Personal Computer
Circuit Design
Tools

intusoft

Magnetics Designer

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Contents

TABLE OF CONTENTS

TABLE OF CONTENTS

Introduction

Magnetics Designer Capabilities

Magnetics Designer is optimized to design layer- and sector-wound magnetics using cores that have rectangular or circular winding areas. Typical designs may include ferrite pot cores, ferrite EI and EE cores, cut C cores, toroids, and EI laminated cores. Magnetics Designer is capable of designing single phase multi-winding transformers operating from 10Hz to well above 1MHz. Typical applications include 60 Hz line transformers using laminated cores, 400 Hz transformers using cut C cores, and high frequency switching regulator transformers using ferrite cores.

Magnetics Designer is also directed towards applications where a specific inductance is required in the presence of any combination of AC and DC current. Typical applications include flyback transformers and switching regulator output filter inductors.

The following figure illustrates the cross-section of a typical transformer or inductor coil. The empty spaces on left and right sides of the windings are called end margins. Note that the insulation between windings (wrapper) extends out to the edge of the end margins. This technique is used to increase the creepage distance between adjacent windings in order to avoid high voltage breakdown due to surface contamination.

The cross-section of a typical transformer or inductor coil
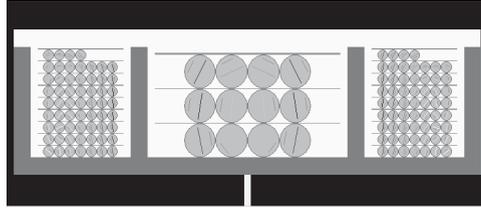
Three windings are shown. The first and last windings are a high voltage primary, split about a low voltage secondary. The dark gray represents a bobbin upon which the coils are wound. The lines through the copper represent the magnetic field, with the higher intensity field shown as black. Only a portion of the core is shown in black, and the winding stack is symmetrical about the bottom of the figure. Magnetic Designer allows you to choose from a wide variety of wire types: **Heavy Formvar**, **Small Formvar**, and **Litz** magnet wire tables include wire gauges from 10 AWG to 40 AWG (European wire sizes are also included); **square** and **double-square** magnet wire tables include wire gauges from 0 to 30 AWG; **pcb traces** are specified by the thickness of copper, minimum trace width, minimum trace spacing, and PWB thickness; **foil** may be specified in various thicknesses. You can create your own wire tables with different sizes of wire. For example, the square and double-square wire tables can be edited to describe virtually any rectangular wire format. You can also describe a table with a sparse set of gauges (i.e., even gauges only). Windings may also be multi-filar.

Three insulation options allow the user to specify layer insulation thickness, wrapper thickness, and end margin lengths. If there are multilayer foil windings, layer insulation may be included between each layer of foil. There is also an option to account for the margin required for inner layer windings to exit the bobbin. Bobbin dimensions are included in a separated data entry page.

Magnetics Designer retrieves core data directly from a database with magnetic and geometric properties for thousands of cores.

You may enter your own core geometries, materials, and wire using the procedures outlined in Chapter 3. On-the-fly reality tests are made as the core database is read in. These tests exploit redundancy in the data in order to detect errors.

After selecting the core family and material, and entering some basic electrical requirements, Magnetics Designer will optimize the design for you using a powerful set of state-of-the-art algorithms. The program will select the core geometry, turns ratio, wire sizes, and number of strands to achieve your design goals and constraints such as temperature rise and window fill.

When finished, the program will predict characteristics such as peak flux density, AC flux density, DC winding resistance, high frequency AC resistance, copper losses (both AC and DC), core loss, leakage inductance, winding capacitance, weight, efficiency, temperature rise, and window fill percentage. For high frequency designs, the program estimates AC losses. A more accurate, although slower field simulation gives higher accuracy results -- especially for unusual winding configurations.

The winding specification and electrical performance specifications may be displayed, copied to a word processor, or output to a printer or text file. The winding specification provides a physical description of the transformer design which includes the core size, core material type, gap length, turns, wire sizes, etc. The performance specification summarizes the electric/magnetic design characteristics such as flux density, magnetizing inductance, DC and high frequency AC resistances for each winding, core and copper loss, and efficiency.

Magnetics Designer also produces a SPICE model and schematic symbol of your finished design, allowing you to use your design with popular schematic entry programs and analog simulators. DXF output of the Bobbin, core and winding geometry allows export to Finite Element Analysis (FEA) software for more detailed analysis of electrical and thermal behavior.

Within the general constraints described on the previous page, you can see that Magnetics Designer has a great deal of flexibility and can handle many different winding configurations, wire types, and core configurations.

The Differences Between the DOS and Windows Versions

The Magnetics Designer software was originally developed by Analytic Artistry, the leader in the field of nonlinear magnetics design software. In 1995, Intusoft acquired the rights to the "Transformer and Inductor Spreadsheet" software, two separate DOS based programs. A large number of changes have been made to the original version, including combining of the various DOS programs into one unified solution. The Core Data Filer program, which was used to edit the core and material databases, is now performed with Microsoft Excel. A detailed description of changes to the original program can be found in the "FAQ.htm" document.

The Differences Between Version 3 and Version 4

The main addition to version 4 is the Bobbin tab which enables you to define winding configurations for side-by-side or sector wound transformers and inductors. A major technological investment was made to describe high frequency behavior using a magnetic field simulation along with a new layer based algorithm in the synthesis portion of the software, for fast optimization. "ReleaseNotes.htm" describes the new features and bug fixes in detail.

Manual Layout and Description

The manual is laid out in 6 sections: Program usage, Editing the core/material database, Magnetics design related information, Generating the requirements needed for a design, Choosing the right core, and Design examples.

To Get Started: Read *Chapter 2* completely in order to understand how to use the program. Pay special attention to the Transformer and Inductor screen explanations. *Chapter 4* will help you generate the proper data required by the program.

Chapter 2 provides an overview of the program and its usage, including how to enter data and get output. The major screens, Core, Transformer, Inductor, Bobbin, IsSpice, Options, Vendor, and Wire, are covered in detail. General information on the SMPS wizard and its use is also provided.

Chapter 3 describes the core database included with Magnetics Designer. Directions on how you can add your own materials and geometries are included, along with examples.

Chapter 4 reviews the fundamental design equations which describe how transformers and inductors function. It also describes the algorithms used by the two programs to select a core and determine the optimum current and flux densities.

Chapter 5 provides application-related information to help designers correctly describe the electrical requirements.

Equations for calculating DC current, AC current, and RMS current are presented for several common waveforms in Appendix A.

Chapter 6 describes various core geometries and materials. Guidelines are presented for selecting core types and material types as a function of the intended application.

Chapter 7 illustrates the capabilities of Magnetics Designer by showing how to design the magnetics for several specific applications. Four examples illustrate how to design a push-pull PWM converter transformer, a forward converter transformer, a DC choke, and a flyback transformer.

MANUAL LAYOUT AND DESCRIPTION

Using Magnetics Designer

Installation

- **Insert the Magnetics Designer CD into your CDROM**.
- **Wait for the auto setup screen to appear <u>or</u> use Windows Explorer to navigate to setup.exe in the root of the CD and launch the setup program**.
- **Follow the instructions on your screen**.

The software is installed, by default, into the C:\Spice8\MAGS directory. You may change this destination; for example D:\Spice8\Mags, however, it is best to keep the default when possible.

A Magnetics Designer program group will be created for you. The program is now called magnetic.exe so that you can keep your old version in another folder in order to compare results.

Hardware/Software Requirements

Magnetics Designer requires Windows 95/98/ME, or Windows NT4/2000/XP. It uses less than 8 megabytes of RAM.

Magnetics Designer can be used on ANY of the above Windows operating systems.

You do not need a different version of the program for each windows environment.

Using Magnetics Designer on a network: There are no special requirements for using Magnetics Designer across a network. The software executable may reside anywhere on your network. However, Magnetics Designer may be run by only one computer at any one time. **Use of the software on more than one computer at any one time is a violation of the license agreement.**

Starting Magnetics Designer

To start Magnetics Designer:

- Double-click on the Magnetics Designer icon.

When you start Magnetics Designer for the first time, you will be prompted to enter your name, company, and serial number.

The serial number for the program is located on the Magnetics Designer CD.

