Advanced Modeling and Simulation

Techniques for Magnetic Components

P. R. Wilson

Analogy Europe, Kembrey Park - Swindon, United Kingdom

Abstract

A new approach for the detailed modeling and simulation of Magnetic Components, such as Power Supply Transformers or Inductors is presented. The models include high frequency capacitive effects, Non Linear Core Models, Material Characteristics and Wire Modeling. The models are created with 4 levels of abstraction depending on the application and level of detail required by the design engineer. The creation of models has been enhanced with the use of a graphical modeling tool which allows topology modeling, top-down versus concentric winding approaches, interleaving of windings and insulators to be taken into consideration.

The use of physical structure and material data for the generation of the models means a model is created which accurately reflects the behavior of the real device across its full operating range of power and frequency. A unified approach has been used which allow a single point of entry to be used for magnetic component data, and any model to be generated. The application of this method for the detailed specification of magnetic components is also presented with a description of the component design process.

Introduction

As the switching frequencies in high performance Switched Mode Power Supplies has increased, the effects of physical aspects of magnetic components have become more important in obtaining a robust design. These effects have also been influenced by the requirement for smaller size and weight, which again have made the physical configuration of the magnetic component more significant in the performance of the overall system being designed as well as the individual magnetic component.

To verify a design’s performance is within specification simulation has become a standard part of the design process for Power Systems, using such simulators as Spice or Analogy’s Saber. With basic simulation models the basic non-linear effects can be modeled with behavioral models of the core such as the Jiles-Atherton Model. However, detailed effects such as interwinding capacitances, wire resistance drops, skin effects, insulator configuration or material characteristics are usually not considered. When these effects are included, they may use in-accurate calculation expressions, which do not give a true picture of the real values. Examples of these approaches may give errors of 50% or greater which makes their use of limited value for accurate simulation.

In the conventional design process it is common for prototypes to be required to measure these parameters before testing the overall design using simulation or prototyping. It is obviously useful therefore if a procedure can be used to easily create accurate models for magnetic component designs, to use in virtual prototyping prior to any preliminary components being manufactured.

In the construction of a procedure for model generation, each effect must be considered in turn, and addressed. For each effect a method of model calculation can then be applied resulting in a parameter or list of parameters describing these effects. The final stage is to collate this information into an integrated form able to accurately represent these effects in a unified model.

It is already well known that some of these effects can be obtained directly using a Finite Element Approach, but this has several disadvantages. The Finite Element Tools require a level of expertise to use which is beyond that of the vast majority of design engineers. This makes them impractical for standard use. They also only give parts of the model at any one time. This means that many setups and simulations must be carried out to obtain the necessary information. Then the user has still to collate this information into a coherent form for a model.

A new software approach now exists for magnetic component model generation which allow the user to specify a magnetic component in terms of its geometry and material characteristics and generate a model including the main effects of this physical model for use in electrical simulators. The software is designed so that it is easy for any design engineer to apply this technique. The use of external Finite Element software for complex physical analysis is not precluded by this technique, but rather is hidden from the designer where possible. In fact the FEA software can be run completely in batch mode with no interaction required whatsoever. All of the required calculations are completed automatically, and a model is generated.

The effect of having accurate simulation models of magnetic components will have a profound effect on the quality of designs produced, as the accuracy of simulated waveforms allows much better design of snubbers, EMI reduction techniques, Power Factor Correction or Harmonics reduction and design performance.

Basic Concepts for Magnetic Modeling

The function of any magnetic component is to provide a link between the electrical and magnetic domains using wound wire (either cylindrical or copper foils) and some magnetic core structure. The core model will have some form of magnetic flux linkage, non-linearity and hysteresis, and losses due to the material used. Conventional modeling approaches have used a lumped element model structure with the magnetic circuit based on an equivalent circuit using reluctances. This circuit requires two basic models, one for the winding which links the electrical and magnetic circuits, and another for the purely magnetic circuit which encompasses the flux path.

To illustrate this concept, if a simple two winding transformer model is presented, we can represent this component using our winding and core models using a simple equivalent circuit as shown in figure 1.

