cores.

ANSYS Maxwell uses an automatic mesh refinement method, only in non-transient analyzes. Therefore, to have a quality mesh in the transitory analysis, the frequency analysis mesh has been imported, which improves the simulation time.

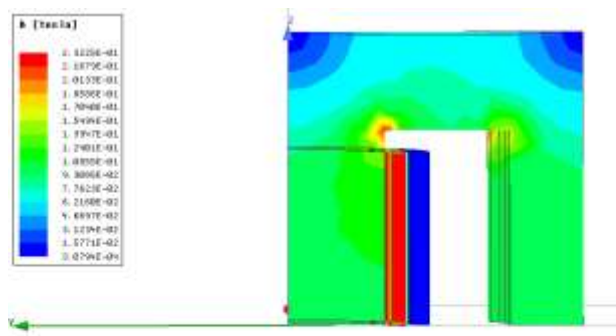


Figure 8 Density of magnetic flux in ferrite core

For both materials there are values calculated automatically by the software. The first parameter analyzed is the magnetic flux density (B), Figures 8 and 9 represent the time interval where the greatest B occurs.

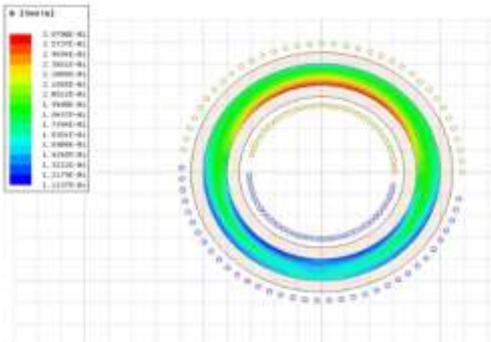
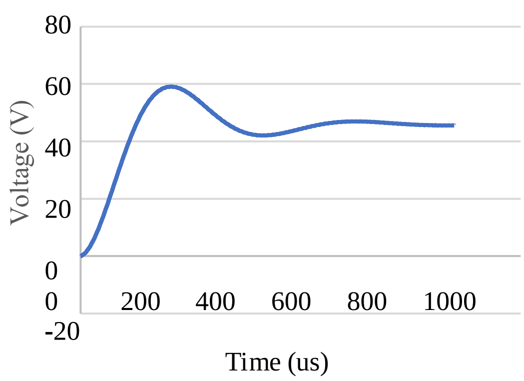
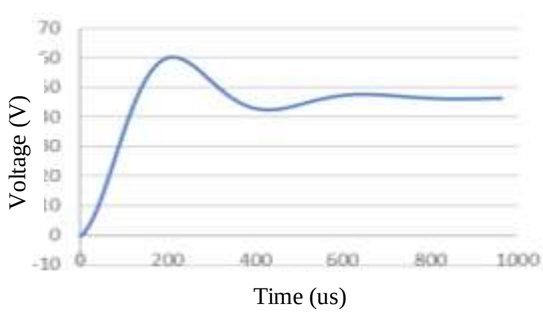


Figure 9 Magnetic flux density in nanocrystal core

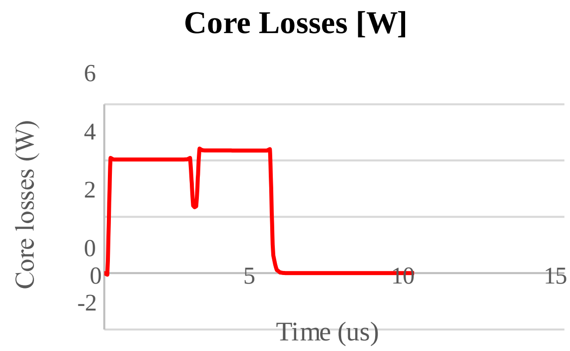
A more prone to saturation nucleus in the ETD34 nucleus can be seen in Figure 8. The saturation point for the 3C90 ferrite is 0.44 T; despite this, in the design it is always advisable to consider a saturation point lower than the real one, to avoid saturating the core, in this case the saturation point fixed is 0.33 T. In Figure 8 the maximum value of magnetic flux is 0.218 T compared to the nanocrystal core B, which is 0.261 T. The saturation point for the design in the nanocrystal core was 0.8 T. By analyzing both nuclei, we can see that the most prone to saturation is the ferrite core. Figure 4 shows the output voltage of the Forward convector with a nanocrystal core. Comparing the output voltage of the nanocrystal core converter with the output voltage of the ferrite core converter (Figure 5), we can see that the latter is larger than the nanocrystal core.



Graph 4 Output voltage of the converter with nanocrystal core

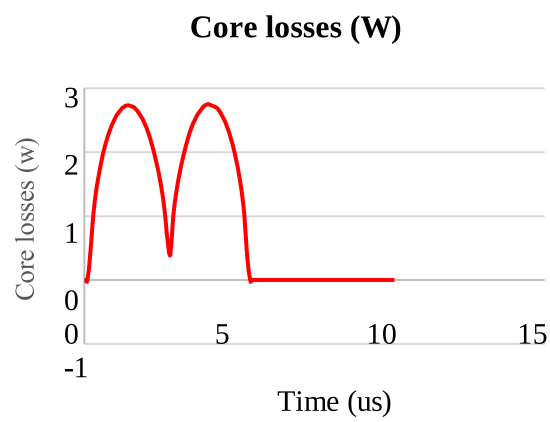


Graph 5 Output voltage of the converter with ferrite core



Graph 6 Loss in the nanocrystalline nucleus

Figures 6 and 7 show the losses in the transformer core built with nanocrystal and with ferrite, respectively. It can be seen that the losses in the ferrite transformer are lower than in the nanocrystal transformer. This is due to the fact that the cross-sectional area of the nanocrystal transformer is smaller, causing a higher magnetic flux density in the nanocrystal core.



Graph 7 Loss in the 3C90 ferrite core

Given the conductivity or material, there are greater losses due to Eddy currents compared to losses of the ferrite core. The losses of the ferrite core are almost entirely attributed to the hysteresis losses of the material and turn out to be smaller than the nanocrystal core.

Conclusions

By analyzing the results obtained in the simulation, a greater flexibility in the design for the nanocrystal nuclei can be observed. Although the losses in the nanocrystalline core are greater compared to that of ferrite, the cross section of the ETD34 core is 4.9 times larger than the core cross section T60006-L2025-W523.

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This represents a larger core and weight; the ferrite core is 3 times heavier than the nanocrystal core, and there is no smaller ferrite core that meets the design specifications of a 500W Forward converter, unless the security saturation point becomes wider, which can create the risk of saturating the core. If the cross section of the nanocrystal core doubled the losses between the cores it would be similar. The nanocrystalline core has greater flexibility in design, due to its high saturation point.

The cross section of the nanocrystalline core can be increased by saving the same dimensions specified in the data sheet, if a greater stacking factor is specified to the manufacturer to cover the cross section with more magnetic material. This type of low-cost cores are used in common mode shock, however, this article demonstrates its wide potential and improvement in power density and losses in electronic power converters, increasing the cross-section of the core to induce less losses by Eddy currents in the material.

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