Make sure to enter the serial number exactly as shown, including spaces. When the program starts, the Core selection screen displays in the Design Info window.
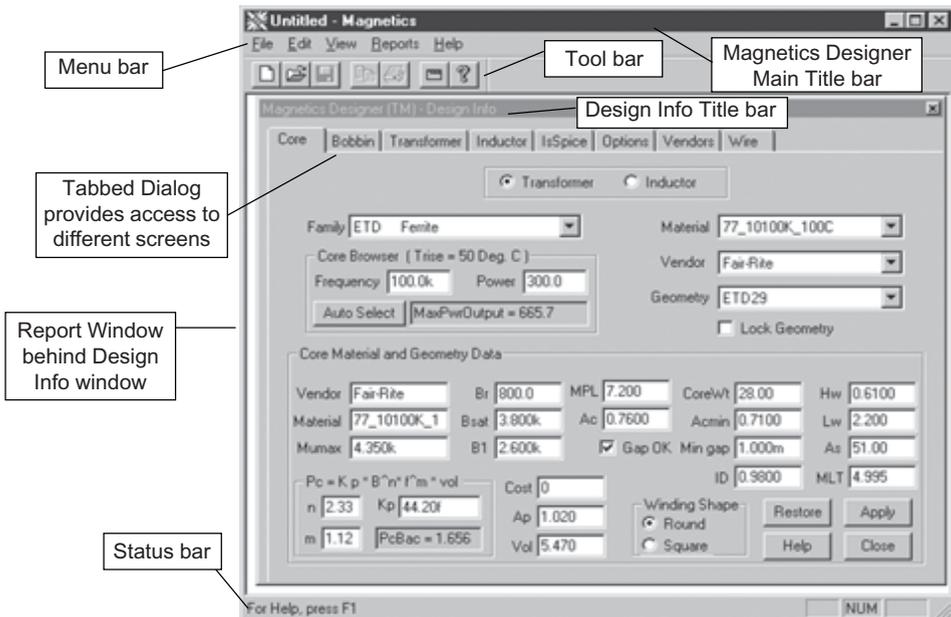
General Program Usage and Flow

The program contains several different screens that can be activated by clicking on the tabs under the Design Info window's title bar. Below is a brief description of the program operation. More detailed explanations can be found later in this chapter.

1) After Magnetics Designer is started, the first task is to select the desired core family and material.

This is done on the core screen (shown on the previous page.)

Magnetics Designer automatically loads the entire core database when it begins.

A core family, material and geometry can be selected from the pop-up menus on the core screen. Using the pop-ups, you can browse through the entire database of cores. The geometrical and material characteristics of each core are shown at the bottom of the screen. Instructions for adding your own cores, material, or wire are described in *Chapter 3*.

Help Note: If you hold your cursor over a particular variable name, a "tool tip", or help balloon, as it is often called, will pop-up.

Core Material and Geometry Data

Vendor Fair-Rite	Br 800.0	MPL 2.580	CoreWt 1.100	Hw 0.3050
Material 77_10100K_1	Bsat 3.800k	Ac 85.53m	Acmin 85.50m	Lw 0.7400
Mumax 4.350k	B1 2.600k	☑ Gap OK Min gap 100.0n	As 5.644

ID 0.3300   MLT 1.995

Pc = K p * B^n * f^m * vol

n 2.33   Kp 44.20f

m 1.12

Cost 0

Ap 19.30m

Vol 0.2207

Winding Shape
◉ Round
○ Square

Restore   Apply

Help   Close

coeff m for Pcore=Kp * B^n * f^m

With a core and material selected, you are ready to start your design. You can click on the Transformer or Inductor tab at the top of the core screen, depending on which device you want to design.

| Core | Bobbin | Transformer | Inductor | IsSpice | Options | Vendors | Wire |

You can add your own equations to the buttons in the User Data area. See the User Data Input/ Output Fields section.

The Transformer and Inductor screens are quite similar. Winding characteristics, both entered and calculated, can be seen in the white "spreadsheet" portion of the screen on the left. The right side contains operational design constraints and User Data buttons that provide output results (copper losses, weight, fill, etc.) and key program inputs, such as the maximum number of strands. You can use this screen to change various aspects of the design, e.g. wire size, wire type, number of turns, gap, etc. All of the key data entries and most of the output results are available on the Transformer or Inductor screens.

Windings may be added, split, deleted and moved using the buttons at the lower left of the screen.
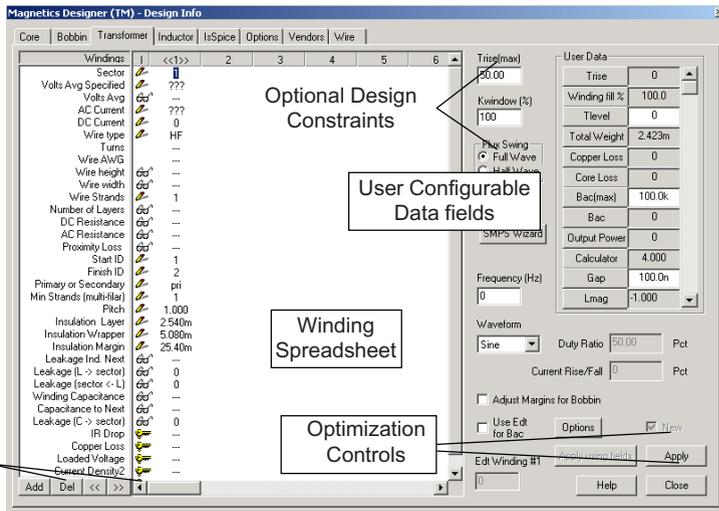
2) The items that must be filled-in on the spreadsheet portion of the screen are shown with 3 question marks, "???." They include the desired voltages and AC (rms) currents. The operating frequency (middle right of the screen), and Edt (volt-seconds) for inductors must also be entered.

You can add, delete and move windings by clicking the orientation buttons at the bottom left of the screen.

3) After entering the electrical data, click the Apply button.

Sample Design:
*Select the **Pot Ferrite** Core Family on the Core Screen. Then enter a **100V** primary with **1Amp** AC current and one **10V** secondary with **10Amps** AC current. Use **100kHz** as the frequency.*
Click Apply.

Click the help button for an explanation of any of the parameters.

This causes Magnetics Designer to optimize the design for the best wire size, number of turns, layers, and strands and calculate the resulting losses, resistance, etc. A complete design that meets all of your design goals and constraints will be produced. You can then choose to alter the design further or save the results.

When you have completed an acceptable design, you can use the Reports menu at the top of the Magnetics Designer screen to print a performance report or a winding sheet suitable as a manufacturing guide. You also have the option of creating SPICE compatible models that can be used with the ISSPICE analog and mixed mode simulator. The Options tab accesses various program defaults such as ambient temperature, insulation thickness, wire type, and units. The Wire tab accesses a screen with impedance information about the device windings and wire characteristics.

There are several example designs located in the Examples directory. You can select and explore them.

Entering Data and Scaling Letters

*The scaling letter M is **CASE SENSITIVE**. Use M for 1E6 and m for 1E-3.*
To avoid confusion you can use Meg instead of M

Numbers may be typed in either decimal form or exponential notation. For example, 1000 may be entered as 1e+3, 1e+03, 10E+2, or 100e1. Likewise, .001 may be entered as 1e-3, 1e-03, .1e-2, or 1000e-6. Numbers may be reformatted by the program. Magnetics Designer also accepts and uses SPICE unit notation using the following key letters:

```
f  = 1E-15    u = 1E-6    M= 1E6 (same as "MEG")
p = 1E-12     m= 1E-3     G= 1E9
n = 1E-9      k = 1E3
```

The SPICE keyletters may be upper or lower case, EXCEPT for the letter "m". Capital M is the same as the SPICE MEG, and equals 1E6. Lower case m is 1E-3 (milli).

Menus

There are several menus at the top of the Magnetics Designer window. The **File menu** contains functions that are used to start a new design, open an old design, and save a design. Both transformer and inductor designs may be active at the same time, and therefore the information from both screens will be stored in the same design file. This is the reason why the File menu function "Save Designs" is plural. Functions for saving and printing reports are also located here.

The **Edit menu** contains functions that are used to undo the last text entry, to copy text that is selected, and to select all of the text in a field. It should be noted that there will be times when the Undo and Copy menu functions will be grayed out. You can still use these functions, even though they can't be selected from the menu, by pressing the appropriate control keys (<Ctrl>+Z and <Ctrl>+C, respectively). This situation will occur when text is selected in a dialog.