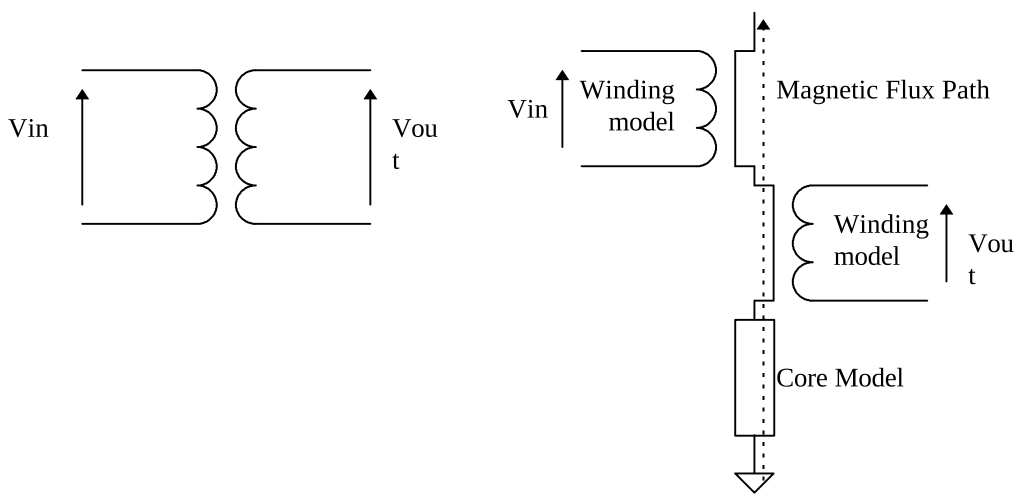


Figure 1 : A two winding transformer and its lumped element equivalent magnetic model

It is clear from the lumped element model used in this example, that there is not much detailed modeling of the core to replicate the physical structure, but the magnetic circuit may be made more complex, by using a network of core models with appropriate dimensions to give a more accurate representation of the true physical nature of the flux patterns inside the core. With this method it is possible to give a model which includes the geometry of the core as well as the location of the windings.

This type of model is extremely useful, particularly in the early stages of the design in order to have an initial approximation of the component performance. The model will be limited, however, to low frequency analysis due to the lack of high frequency effects in the model.

Requirements for models

The requirements for models to be trusted by designers in simulations of switching systems across a wide frequency range mandate the core material hysteresis curve to be defined, any gaps defined in the core, orientation and positioning of the windings, the conductor type (wire, Litz wire or copper foil), AC resistance and inductance. These parameters are not easily obtained analytically from a definition, and usually require measurements to be made prior to any effective modeling and simulation.

Extending the useful frequency range of transformer models

The method whereby the basic low frequency models can be extended to the high frequency range is to include the frequency dependent complex impedances of the winding and inter-winding structures. To extend the frequency range of the models requires the use of either an analytical representation of Maxwell's equations or a numerical approximation such as the Finite Element Method [1],[2] to realize a more general model. In a large number of magnetic components it is possible to approximate the magnetic equations using a one-dimensional approximation of Maxwell's equations. It is beyond the scope of this paper to detail this approach, but the method is described in [3]. In summary, the technique allows each winding to be represented using a lumped element model of the physical characteristics of the layer, with the elements able to be given values directly from the physical dimensions of the layer in the magnetic component. The lumped element layer model is shown in figure 2 below.

