Teaching Magnetic Design using CAD tools

Roberto Prieto, Jesús A. Oliver and Pedro Alou

Centro de Electrónica Industrial

Universidad Politécnica de Madrid

***Abstract*. Design of magnetic components is a multivariable problem. There are many different combinations of shapes, sizes and materials for the core with many diameters for the wires. So it is difficult to find the optimum design without a great number of iterations. Analytically only a few combinations are usually studied but it is very easy to take into account all the combinations using a CAD tool [1]. In this work the CAD tool used is PExprt (ANSYS [2]) which is being developed at UPM-CEI.**

I. ANALYTICAL DESIGN

Design of magnetic components for power converter is based on the specifications of the power converter (input voltage and current waveforms).

A. Inductors analytical design

To design the inductor it is necessary to select both the core and the conductors. The core is characterized by the size, the shape and the material. The size is commonly selected in order to manage the specified power. The shape depends on the specific application of the component. The material is selected in terms of the switching frequency of the converter. The type of conductor (solid wire or Litz wire) is function of this frequency too. The conductor area implies a limit on the losses and is commonly selected considering the skin effect. The number of turns, N, is selected in order to avoid core saturation (1).

$$N = \frac{L \cdot i_{max}}{A_e \cdot B_{max}} \tag{1}$$

With L and N it is possible to calculate the total reluctance of the component, which determines the gap dimensions, if it is necessary.

Once the design is obtained the next step is the losses calculation:

- Core losses are well evaluated with vendor databooks or with the classical Steinmetz model. This model appears in equation (2).

$$P = V_e \cdot k \cdot f^{\alpha} \cdot \left(\frac{\Delta B}{2}\right)^{\beta} \tag{2}$$

Where k, α and β are properties that depends on the core material and the frequency and Ve is the effective volume of the core. The goal of the design is to find the magnetic component with least losses, so it is not necessary a very accurate result because the comparative analysis of different designs is more important. A trade-off between precision and efficiency is needed, so the Steinmetz model is considered the best.

- **Wire losses** have two components Direct Current (DC) losses and Alternating Current (AC) losses. The AC wire losses are produced by the mechanisms of skin effect and proximity effect. Analytically, wire losses are usually evaluated with the following equation:

$$P \cong R_{DC} \cdot I_{eff}^2$$

$$R_{DC} = \rho \cdot \frac{l}{s} \tag{3}$$

Where only DC resistance (RDC) is considered but not AC resistance. This is not very recommendable if the ripple of the current waveform is important compared with the DC level (then AC resistance is not negligible).

If the losses value is right the process is finished, otherwise a new design must be recalculated (iterative process). It is not effective to do a lot of iterations and so it is difficult to obtain the optimum component.

B. Transformers analytical design

In a transformer the combinations are multiplied by the windings number. The initial specifications of the converter define the value of turns ratio. In a transformer the rules to select the core and to select the conductor type are the same as in the inductor. But the conductor area is selected to optimize the losses. Usually the different wires of the windings have the same current density. The following step is to obtain the number of turns of primary side which maintain the core losses bellow a fixed value.

Losses calculation is equal than for the inductor. If the core losses and the wire losses are right the design is finished, otherwise it will necessary to redesign the component. However, not always the optimum design is to reach the same core losses and wire losses, it depends on the kind of core material.

II. CAD DESIGN

The use of the software tool makes possible a better optimization of the components by analyzing a lot of combinations of wires, bobbins and cores possibilities. This would take a lot of time in an analytical way.

A. Inductor and Transformer Losses

- **Core losses.** Steinmetz model continue being the best in the trade-off between efficiency and accuracy.

- **Wire losses.** Both DC losses and AC losses are considered. The expression for the losses is:

$$P = \sum_w R_w \cdot I_w^2$$

(4)

Where Rw and Iw are the resistance and current for the w-th harmonic. So, it is necessary an harmonic decomposition of the current waveform and to know the dependence of the resistance with frequency.