The **View menu** contains functions that are used to turn the tool bar, status bar, and Design Info dialog (main data entry dialog) on and off. Turning the Design Info dialog off is useful when you want to see the results of a Report which is shown in the window behind the Design Info dialog.

The **Reports menu** contains functions that are used to display performance reports and winding sheets for your transformer or inductor designs.

The Tool Bar

File   Edit   View   Reports   Help

Toggles display of Design Info window on and off

The tool bar, just below the Magnetics Designer menu bar, contains several icons. They are used, in the order shown, for

accessing files (New, Open, Save), copying of selected text, printing reports, toggling the display of the Design Info dialog, and on-line help.

Saving a Design

To save the current design, select Save Designs from the File menu. Any and all information on both the transformer and inductor screens will be saved. You can also save the current design under another name by using the "Save Designs As..." function. The Magnetics Designer file extension is *.MAG.

Opening a Saved Design

To open a previously saved design, select the "Open..." function from the File menu and navigate to the desired file.

Important Note: When opening designs which were created using a prior Magnetics Designer version, check the "Use Current Equations" check box in the Options tab before loading the file. This causes user.equ to be used instead of the buttons which were stored with the file.

Printing a Report

Magnetics Designer can generate informative printed reports. Once a report is displayed (via the Reports menu), you can select Print Preview from the File menu to see the report before printing it. Selecting Print from the File menu will cause the displayed report to be printed. You can print or copy a report only after a valid design has been generated. (See Generating Reports for more information.)

Note: Reports are the ONLY hardcopy printouts that Magnetics Designer produces. However, the reports may also be copied, as text, to other applications such as Microsoft Word, or to any text editor.

Saving a Report

The "Save Report..." function allows you to save an ASCII text version of the currently displayed report to a file. Reports can be saved only after a valid design has been generated. The following file extensions identify the type of report:

See Generating Reports for more information.

TPS - Transformer Performance Summary
TWS - Transformer Winding Sheet
IPS - Inductor Performance Summary
IWS - Inductor Winding Sheet

Exiting the Program

To exit Magnetics Designer, select Exit from the File menu. You can also press Control+Q, but only if the main Magnetics Designer title bar is highlighted. If the Design Info dialog's title bar is highlighted, you will first have to click on the Magnetics Designer main title bar.

The Core Screen

The Core screen consists of the following components:
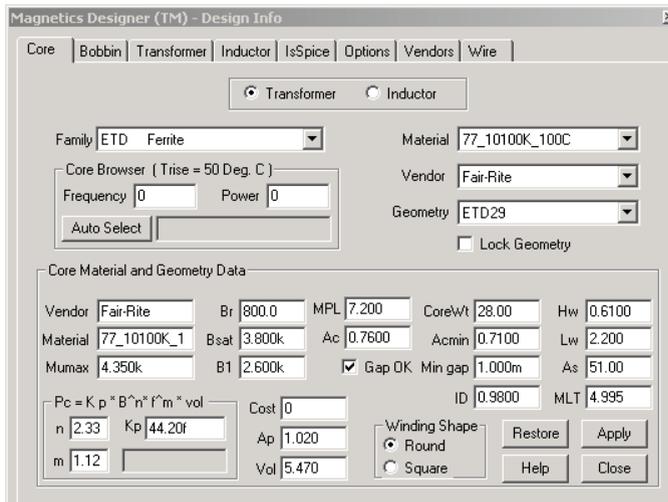
See Chapter 6, Choosing The Right Core, for more information on core material.

Detailed explanations of the core family names and materials are available in the on-line help.

Make sure that you enter the correct values for the average voltage and AC RMS and DC current.

See the Core Database listings in the on-line help for a description of E-I lamination geometries.

Transformer & Inductor radio buttons - Magnetics Designer allows you to independently design both a transformer and an inductor at the same time, each with different cores. These buttons are used to select which device you are configuring.

Family pop-up - Contains a listing of the core families or types.

Material pop-up - Contains a listing of the core materials for each vendor in the family.

Vendor pop-up - Contains a listing of the vendors which support the selected family.

Geometry pop-up - Contains a listing of the available core geometries for the selected family, material, and vendor.

Core Browser - Allows you to select a core geometry based solely on the operating frequency and expected core power capacity. The function allows you to easily compare materials and families to find the best core for a specific application. High frequency wire loss is not included in the estimate so that the predicted maximum power is higher than will be achieved when the design is made using the Transformer or Inductor tab.

Lock Geometry check box - Causes the selected geometry to be locked. Magnetics Designer will not change the geometry during the optimization process if this box is checked.

Core Material and Geometry Data - These fields show the particular characteristics of the selected core. You can point at the various names on the screen and a help pop-up box will appear, showing the full name and units of the parameter. All of these parameters are defined in Appendix B (Parameter Definitions and User Data Variables).

Pc = Kp* B^n*f^m*vol - The core loss equation (See Chapter 4) and its associated coefficients.

Gap Ok - If this box is checked, the program will adjust the gap value to make inductors. The gap parameter is located in the

User Data section of the Transformer or Inductor screen. Gaps can be in the center leg or split equally using the options dialog in the Bobbin or Transformer or Inductor tab.

Winding Shape radio buttons - Used to set whether the windings are in a square or round configuration.

The Design Wizard

Make sure that you enter the correct values for the average voltage and AC RMS and DC current.

Magnetics Designer designs the magnetic from the terminals inward. Therefore, the information that the transformer requires is limited to performance characteristics of the magnetic and not the system in which the magnetic will be used. The Design Wizard can be used to create your design for you. Simply answer the wizard's questions as it guides you through the automated process.

To run the Design Wizard:

- Select the Design Wizard function from the File menu.

- Follow the instructions.

Advanced users can begin the design process by manually selecting a core as described in the next section.

The SMPS Wizard

SMPS design wizards are available to help you through the Transformer and Inductor design process .

Simply enter the input power supply voltage and the output voltage(s) and current(s) along with frequency, duty ratio and ripple current and Magnetics Designer computes the Transformer or Inductor spreadsheet entries. An automatic design phase synthesizes the transformer/inductor. You can then interact with Magnetics Designer to perfect the design. When acceptable results are achieved, an IsSpice model is generated for use in one of the template power supplies.

A number of working power supply designs have been placed in a template framework. These templates include Flyback, Forward and Push-Pull topologies. These templates accept the IsSpice transformer models generated using Magnetics Designer for cycle by cycle switching simulations. The transformer parameters can also be input to the "Average" models.

Running the Buck SMPS Wizard

- Click the SMPS Wizard button on right middle section of the Transformer Tab.
- Select ETD Ferrite from the Family pulldown menu.
- Select Fair-Rite from the Vendor pulldown menu.
- Select 77-101100K_100C from the Material pulldown menu.
- Enter 28 for Voltage for Winding 1, then press insert.
- Enter 5.5Volts and 10Amps for Winding 2.
- Change the on duty ratio to .5 and the ripple to 25%
- Press Apply
- Press the bobbin tab to view the windings.
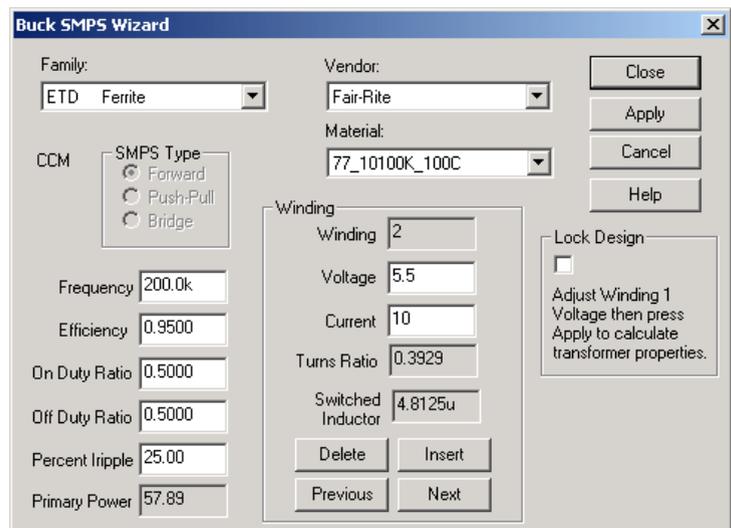
To get an accurate Spice model; the strands need to lie flat in a single layer, they can't be twisted. Change the wire strands or Wire AWG to make sure each winding spreads across the bobbin in a single layer.