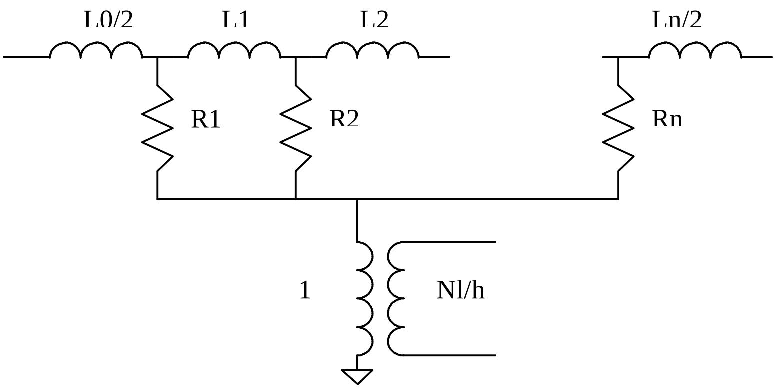


Figure 2 : Equivalent circuit Model for a layer

The number of elements in each layer model is calculated directly from the frequency range required and the thickness of the layer using the expression :

$Fmax = 17.77.10^{-3}.n^2/e^2$

Where : n is the number of elements, and e is the layer thickness. If we take a 1mm layer, for example, if the maximum frequency required is 1MHz, then the number of elements will be 8.

Using this approach, more accurate models of the magnetic component can be generated, which will give accurate models of the winding resistance, and leakage inductance across the desired frequency range for structures can be generated.

Using the Finite Element method for Model Generation

The final method for model generation presented in this paper makes use of the Finite Element method to effectively carry out physical measurements of a physical model of the magnetic component, and use the results of this physical simulation to create a more accurate model of the component.

The basic classical model of the magnetic component is first extended by applying complex impedances as shown in figure 3 around the basic model structure which will implement the frequency and geometry dependent characteristics obtained from the Finite Element Simulations. This structure will obviously become more complex as windings are added, with inter-winding models for each winding added. The individual impedances are calculated by using the Finite Element Solver to calculate an AC Magnetic Analysis (For inductance effects) and a DC Electric Analysis (for Capacitive effects), and then the parameters for the impedances extracted.

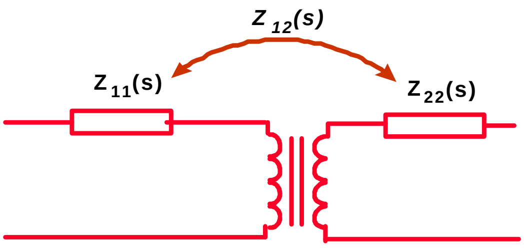


Figure 3 : Modified Model Structure

The Finite Element Analyses are computed for a number of frequencies within a specified range of operation, and then from this the frequency dependent characteristics obtained. This method gives the potential for much better accuracy than the analytical methods used until now due to the minimal approximation used (the actual geometry is simulated), and this is demonstrated with comparisons with practical measurements in [4] and later in this paper.

Application of Modeling techniques in Magnetic Component Design

So far in this paper 3 methods have been presented for modeling magnetic components which can be summarised in table 1.

Method	Geometry Approximation	High Frequency Effects	Low Frequency Effects	Speed of Model Generation	Full Geometry
Reluctance	✓	-	✓	FAST	-
1D Analytical	✓	✓	✓	FAST	-
Finite Element Extraction	✓	✓	✓	SLOW	✓

Table 1 : Summary of Methods

Each method has its advantages and disadvantages, but all have applicability for the designer who needs to simulate using the models. For example, if the model is required for only low frequency work (<1kHz), then the reluctance model will probably be accurate enough. If however a detailed model including fringing effects, and skin effect, is required then the Finite Element Method would be recommended. In all cases a modeling approach using a common entry interface would be desirable, which not only acts as a modeling tool, but also includes component specification as this involves much of the same information. Once the basic component has been specified, then a simple approach for the designer to choose which level of model is required is the easiest method for generating the model with the required parameters and accuracy.

The required design flow is shown in figure 5. The common items are entering the physical data, defining the materials and specifying the windings. The user then decides which level of model to create and also the component specification. The model can then be used to test the component, and the specification updated as necessary.