Another way to calculate wire losses is with Dowel model, which allows splitting up the losses due to skin effect and the losses due to proximity effect.

It also takes into account the fringing flux, caused by the effect of the gap [3-4], which modifies the window energy. This means a different gap length too.

Especially significant is the losses optimization. In an analytical way the optimization can be done refereed to the flux density (if the current ripple is big) or to the number of turns (if the current is mainly DC). The frontier between two limits is not clear. As a solution the CAD tool optimize both of them, starting with the design with the minimum number of turns and increasing it discreetly, it finds a minimum in the losses.

B. CAD Design versus Analytical Design

- CAD design is more flexible than analytical design and it is not necessary to be an expert designer.

- Design of magnetic components is a multivariable problem and the optimization is not easy. However, using a CAD tool it is very easy to take into account all the combinations.

- Analytical equations of magnetic components are difficult to solve, but it is easy to implement these equations in a software tool.

- The main drawback is that it is necessary to buy and to learn how to use the different CAD tools.

PExprt specific advantages

- It has a friendly interface.

- It prevents construction problems, by selecting only the stock components.

- The output of the analysis is a list of components (Figure 1.), so the designer can compare different designs and choose the better using his/her own guidelines (less power losses, volume, height, footprint, temperature...).

Figure 1. List of results of PExprt.

- It allows a quick documentation, because of the easy generation of text files and screen captures.

- It also allows an automatic model generation of the magnetic component. The model can be 1D analytical, based in transmission lines for PSpice and Simplorer simulators. It is also possible to obtain a 2D/3D model, based in Finite Element Analysis Tools (FEA). It is very useful to have a model to study the component not only as an isolated component but also as a part of a power converter.
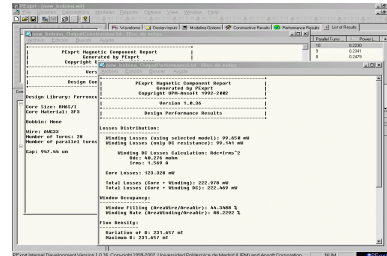

Figure 2. PExprt Text Files for documentation.

C. Design Steps

Next, the design steps of magnetic components with PExprt are described (grouped by sections).

Specifications

There are two ways to input the initial specifications of the power converter, which are shown on Figure 3. The first one is using the current and voltage waveforms and the second one with the specific topology of the power converter.
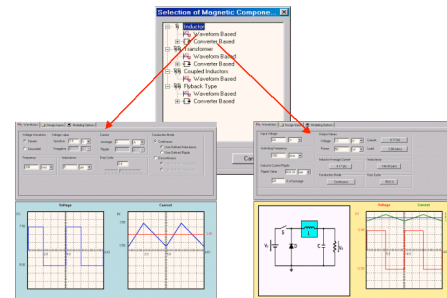

Figure 3. Diagram of PExprt Input Specifications

If the input is based on the waveforms, there is not any restriction in the type of inductor or transformer that can be designed.

If the input is based on the converter specification, the available are:
- Inductor of a Buck.
- Inductor of a Boost.
- Inductor of a Buck-Boost.
- Transformer of a Classic Forward.
- Transformer of a Half Bridge.
- Transformer of a Full Bridge.
- Transformer of a Half-Bridge.
- Transformer of a Push Pull.
- Transformer of a Flyback.

Component Selection

The next step is to select the desired components from the Design Libraries of the vendor (Figure 4.). These components are the shape, size and material of the core, the bobbin, and the wire types.
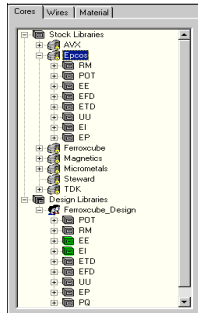

Figure 4.   Component Libraries

Designing with a CAD tool allows a better design optimization, by analyzing a lot of combinations of wires, bobbins and cores. This analysis will cost a lot of time in an analytical way.