- Change Winding 1 primary Wire AWG=14 and Winding 2 secondary Wire AWG=12

The leakage Inductance will be reduced from 519.5nH to 525.8nH. For low voltage designs, the turn-off over shoot is limited to Vthreshold*Leakage/Lsource. Low leakage inductance can eliminate the need for snubber components.

- Press Apply using fields button

Note that the temperature didn't change much. That is the characteristic of barrel wound transformers when the windings spread all the way across the bobbin.
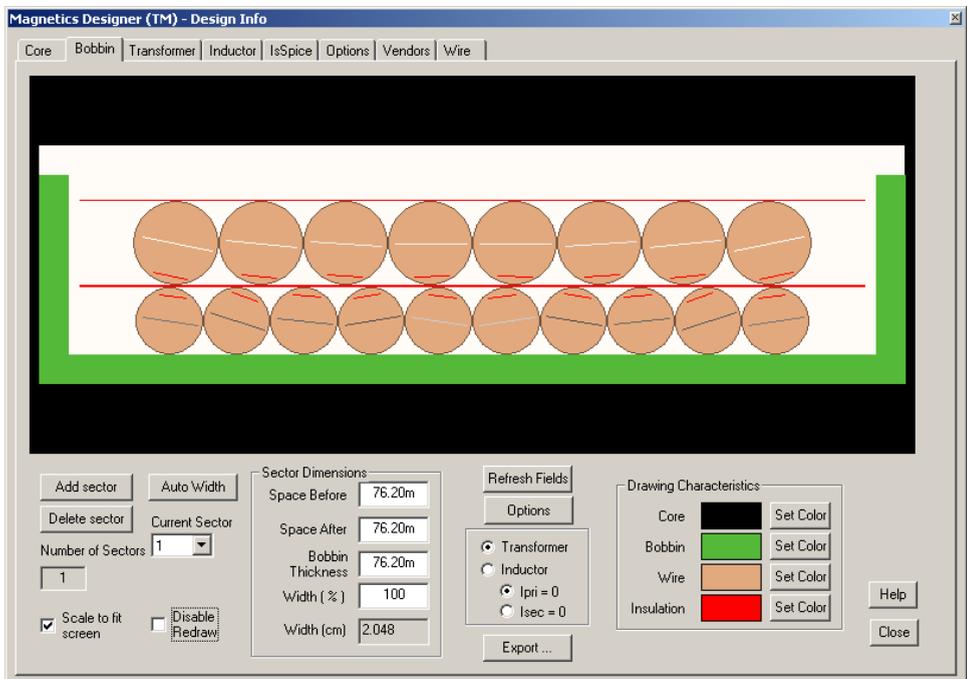
If you have any ICAP/4 SPICE software available, you can perform the following steps:

- Go to the IsSpice tab and copy the netlist from the copyright notice to the end.
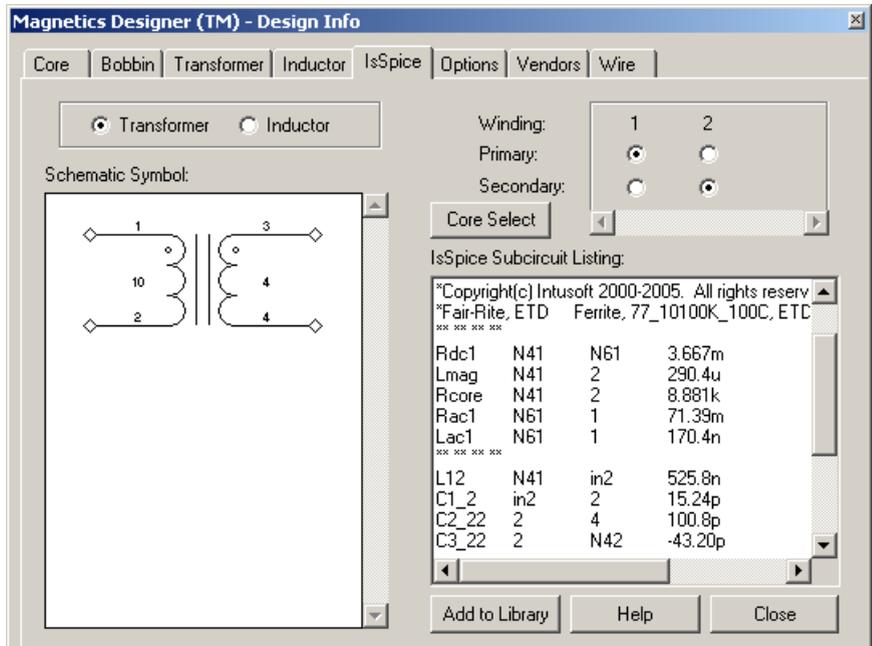
- Open the ForwardXfmrTest.DWG in wizardExamples folder and paste the models into the X3 subcircuit. To do that, double click on X3 part and then click on the .SUBCKT data field.

- Click on the enter button that appears to bring up Edit Subcircuit dialog.

- Select the part of the model to be replaced and paste the new model in. That's a shortcut that avoids making new library entries when you are doing what-if analyses.

- Now modify the parameters text box located at bottom left of the schematic to match what was entered in SMPS wizard.

Input Voltage   Vin=**28**
Output Voltage   Vout=**5.5**
Switched Inductor   Lsw=**4.8125u** (Given by SMPS wizard)
Frequency   F=**200k**
Output Current   Iout=**10**
Load Resistance   Rload=Vout/Iout
On Duty Ratio   Don=**.5**

- Simulate the design

- On the schematic, right mouse click on Scope5 text block located at bottom right and choose Send Script.

The AC and DC currents in the windings will be given in the output record window. Update the inductor spreadsheet to refine your loss predictions.

The Flyback SMPS Wizard

- Start MD and select the inductor tab. Then press the SMPS Wizard button.

New SMPS Wizards provide an easy to use, simplified design method. Users can interact with the Wizards to modify the end design.

- Enter 150 for Voltage then press insert.

- Enter 5.5Volts and 10Amps for the new winding

- Press Apply

- Press the bobbin tab, notice that the first winding extended into a second layer.
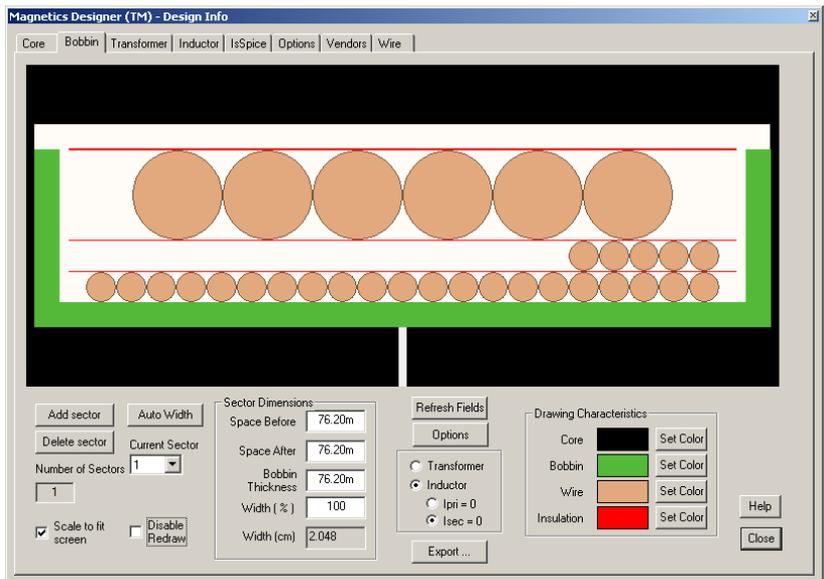
- Go back to the inductor tab and increase the Wire AWG for Winding 1 to 22 to get 1 layer

- Press Apply using fields, note the temperature increase

- Go to the bobbin tab and increase bobbin thickness to center the winding.

- Go back to the inductor tab and Apply using fields.