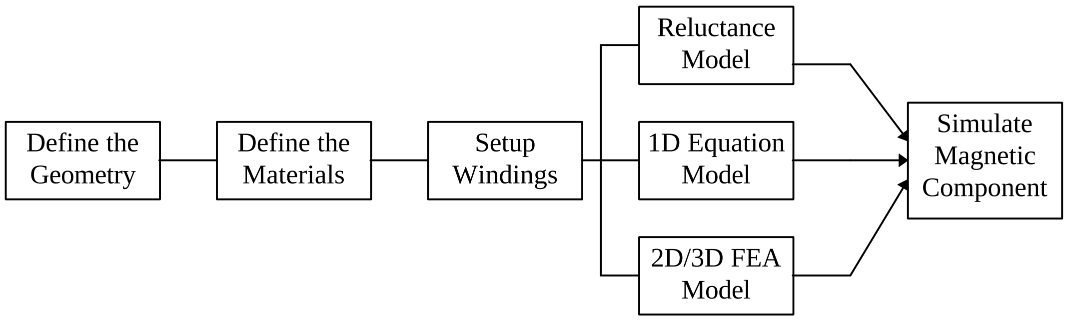


Figure 5 : Magnetic Component Design procedure

Now although each of these tasks are possible to be completed manually, it is advantageous if a common approach can be used, so that the magnetic component can be designed in a single design tool, with easy to use interface features including access to core and material libraries, definition of windings, physical layout definition, model generation facilities and links to FEA (Finite Element Analysis) tools. With these requirements a new magnetic design tool, SaberMMP, was designed and implemented to manage this design process. The user interface for SaberMMP is shown in figure 6.

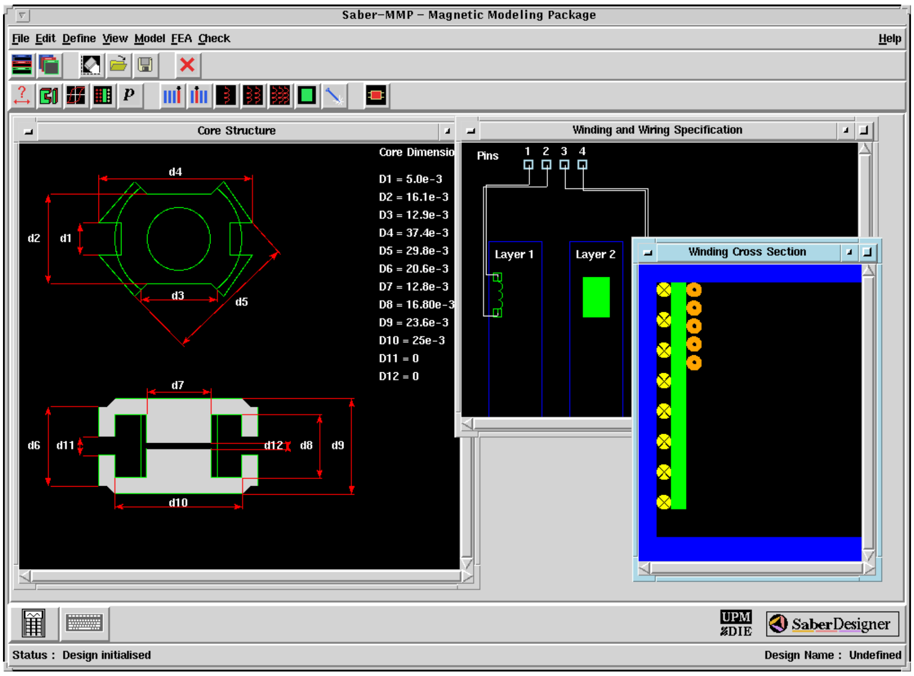


Figure 6 : Magnetic Modeling Package User Interface

As can be seen from the interface, the design tool allows the magnetic component designer to select a core structure, defining it's physical dimensions and material characteristics. The user has access to a schematic editor to allow the addition of windings and insulators, which can also be viewed using the winding layout window, showing how the windings are configured in the winding window. To illustrate how the design tool is used a 2 winding transformer design is presented.

Core Structure and Material Definition

The definition of the core structure and material is obtained from either library materials and cores or by defining dimensions or curves from data sheets supplied from the magnetic material manufacturers. For example, if the core required is an RM12 core, this can be selected from the library, or the dimensions entered into the required fields in the new core structure definitions form as shown in figure 6.