Design Inputs

The main options are (Figure 5.):
- The gap can be central, can be divided in both legs or the magnetic component can have no gap.
- The design can be with or without bobbin.
- The wire geometry can be planar, concentric or toroidal.
- The separation between the wires of a layer or between different layers must be specified.
- Winding distribution can be 2D, 1D partially full or 1D completely full.
- The user can limit some values, for example the temperature rise, the gap size, the number of parallel wires.
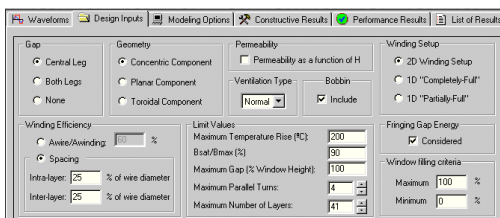- The fringing gap energy can be considered.

Figure 5.   Design Inputs

Modeling options

Modeling options are divided in three groups.
- **Wire losses calculation.**

Wire losses have two components, the Direct Current (DC) losses and the Alternating Current (AC) losses. The AC wire losses are produced by the high frequency mechanisms of skin effect and proximity effect.

PExprt has three options to calculate the losses:

- **Only DC losses**

Then, the equation to evaluate the losses is:

$$P \cong R_{DC} \cdot I_{eff}^{2}$$

$$R_{DC} = \rho \cdot \frac{l}{s} \tag{6}$$

Analytically, this is the way to evaluate the losses, without taking into account AC losses. This s not very accurate in the designs with an important current ripple compared with DC level, because AC losses are not negligible.

- **DC losses and AC losses:**

Skin effect only or Skin and Proximity effects (Dowell model [5])

In these cases, the expression for the losses is:

$$P = \sum_{w} R_{w} \cdot I_{w}^{2}$$

$$\tag{7}$$

Where R_{w} and I_{w} are the resistance and current for the w-th harmonic. It is necessary a harmonic decomposition of the current waveform and to know the dependence of the resistance with frequency.

Therefore, AC losses calculation is not effective analytically. However, it is very easy to compute AC losses with a CAD tool like PExprt.

- **Losses optimization.**

There are two optimization modes. In Mode 1 the optimum number of turns is calculated to minimize the total losses. In Mode 2 the optimum number of turns with the optimum parallel wires are calculated to minimize the total losses.

- **Options of the List of Results.**

The list of results can be made with all the solutions or with a limited number of solutions that keep some requirements (minimum losses, minimum volume, minimum temperature rise...)
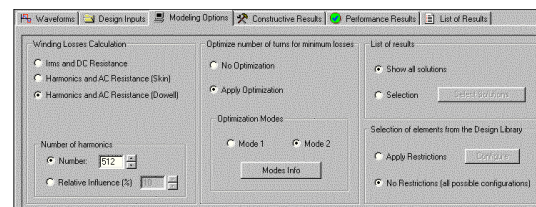

Figure 6.   Modeling Options

List of Results

The output of the analysis is a list of components (Figure 1.). PExprt does not calculate only one design, but a list of possibilities for the specifications. The designer selects the most suitable with his/her own design guidelines.

If a design is selected out of the list of results, it is possible to see the constructive results and the performance results.

Constructive Results

For example:
- Wire type.
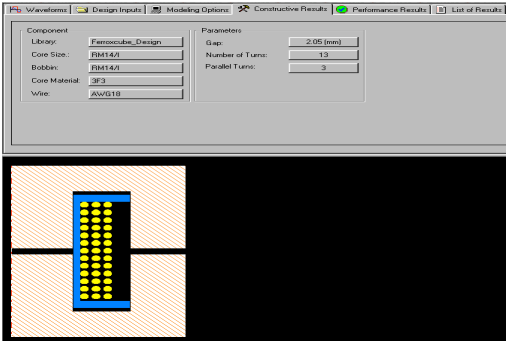- Number of turns.
- Gap length.
- Core size and material.