- The increased bobbin spacing reduced the increased temperature rise, increased leakage inductance, reduced eddy current loss and lowered total power loss.
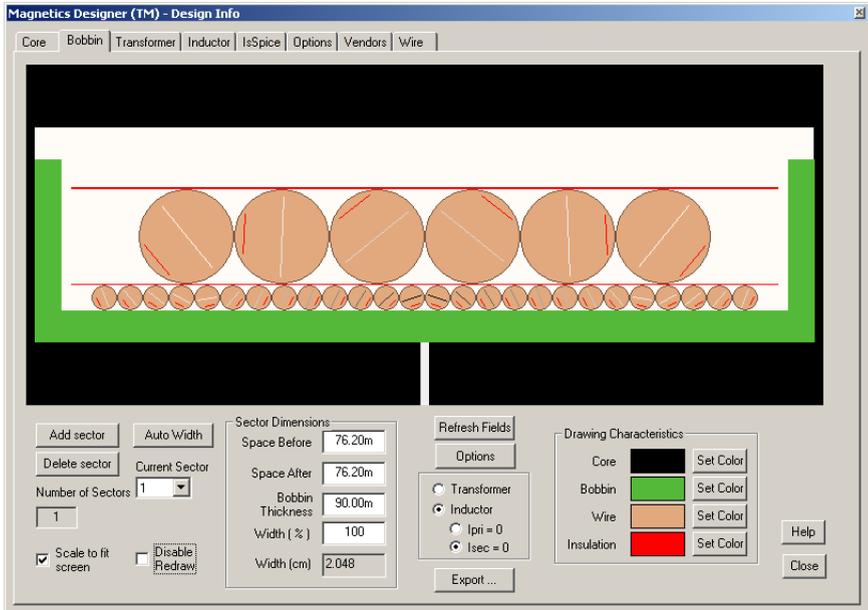
To get an accurate Spice model; the strands need to lie flat in a single layer, they can't be twisted. Alternatively, you could have used Litz wire with its increased cost and handling difficulties.

If you have any ICAP/4 SPICE software available:

• Now go to the IsSpice tab and copy the netlist from the copyright notice to the end.

• Open the FlybackXfmrTest.DWG in wizardExamples folder and double click on X11 part.

• Double click on the .SUBCKT data field. Select the part of the model to be replaced and paste the new model in. That's a shortcut that avoids making new library entries when you are doing what-if analyses.

• Now modify the parameters text box located at top right of the schematic to match what was entered in SMPS wizard.
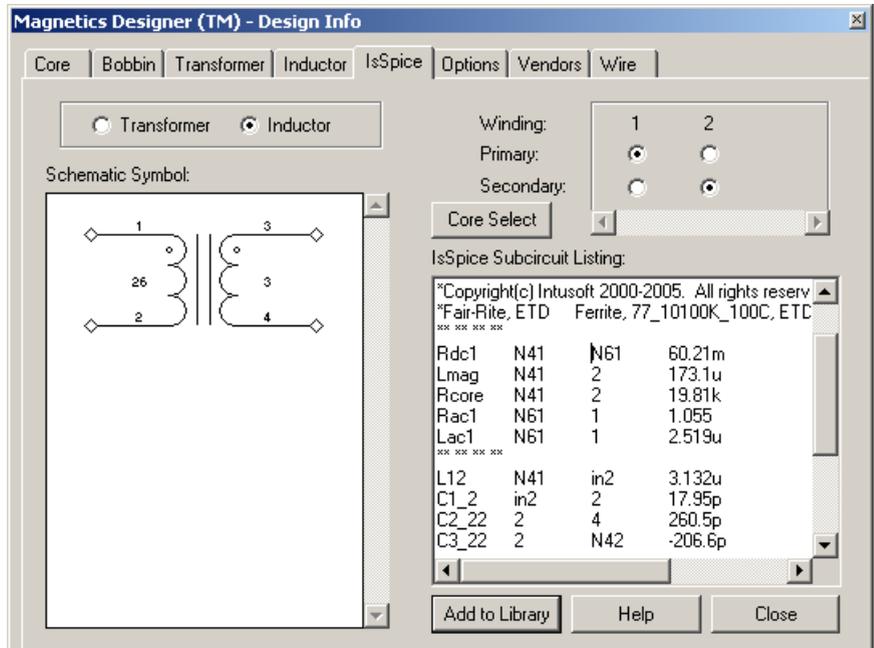
Output Voltage	Vout=**5.5**
Output Current	Iout=**10**
Input Voltage	Vin=**150**
Load Resistance	RLOAD=Vout/Iout
Switching Time	Tsw=15u
Duty Ratio On	Don=**.25**
Time On	Ton=Don*Tsw-.45u

- Simulate the design

- On the schematic, right mouse click on Scope5 text block located at bottom right and choose Send Script.

The AC and DC currents in the windings will be given in the output record window. Update the inductor spreadsheet to refine your loss predictions.

Core Selection

**To select a particular core:**

- First, select the core family from the Family pop-up. Then, select the material and the core vendor.

Selecting a geometry is not necessary. After the design requirements are entered on the Transformer or Inductor screens, Magnetics Designer will optimize the design and choose the correct geometry for you from the family you have selected (See Geometry pop-up).

The units of various core parameters can be set in the Options Screen.

You can scan though the characteristics of different materials and geometries by simply clicking in the appropriate field and pressing the up/down arrows. As each selection is made, the corresponding core parameters will be displayed.

You can also use the Core Browser function to select the smallest geometry core in a family for the desired power capacity or you can use the Design Wizard outlined on the previous page.

Core Browsing

You can use the up/down arrows to cycle through the items in a pop-up and the program will update the maximum power.

The Core Browser function can make an initial geometry selection for you, based only on the output power and the operating frequency specifications.

To use the Core Browser:

- Select a core family and a material from the Family and Material pop-ups, respectively.

- Enter the operating frequency in the Frequency field, and the desired core power capacity in the Power field.

- Click the Auto Select button.

Changing Core and Material Data

The Core Material and Geometry Data fields show the characteristics of the selected core, material, and geometry. You can change the characteristics, temporarily, *for the current session,* by simply typing a value in the desired field. Any changes made WILL NOT be permanently saved in the core database.

When you change to another screen, you will be presented with a message dialog indicating "Do you want to change your working copy of the core and geometry database?"

HELP TIP: You can point at any variable name on the core screen with the mouse, and the parameter's definition and units will pop-up on the screen.

Selecting **Yes** will cause the changes to be accepted, saved in a <u>working copy</u> of the core database, and applied to the design. You will then be transferred to selected screen. Again, the changes will NOT be permanently saved to disk.

Selecting **No** will cause you to be transferred to selected screen without applying the changes to the design. Any changes made while you where in the screen will be reset to the values shown when you first entered the screen.

While you are in the Core screen, you can restore changed values by clicking the Restore button. If you had selected Yes in the "Do you want to change your working copy..." dialog, then you will have to exit the program to retrieve the original values from the core database.

Locking a Core Geometry

Magnetics Designer will adjust the core geometry if a new design optimization is performed in the transformer or inductor screen and the requirements/new winding arrangement dictate that one is required. However, if the Lock Geometry box is checked, then Magnetics Designer will not change the core geometry.

To lock a particular core geometry:

- Select the desired geometry from the Geometry pop-up in the Core screen.

- Check the Lock Geometry box.

Locking the geometry is useful when you want to adjust the design characteristics, but you don't want Magnetics Designer to have the freedom to change the geometry.

Generating a Design

Information on generating values for the required parameters can be found in Chapter 5, Generating The Design Requirements.

There are two basic methods for calculating the performance of your magnetic device. The first allows Magnetics Designer to have complete control over the configuration (core geometry, turns) and makeup (wire size, strands) of the magnetic device. When this method is initiated, Magnetics Designer will perform a large number of calculations and manipulations in order to generate the best overall design. (The process is reviewed in Chapter 4, Core Selection Algorithm). Your requirements (voltages, currents) and design constraints (temperature rise, window fill) will be taken into account and met, if possible. This action must initially be done in order to generate a valid design.

The second method is used in a more "incremental" examination mode where changes are performed one at a time in order to see their effects on the current design. Both methods will produce output values (weight, power loss, resistance, temperature rise) for you to examine.

In general, if you want to give Magnetics Designer the freedom to design or redesign the magnetic device using its full power, you should choose method #1. For instance, you would choose method 1 if you want to see the effect of a geometrical (new core, different wire type or strand limit) change or a design constraint change. Method 1 is often referred to as "doing a new design."

Note: You must first enter all of the design requirements discussed in the Transformer and Inductor screen sections before you can generate a new design.

(Method # 1) To generate a new design for the first time, taking into account all design goals and optional design constraints:

- Check the New box in the Transformer or Inductor screen and click the Apply button.