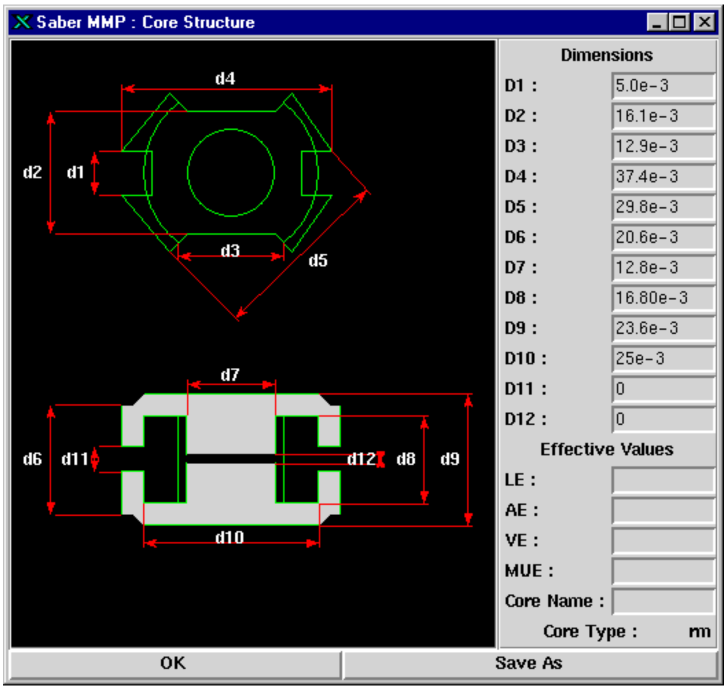


Figure 6 : Core Structure Definition

At this point it is also possible to modify the library parts to include specific air gaps, or custom modifications such as low profile sizes by editing the definitions of the specific dimensions. The material characteristics are entered using similar methods.

Winding and Insulator Specification

The windings and insulators are specified using the winding connection schematic editor as shown in figure 7. The editor allows the placing of magnetic windings, and the definition of their wire size (or copper size for Planar devices), the inter-turn spacing, the number of turns and the orientation (note the dot notation for ease of polarity checking). The conductivity is used to automatically assign the wire resistance depending on the number of turns and the effective radius.

When the parameters for each winding are entered, they are reflected in the winding layout, also shown in figure 7, allowing the user to verify that the windings defined will fit correctly inside the core geometry specified. Also defined in the winding specification schematic are the external connection pins and the wiring of the windings to these pins. This must also be accounted for in the final model or specification.