Figure 7. Constructive Results

Performance Results

For example:
- Losses.
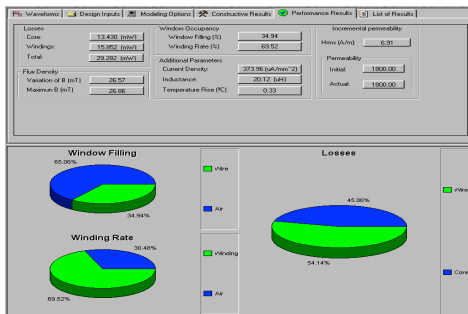- Window occupancy.
- Flux density.

Figure 8. Performance Result

Modeling

There is a link with the Maxwell FEA tool, for a 2D/3D modeling of magnetic components.

There is also another one for building a 1D analytical model based in transmission lines to study the global converter. The model can be implemented in an electrical simulator, like PSpice or Simplorer.

III. EXAMPLE. TRANSFORMER OF A FLYBACK.

A. Specifications

The main converter specifications are shown in the following table. The circuit is shown in Figure 9. The transformer is working in Continuous Conduction Mode.

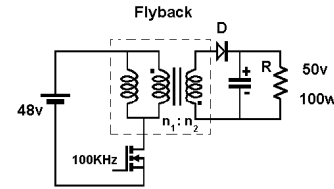| Input Voltage	48 V
Output Voltage	50 V
Power output	100 W
Switching Frequency	100 kHz
Maximum Current	0.458 A
Current Ripple	1.66 A
Inductance	150 mH
Duty Cycle	50%

Table 1. Converter Specifications

Figure 9. Flyback topology

B. Analytical Design

The Analytical design of the inductor has been obtained in the way described in previous sections:

	Design A.1	Design A.2
Core Size	RM12/I	RM12/I
Core Material	3F3	3F3
Primary		
Irms	2.83 A	2.83 A
Wire Diameter	0.4 mm	0.4 mm
Number of Turns	27	27
Number of Parallel Turns	3	5
Secundario		
Irms	2.95 A	2.95 A
Wire Diameter	0.4 mm	0.4 mm
Number of Turns	27	27
Number of Parallel Turns	3	5
Gap	855 mm	855 mm
Windings Losses	1.24 W	744 mW
Core Losses	37 mW	37 mW
Total Losses	1.51 mW	781 mW

Table 2. Results of the analytical designs

Designing is an iterative process. As the winding losses were very high in Design A.1, a new design of less losses (Design A.2) is obtained with more parallel conductors in both primary and secondary side of the transformer.

C. PExprt Design

PExprt data input is based on the converter specifications. The input voltage and current waveforms on the transformer extracted from the tool are shown in Figure 10. and Figure 11.
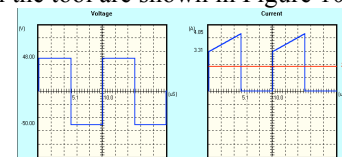

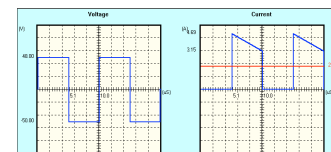*Figure 10. Voltage and Current waveforms on the primary side*

Figure 11. Voltage and Current waveforms on the secondary side

Searching for the Analytical Design with PExprt

Among the numerous solutions that are calculated with PExprt, one of them (Design B) is equal to the analytical design (Design A.2):

| Core Size	RM12/I
Core Material	3F3
Primary	
Irms	2.9 A
Wire Diameter	AWG27 0.4 mm
Number of Turns	27
Number of Parallel Turns	5
Secondary	
Irms	2.8 A
Wire Diameter	AWG27 0.4 mm
Number of Turns	27
Number of Parallel Turns	5
GAP	873.8 mm
Window Filling Factor	48.8 %
Windings DC Losses	**836.523 mW**
Windings AC Losses	881.1 mW
Core Losses	35.1 mW
Total DC Losses	**871.6 mW**
Total AC Losses	916.2 mW
Temperature Rise	16 ºC