If the optimization algorithms dictate, Magnetics Designer will try several different core geometries in the family, wire sizes, number of strands, and turns ratios, in order to meet your design constraints. A review of the geometries tested will be reported in the "History of Core Trials" dialog. For each geometry, the window fill and temperature rise will be reported. Hints on how to improve your design will also be given in the "History of Core Trials" dialog.

History of Core Trials

Geometry	Window Fill	Trise
EI 16	95	161
EI 19	55	56.1
EI 22/19/6	56	33.6
EI 25	38	16.8

Hints:
Winding 2 may benefit from using litz wire

OK
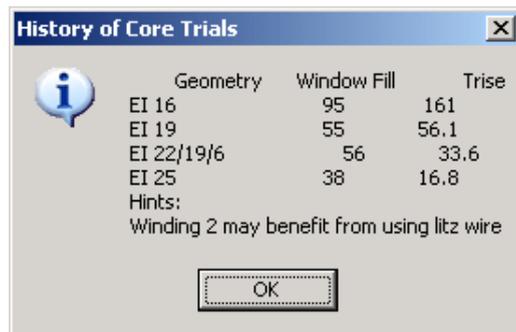
Results of the optimization process show the core geometries tested along with the best fill and temperature rise for each case.

To get the design that resulted in one of the suggestions listed in the History dialog:

- Select and lock the desired geometry you want to use in the core screen.

- Perform a new design by checking the New box and clicking the Apply button.

The second method uses the existing configuration (core geometry, etc.) and simply recalculates the performance based on a single change.

(Method #2) To examine the effect of a single parameter change in the current design:

- Make the change and click the Apply button.

Magnetics Designer will normally recalculate each and every time a new value is entered in the winding spreadsheet area or a new screen is displayed. Clicking the Apply button, pressing the Tab key or the Enter key will also cause a recalculation. The effect of any of the design parameters in the winding spreadsheet or User Data areas may be examined in this way. Each time a parameter is changed, the complete design is updated and the display is altered immediately to reflect the current design status.

The Transformer Screen

The Transformer screen is composed of five areas:

- **Required Inputs and Optional Design Constraints**
- **Winding Spreadsheet**
- **Winding Orientation Buttons**
- **Optimization Controls**
- **User Configurable Data Fields**

Optimization Controls were discussed in the preceding "Generating A Design" section.

We will discuss them one at a time. Before a design can be generated, you must first select a core family and material and then enter all of the required parameters. **The required input parameters for a transformer are:**

> **Frequency**
> **Volts Avg Specified**
> **AC Current**
> **DC Current**

The frequency entry is located at the middle right of the Transformer screen, while the winding related parameters are located in the winding spreadsheet area.

Frequency: Operating frequency of the transformer.

Volts Avg: This is the average voltage across the winding. Specifically, Volts Avg is the voltage over a half cycle, which results in the desired flux change. For a pulse width modulated rectangular waveform, Vavg = Duty Cycle x Peak Voltage. For a sine waveform, Vavg = $(2/\pi)$ Vpeak.

AC Current: The AC current entry is the RMS AC component of current in a winding after the DC component has been subtracted. For a square wave current, the AC RMS current is the peak to peak current divided by 2. For a sine wave current, Irms is equal to .707 times the peak current. The program assumes that the RMS current is a sine wave operating at the operating frequency if the Waveform pop-up (located under the Frequency entry) is set to Sine. Magnetics Designer will account for the increase in AC resistance due to higher order harmonics if the Waveform pop-up is set to Pulse.

DC Current: This is the DC component of current in a given winding, i.e., the average value of the waveform over a complete cycle. For example, if the current is a 0 to 10 Amp, 50 percent duty cycle square wave, the average value is 5 Adc. Typically, forward converter windings and push-pull windings have a DC component current, while bridge inverter windings and bridge rectified windings will not have a DC component.

Optional Design Constraints

The optional design constraints may be used to override the internal defaults used by Magnetics Designer. The internal defaults are different from the default values shown in the Bac, Bpk, and Max Idens fields. The values shown are uncharacteristically high so as not to affect the design process. Changes to these entries are not required before a design can be generated by Magnetics Designer.

A description of each of the optional design constraints follows:

*For more
information, see
the section on
AC Resistance
for Pulse Wave
Excitation.*

Waveform - Sine/Pulse pop-up: This selection determines the type of waveform used to calculate AC resistance. The selected waveform can affect the amount of losses, and therefore, temperature rise, which dramatically depends on your frequency and winding configuration. When Pulse is selected, you can enter duty ratio (50% for square waves) and for transformers you can define the current rise/fall time AC resistance is computed for pulse wave harmonics (up to the 100th harmonic) when Pulse is selected. The current rise/fall time affects the higher frequency harmonics and in certain cases may cause significant temperature change. The resulting impedance changes can be seen in the Wire screen.

*The wire screen
shows the
effects of the
sine/square
waveform
changes.*

You will get different results if you generate a design with the sine or pulse waveform set initially, versus simply switching between the Sine or Pulse choices after the design is generated. This is due to the fact that Magnetics Designer takes into account the AC resistance in its optimization algorithms.

*Bp(max),
Bac(max), and
Idens(max) are
in the User
Data list.*

Bp(max): Bp(max) is a design constraint which limits the peak flux density. In general, if this parameter is not specified, the program will limit the maximum flux density to less than 80% of Bsat. In general, the program will use the lower constraint (either the default or the specified Bp(max).

Bac(max): Bac(max) is a design constraint which limits the maximum AC flux excursion to a value which may be less than

the optimum flux excursion. The program will select the optimum flux excursion which results in an acceptable temperature rise. If the constraint is less than the optimum, the operating flux density will be reduced to the value allowed by the constraint.

Idens (max): Idens (max) is the maximum allowed current density for any winding. This constraint will override the design optimization algorithm and increase the wire size, if required.

Flux Swing: Two types of flux excursions are allowed. **Full Wave** is a symmetrical swing about B=0, which is limited in both extremes by Bsat. This type of flux swing is typical of push-pull and bridge inverters, as well as low frequency power transformers operating from AC mains. **Half Wave** is an asymmetrical flux swing which starts at the residual flux density (Br) and is limited by Bsat. This type of flux swing is typical of forward converters and pulse transformers.

Trise(max): Trise is the maximum desired surface temperature rise, assuming that the device is suspended in air with no appreciable air flow (For Thermal level 0, Tlevel=0). With significant air movement or with the core tightly coupled to a good heat sink, the actual temperature rise will typically be 40 to 70 per cent of the predicted Trise number. You can change the thermal model and the thermal coefficients used. (See the Thermal Models section).

The temperature of the air surrounding the inductor (ambient temperature) can be changed in the Options screen.

Kwindow(%): This is the maximum allowed fill constraint. You can use this constraint to provide extra design margins. In general, the program will select a core which will have sufficient room to wind all of the desired windings and achieve the desired temperature rise when v is 100%. For machine wound toroids, **Kwindow is commonly set to 55% to make room for the shuttle. The bobbin tab shows the remaining 45% as insulation. When wires penetrate this region, the winding may have to be finished by hand.**

Setting Kwindow below 100% can sometimes cause the optimization algorithm to come up with a different winding configuration and may be required in the program if the fill specification is not met.

Note: The calculated temperature rise and window fill values can be found in the User Data area of the Transformer or Inductor screens. (See the *User Data Area: Calculated Parameter*s for more information).

Adjust Margins for a Bobbin (check box): If this box is checked, Magnetics Designer automatically makes room for wires to exit from the bobbin wound (or pot core) designs. The available window room is reduced by the required wire thickness. For windings with an odd number of layers, room to exit on both ends of the bobbin is provided. The thickest previous margin is used for all subsequent windings. For example, use of heavy wire on the first layer will penalize other layers.

Apply Using Fields (button): Pressing this button causes the program to calculate the magnetic fields in the winding stack. The result of these calculations are then used to calculate AC losses, including eddy current losses in the wire near an air gap, proximity loss in shield windings and Rac for all winding configurations. The time required for these calculations precludes their use in the optimization process. If you suspect your design is influenced by these kinds of losses, you should use this feature after performing the initial design. The field map is shown in the Bobbin tab. The time required to perform the analysis is proportional to the square of the turns in the design. An abort button is available during the calculation to terminate the calculation if you accidentally press the button for an inappropriate design. After performing the calculation, a green "LED" is shown next to the Options button. Pressing this button will change the calculation method back to the field estimation method and the "LED" color will change to red. This toggle capability will last as long as the field solution is valid. Making changes that invalidate the solution will cause the "LED" to disappear.