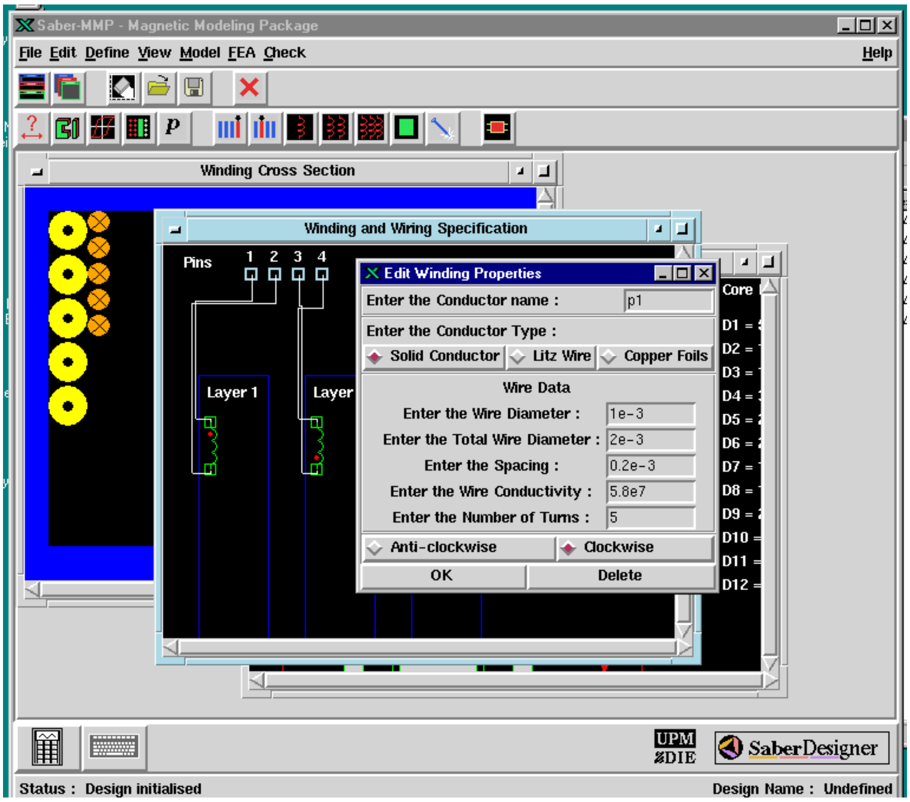


Figure 7 : Winding Definition and Connections in SaberMMP

Model Generation

On completion of the component specification by wiring up the connection points, the model menu can be used to generate models using reluctance, 1D or FEA modeling tools built in to the interface.

Transformer Model Example

To illustrate the modeling approach and its application to a practical example, a two winding transformer was designed using different wiring approaches and comparisons made between simulated and measured results. In this case an external Finite Element Solver was used to generate a 2 dimensional model of the transformer for simulation in the Saber Simulation Program from Analogy.

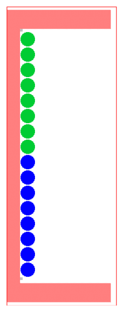


Figure 8 : Side by Side Topology

The first option tested used two windings side by side as shown in figure 8, and this was defined simply using the graphical user interface winding specification manager. The component was defined as a concentric model with standard solid wire conductors with 8 turns each on the primary and secondary of the magnetic component.

This was simulated using Saber to evaluate the A.C. Resistance and reactance against frequency, and these results are shown in figure 9, compared with measured results for the same transformer. The magnetic

Component was an RM12 core, made of 3F3 material, and the wire diameter was 0.7 mm. The results show a good correlation between measured and simulated results across the frequency range defined (up to 700kHz).