Table 3. Design B
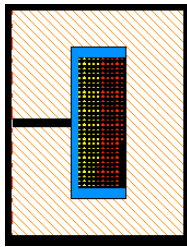
Figure 12. Axial View of the Design B

The losses results are very similar. There are only little differences with the winding losses because of the effective currents, which are not exactly the same for both designs.

Using the wire diameter as degree of freedom and keeping the core constant.

The core is kept constant and all wires of the stock library are selected. PExprt design of fewer losses is the previous one. The harmonic content of the current waveform is very high, so the wire selected analytically is the best. Skin effect must be considered for the wire selection.
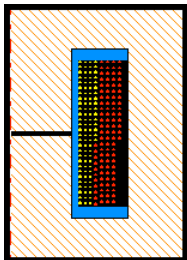

Figure 13. Axial View of the Design C

Changing the core type

If the core selected is smaller, there is not a design of fewer losses than the Design B.

If the core selected is bigger (RM14/I), the losses decrease:

Core Size	RM14/I
Core Material	3F3
Primary	
Irms	2.9 A
Wire Diameter	AWG25 (0.51 mm)
Number of Turns	20
Number of Parallel Turns	5
Secondary	
Irms	2.8 A
Wire Diameter	AWG24 (0.57 mm)
Number of Turns	20
Number of Parallel Turns	5
GAP	633.4 mm
Window Filling Factor	42.5 %
Windings DC Losses	**405.9 mW**
Windings AC Losses	444.7 mW
Core Losses	58.2 mW
Total DC Losses	**464.1 mW**
Total AC Losses	502.9 mW
Temperature Rise	6.3 ºC

Table 4. Design C

It is interesting to increase a bit the size of the transformer because the Window Filling Factor of Design B is very high and it can be difficult to build. With this new design, Design C, winding losses fall and core losses are still low, so it is a very good design.

Gap effect

In this section, the purpose is to emphasize the utility of use 2D/3D FEA models to design magnetic components. With these models it is possible to study the gap effect in the losses of the magnetic component.

The way to use a FEA model is with PExprt Analysis Mode. Previously, a PExprt FEA model must be extracted from the appropriate link. It is easier to implement these models in a CAD tool versus its use in the analytical design.

The design selected is Design B. It has not a very big gap but as it is a design with a lot of turns, the gap effect becomes very important, so accurate winding losses can be calculated with this model:

Core Size	RM12/I
Core Material	3F3
Primary	
Irms	2.9 A
Wire Diameter	AWG27(0.4 mm)
Number of Turns	27
Number of Parallel Turns	5
Secondary	
Irms	2.8 A
Wire Diameter	AWG27 (0.4 mm)
Number of Turns	27
Number of Parallel Turns	5
GAP	873.8 mm
Window Filling Factor	48.9 %
Windings DC Losses	836.5 mW
Windings AC Losses	**25.3 W**
Core Losses	**43.1 mW**
Total DC Losses	879.2 mW
Total AC Losses	**25.4 W**
Temperature Rise	442.2 ºC

Table 5. Design C modified

AC losses have a great increase compared with the Dowell

model losses [5]. This can induce errors when less losses design is being selected, and this is illustrated with the following example.

In Figure 14. , there is a list of results calculated with Dowell model sorted by losses.