Options (button):
The Options button brings up an Options Dialog that sets parameters associated with the Field solution. The gap Coefficient is the only parameter that you would ordinarily change. It defaults to .5, meaning that the gap is split in two parts. If you use a single gap in the center leg, it should be set to 1.0. Refer to the Options Dialog description for more information.

Winding Spreadsheet

The Windings Spreadsheet area is the key to the Magnetics Designer program. It contains the majority of the important input and output fields. When you begin a design, most of the fields will be empty. Only those that are required (question marks) or have preset defaults will be filled in.
To enter data into a spreadsheet field:

- Click on the desired field. Enter the value.

Your new value will be applied to the design if: the Tab key or Enter key is pressed, the mouse is clicked outside the field, you change tabs, or you click the Apply button.

You can click the mouse or press the Tab key to move between fields. The Tab right function under the View menu will allow you to either move the selected field up and down or left and right with the press of the Tab/Shift Tab keys, respectively.

Windings: The (sequential) winding number is assigned by the program. You can, however, move windings around at any time. This is described later in the chapter. Each new winding will be inserted in the next available position. A maximum of 32 windings are allowed. Magnetics Designer assumes that the finished transformer will be constructed from the inside out, starting with winding 1.

Volts Avg Specified, AC Current and DC Current are described in the previous section.

Sector: Sectors, identified in the Bobbin tab are numbered from 1 to 32. Enter the sector number in which this winding is to be placed. The default is 1. If you change the number here, the number you enter must correspond to a sector number in the Bobbin tab. Conversely, you must change the sector entry here before deleting it in the Bobbin tab. The program enforces this logic using error dialogs.

Volts Avg Specified: This is the output voltage of the winding. It may be different from the Volts Avg Specified. In general, Magnetics Designer will make the primary and lowest turns secondary voltage come out correctly. The accuracy of the output voltage for other windings will depend on the achievable turns ratios. See the *Getting The Voltages Right* section later in this chapter.

The default wire type is set in the Options Screen.

Wire Type: A variety of wire types are included with Magnetics Designer. You can select the wire for the selected winding using the wire pop-up. Included are heavy insulated magnet wire, single insulated magnet wire, Litz wire, square magnet wire, and double square wire, printed circuit board traces or foil. Wire size will vary for each type of wire. However, you are free to create your own wire types and sizes. (See Chapter 3).

The names in the pop-up are taken from names of the wire files stored with Magnetics Designer. HF is for heavy formvar, SF is for small formvar, Sq is for square, Dsq is for double square, Pc1 and Pc2 are 1 oz. and 2 oz. copper traces, respectively. Nef and nehf are New England wire company formvar and heavy formvar, respectively. Eur stands for formvar using European wire sizes.

Wire Notes: For high frequencies , in excess of 40 kHz, you may want to specify Litz wire. Selecting conventional magnet wire may result in excessive AC resistance and the temperature rise may be too high. The design optimization process mitigates the problem. Manufacturing costs could be excessive using Litz wire.

If foil is declared, the wire size is equal to the foil thickness. The width of the foil is equal to the width of the bobbin less two times the specified end margin. When specifying foil, it should be remembered that each layer of foil should be separated by a layer of insulation to prevent successive turns from shorting together. To specify an electrostatic shield, use a 1 turn foil winding with the appropriate thickness of wrapper insulation, and end margins to satisfy the voltage breakdown requirements between the windings and the shield.

TURNS: The total number of turns for a given winding.

Wire AWG: The wire size for magnet wire is the gauge of the wire (specified in AWG, American Wire Gauge). For Litz wire and pcb traces, the gauge is that of a standard magnet wire having the same usable cross-sectional area of bare copper. For foil pcb and round wire, this mapping will allow you to get the same resistivity for the same gauge, although the build constraints will be different.
For foil, the size is the thickness of the foil. The width of the foil is assumed to be equal to the width of the bobbin minus the end margins. For PCB traces, the thickness (thickness of copper) is specified in the wire file (pwb1.w, pwb2.w, or if user generated, File_Name.pw) along with the minimum trace spacing and minimum trace width. The latter two are used to find out what the minimum wire gauge should be and how much wire you can get on a layer. The PWB thickness entry in the PCB wire file is used to calculate the build.

Wire height, Wire width: This is the width and height of a square box that would surround the bare copper wire plus insulation. While you can not directly change the value of the wire height and width, you can use the Wire AWG number as a pointer to a specific wire size. The units are determined by the Window setting in the Options screen.

Wire Strands: This is the number of parallel strands (or layers of foil). If a winding has 5 parallel strands of heavy insulated 28 AWG magnet wire, the entry in Wire AWG will be 28, the entry in the Wire Type column will be HF, and the entry in the Wire Strands column will be 5.

The specified wire option applies to all windings of the device. Foil is not allowed in this algorithm since the cross-sectional area of foil is not defined until the core is selected, and the fill factor cannot be defined until the insulation thickness is known.

Number of Layers: The program calculates and continuously updates the number of layers of wire or foil for each winding. If possible, it is desirable to avoid fractional layers.

Note: The number of layers in a foil winding is equal to the number of turns times the number of parallel strands. That is, a 10 turn winding with 2 layers of foil in parallel has 20 layers.

DC Resistance: The program calculates and continuously updates the DC resistance of each winding. The resistance does not account for leads leaving the device, and therefore may sometimes be smaller than the actual measured values.

AC Resistance: The program calculates and continuously updates the AC resistance of each winding. You can use the Wire screen to see a graph of the AC resistance versus frequency. Both skin effect and proximity effects are considered. The Waveform pop-up can be used to calculate the AC resistance for either a sine or square waveshape.

Proximity Loss: When a winding experiences a magnetic field greater than its own, additional eddy currents will be generated. Losses from these eddy currents are accounted for in this proximity loss entry. These entries are for more accurate if calculated using the Apply Using Fields button.

Start ID, Finish ID: The ID numbers are automatically generated for the start and finish leads of each winding. Their order is important as it indicates how Magnetics Designer expects the transformer or inductor to be wound and connected (for series or parallel windings). A winding is wound from the left to the right if the Start ID number is greater than the Finish ID number. It is wound from the right to the left if the Finish ID is greater than the Start ID. Numbers greater than 1000 are used to designate series split winding connections. Windings that are in parallel will have the same ID numbers. You may click in the ID fields and assign numbers to achieve different types of connections. Two windings are connected if their numbers are the same.

Important Note: The magnetic device is built outwardly from the bobbin, starting with the winding on the left, usually the primary. If a winding ends with a smaller ID than it starts, the winding will start on the right. The start location will affect the interwinding capacitance, so be careful if you change the numbers.

Primary/Secondary: This entry is used to designate whether the winding is a primary or a secondary. The primary/secondary flag affects the internal magnetic fields. Primary fields are in one direction and secondary in the other. The direction of the fields affects the calculation of AC resistance.

Min Strands(multi-filar): Specifies the minimum number of strands for each winding. This can be used to achieve multi-filar windings. You will have to describe the pin connections for these windings in notes on your transformer winding sheet. The IsSpice model doesn't produce multi-filar models. Remember, the voltage stress between turns on mult-filar winding can be quite high.

The default winding pitch is a user variable. See the User Data area.

Pitch: Specifies the pitch in wire diameters. Normally the pitch is 1.0. For multi-stranded windings the pitch is measured in the diameter of a single strand. Strands are grouped together so that a layer consists of an integer number of strands. No pitch is attributed to single turn windings. You will have to figure out how to make foil or muti-strand windings exit the bobbin. You can use pitch to fill out fractional windings.

Insulation Layer, Insulation Wrapper, Insulation Margin: You may specify three insulation types: layer insulation, winding wrappers, and end margins. Layer insulation is a thin layer of insulating material such as paper or glass cloth which isolates each layer from the next layer for any given winding. Winding wrappers are thin layers of insulation which separate successive windings. End margins are unused sections at the end of the bobbin or coil form where no wire is wound. As wrappers typically extend the full width, the creepage distance between successive windings is approximately 2 times the end margin.

When high voltage isolation is required between windings, insulation thickness will typically be on the order of .025 (10 mil)cm for every 1000 volts of isolation. Creepage distances will be on the order of .25 cm (100 mil) per 1000 volts of isolation.