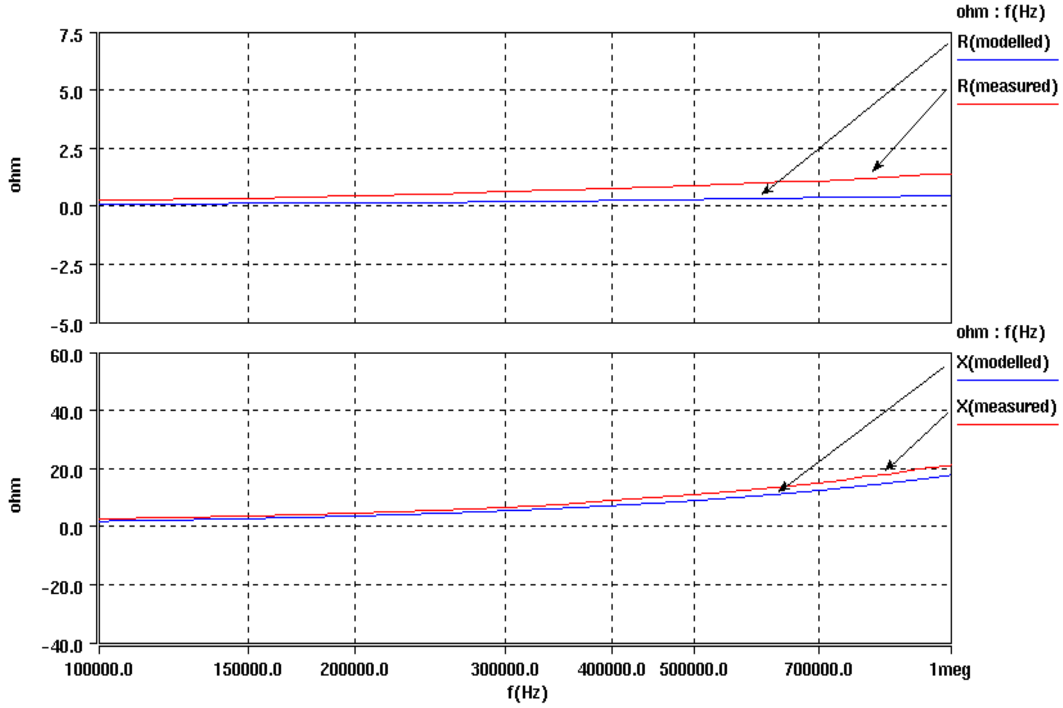


Figure 9 : Side by Side Windings Measured and Simulated Results

The windings were then redefined using the interleaved approach. This is where the windings are wound with the primary and secondary side by side on each turn. This method is usually implemented by winding a bifilar wire the required number of turns. The new layout of the windings is shown in figure 10, and clearly the effect is designed to reduce the leakage inductance between the windings.

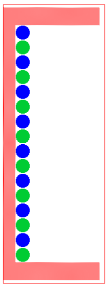
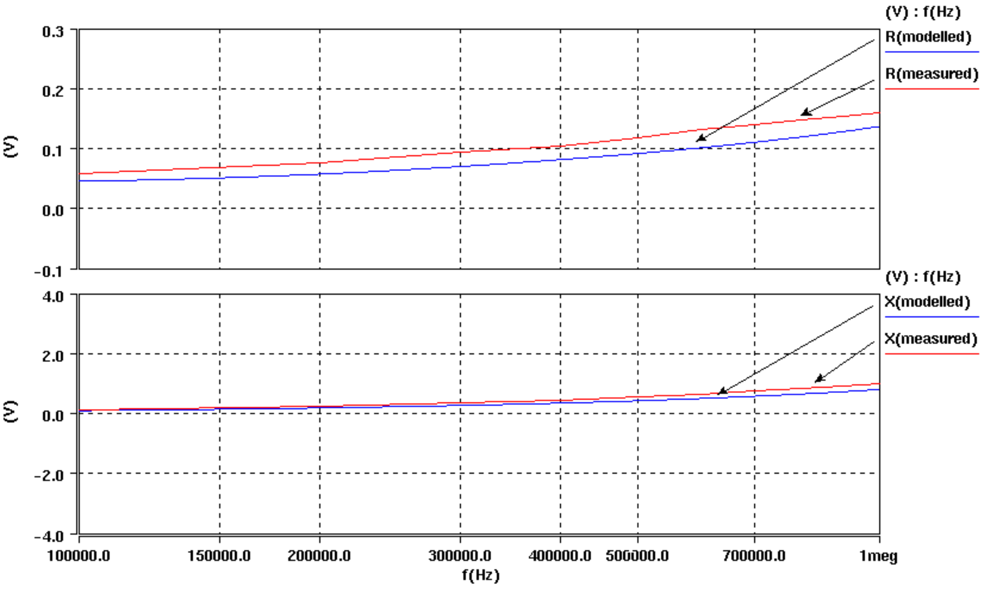


Figure 10 : Interleaved Winding Layout

The transformer was then re-modeled using the new winding layout, and resimulated. The new simulation results were also compared with a real transformer, and these results are shown in figure 11. It is clear that again there is a good correlation between the simulated and measured results, and that the level of AC resistance and reactance has much reduced to this different winding layout.



Interleaved AC Resistance and Reactance

Conclusions

The methods used in the generation of models for simulation are significant to the design engineer involved in designs requiring accurate modeling of the higher order effects of magnetic components. These effects are usually crucial in the performance of Power Supply or Power Distribution Systems and are widely used in the motor drive or commercial applications such as CRT drives and Lighting circuits. Effective modeling of the magnetic component is essential to achieving a robust and correctly operating design.

The effect of having accurate simulation models of magnetic components will have a profound effect on the quality of designs produced, as the accuracy of simulated waveforms allows much better design of snubbers, EMI reduction techniques, Power Factor Correction or Harmonics reduction and design performance.

References

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