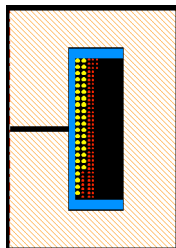*Figure 14. List of results.*

Figure 15. Axial View of the Design D

Two designs are compared; the Design B (in blue) and the following design in losses, named Design D (in red). Design D has more losses than Design B, but the gap of Design D is smaller. As the gap effect increases the losses, this influence will be less considerable in Design D. This can be observed in the following table:

	Dowell model	PExprt model
Core Size	RM14/I	RM14/I
Core Material	3F3	3F3
Primary		
Irms	2.9 A	2.9 A
Wire Diameter	AWG23 (0.64mm)	AWG23 (0.64mm)
Number of Turns	20	20
Number of Parallel Turns	2	2
Secondary		
Irms	2.8 A	2.8 A
Wire Diameter	AWG27 (0.41 mm)	AWG27 (0.41 mm)
Number of Turns	20	20
Number of Parallel Turns	4	4
GAP	633.4 mm	633.4 mm
Window Filling Factor	21.7 %	21.7 %
Windings DC Losses	785.2 mW	785.3 mW
Windings AC Losses	**858.5 mW**	**12.9 W**
Core Losses	58.2 mW	67.8 mW
Total DC Losses	**843.5 mW**	**853.1 mW**
Total AC Losses	**916.7 mW**	**13 W**
Temperature Rise	10.8 ºC	154 ºC

Table 6. Design D

PExprt losses of Design D are smaller than the ones of Design B. If the effect of the gap in the losses is taken into account, the position of both designs will exchange the order in the list of results.

Finally, PExprt losses of Design C have been calculated in order to study if this design is still the optimum design:

Core Size	RM14/I
Core Material	3F3
Primary	
Irms	2.937 A
Wire Diameter	AWG25 (0.51 mm)
Number of Turns	20
Number of Parallel Turns	5
Secondary	
Irms	2.878 A
Wire Diameter	AWG24 (0.57 mm)
Number of Turns	20
Number of Parallel Turns	5
GAP	633.4 mm
Window Filling Factor	42.5 %
Windings DC Losses	405.9 mW
Windings AC Losses	14.3 W
Core Losses	67.8 mW
Total DC Losses	473.7 mW
Total AC Losses	**14.4 W**
Temperature Rise	180.8 ºC

Table 7. Final design

Design D presents fewer losses than Design C, because the first one has less number of turns. The optimum design (of less losses) has changes when a PExprt model is used.

IV. CONCLUSIONS

As the current ripple is important, skin effect must be considered for the wire selection. That is why the wire selected analytically is the PExprt optimum too.

Other way to compute AC wire losses is the use of 2D/3D FEA models and, so 2D/3D effects can be taken into account, for example, gap effect. If the gap effect is important, as in this example, these models are very useful: there are changes in the design positions in the list of results ordered by losses. It is easier to implement these models in a CAD tool versus its use in the analytical.

This example has illustrated the advantages of using magnetic design CAD tools in order to teach particular effects. The combination of slides, blackboard and CAD tools are an excellent receipt for explaining magnetic design.

V. REFERENCES

[1] Final Master degree work "Diseño de Componentes Magnéticos para Alta Frecuencia", R. Rubio, División de Ingeniería Electrónica (E.T.S.I.I, UPM).

[2] Ansoft Corporation. Web site, http://www.ansoft.com.

[3] "Air-gap reluctance and inductance calculations for magnetic circuits using a Schwarz-Christoffel transformation", Balakrishnan, A.; Joines, W.T.; Wilson, T.G. Power Electronics, IEEE Transactions on , Volume: 12 Issue: 4 , July 1997 Page(s): 654 –663

[4] "New modeling strategy for the fringing energy in magnetic components with air gap", Escribano, L.M.; Prieto, R.; Oliver, J.A.; Cobos, J.A.; Uceda, J. Applied Power Electronics Conference and Exposition, 2002. Seventeenth Annual IEEE, 2002 Page(s): 144 -150 vol.1

[5] "Effect of eddy currents in transformer windings", P. L. Dowell. Proceedings of the IEE. Vol 113 no.8. August 1966.Page(s).1387-1394