High voltage design can take advantage of the Sector wound capabilities, using the Bobbin tab to define the geometry.

Leakage Ind. next, Winding Capacitance, Capacitance to next: These are geometrically defined parasitic elements. To see how they are calculated and defined, see the Leakage Inductance, Winding capacitance, and IsSpice Model sections in *Chapter 4*.

See "Increasing Accuracy of the Loaded Voltage" for more information.

IR Drop: The voltage drop for each winding.

Copper Loss: The copper loss for each winding.

Loaded Voltage: The voltage output under loaded conditions. Winding 0 is assumed to be the primary winding.

Current Density: The current density for each winding.

ICONS
The eye glasses icon indicates that data rows can only be viewed. The pencil icon indicates that the parameter values for this row can be entered, but are not necessarily required. Some of the pencil fields, such as turns, are calculated for you. The key icon may be clicked in order to reveal a user-editable dialog. The dialog will initially describe the operation of the parameter, but you can enter your own equation for the parameter in a manner similar to the User Configurable Data fields. In fact, the dialogs displayed by clicking on the key icons for the Leakage Ind. next, Winding Capacitance, Capacitance to next items are the same as the ones for the Ln, Cs, and Cn User Data buttons.

Splitting, Adding, Moving and Deleting Windings

Windings are setup and configured in the spreadsheet area. You may add, move, delete, and configure windings in any manner before you allow Magnetics Designer to perform the initial design calculation. After the initial design is performed, you can also split windings in series or parallel. Winding configuration is performed by the orientation buttons at the bottom left of the transformer or inductor screens.

To select a winding:

• Click anywhere in the column associated with the winding. You will see "<< >>" symbols surrounding the winding number of the winding which you have selected.

The winding number is located at the top of the winding spreadsheet area.

To move a winding:

• First, select the winding you want to move. Click the << or >> buttons at the bottom of the spreadsheet area.

The >> button will move the selected winding to the right, while the << button will move the selected winding to the left.

To add a winding:

• Check the New button if it is not already checked or grayed out. Click the Add button at the bottom left of the spreadsheet area.

A new winding will be inserted in the last position. You can then move the winding into another location, if desired.

To split a winding in parallel:

• Generate a valid design. Click the Split button (formerly an Add button) at the bottom left of the spreadsheet area.

The two windings will have the same ID numbers. Magnetics Designer is smart enough to split the currents. If desired, you may initially configure your windings in any manner you choose, including setting up the windings as if they had been split.

When the New box is checked, the left most orientation button is set to Add windings. If new is not checked, the button will change to a Split button.

Series split windings will have ID numbers of 1000 or greater.

Note: If you split the primary winding into two sections in series, the first series winding then becomes the primary. Changes made to the inner primary winding are not treated as drive winding changes.

To split a winding in series:

- Generate a valid design. Press and hold the <u>control key</u> and click on the Split button.

You can interleave windings by splitting them (in series or parallel) and then moving the resulting windings around.

To recombine a split winding or delete a winding:

- Click on the winding you want to delete. The << >> symbol will pop-up around the winding number at the top of the winding spreadsheet area.

- Click the delete button at the bottom left of the spreadsheet area.

If the winding was created by splitting, then it will be recombined. For parallel splits, the voltages of the two windings will stay the same while the currents will increase. For series splits, the voltages of the two windings will increase while the currents will stay the same.

Center-Tapped Windings

Two windings may be configured to be a single center-tapped winding by setting the Start ID number of one winding and the Finish ID number of the other winding to the same value.

To make a center-tapped winding:

- Add two windings with the desired Volts Avg Specified, AC, and DC currents.

- Click in the Start ID field of the second winding. Set the value to the same value that is shown in the Finish ID field of the first winding.

Optimizing a Design

Core Geometries

The "History of Core Trials" dialog also provides a list of the tested geometries. You may find that a rejected geometry did not meet the desired fill or temperature rise goals, but was close enough for your design needs.

To find out what geometry is currently selected, you can simply switch to the Core screen and observe the Geometry field. You can also access any desired core parameter, such as the area product, and change its value to explore "what-if" scenarios (See the Changing Core and Material Data section).

To experiment with a rejected geometry:

- Select the desired geometry in the Core screen. Check the Lock Geometry box.

- Proceed to the Transformer or Inductor screen and generate a New design by checking the New box and clicking the Apply button.

Magnetics Designer will report the same results as shown in the core trials dialog for the locked geometry. You can now hand optimize the design parameters.

The Build

The "History of Core Trials" dialog often provides hints on how to improve your design. For example,

To change a wire type (to Litz or foil):

- Select the desired wire for the appropriate winding from the Wire type pop-up in the winding spreadsheet area.

- Check the New box and click the Apply button.

To change the number of strands:

- Enter a new value into the Max Strands field in the User Data area and generate a new design (check the New box and click the Apply button), or

- Click in the Wire Strands field for the desired windings and change the number of strands. Then the click Apply button.

The winding pitch is a user variable and can be defined in the User Data fields.

Splitting a winding, or windings, is often suggested. This process was discussed in the previous section.

The build algorithm assumes that the round wire occupies a square area which has the sides equal to the diameter of the wire. In addition, wires have some very small spaces between them; this slightly reduces the turns per layer. The number of turns which can fit on one layer is equal to :

$$Turns/layer = \frac{(bobbin\ length - 2\ x\ m\arg ins - pitch * wire\ width)}{(Wire\ width * strands + (1 - pitch) * wire\ width)}$$

The build algorithm further assumes that once a layer has been started, no other winding may occupy the remainder of that layer. That is, if the calculated number of layers is found to be 1.1 layers, the build algorithm assigns 2 layers to that winding. Therefore, when fractional layers (between .1 and .7) are encountered, it may be wise to substitute two or more smaller wires for each larger wire. This is accomplished by changing the number of parallel wires (second design options column) from 1 to 2 and reducing the wire size (increasing the AWG number three sizes). For example, two parallel 24 AWG wires have about the same cross-sectional area as one 21 AWG wire.

In this program, the size of Litz wire is described using the term AWG even though Litz is not generally specified in this manner. For example, when buying Litz wire, it is typically specified as Type I (single bundle), 40 strands of 36 AWG wire. An equivalent AWG rating is given to Litz which is based on the cross-sectional area of the <u>bare copper</u>. Therefore, 28 AWG Litz wire

has the same bare copper area as 28 AWG magnet wire. However, due to the poor utilization of the cross-sectional area, 28 AWG Litz wire will have a considerably larger diameter than the magnet wire. You can create your own Litz wire tables in order to account for the different insulation to bare copper ratios that are found with different braiding configurations. An additional factor (approximately 10%), accounting for the twist in the wire bundle, is included in order to better estimate the DC resistance. It is also assumed that you are using an appropriate braiding configuration for the frequency of operation, and therefore, the frequency related AC resistance effects are negligible.

Square wire has slightly more cross-sectional area than round wire of the same gauge. Double square wire has twice the cross-sectional area as a corresponding gauge of square wire (thus the name double square).

For foil, you may need to enter thicknesses which are not currently listed in the default wire file, foil.w. To add your own thicknesses, you can create your own foil wire file (See *Chapter 3*) or you can simply edit the ASCII foil.w file and add your own thicknesses.

User Data Area: Calculated Parameters

In addition to the parameters displayed in the winding spreadsheet, Magnetics Designer provides important information in the User Data area of the transformer and inductor screens. These items are updated each time a design change is made. The area is composed of a column of buttons, each with its own display field. Some of the items such as Trise only provide output. Others, like Max Strands, are inputs to the program and can dramatically affect the design outcome. Gap is a third type which provides both input and output. You can change the values of the input parameters simply by typing into the data field.

The following list describes the default contents of the User Data fields. The format is:

Button name (type of number) - description, Equation, Units (listed only if they can be changed), and/or Default value.
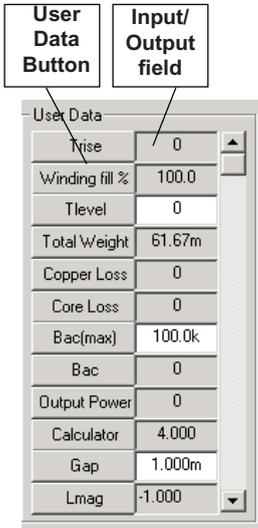
Trise - The temperature rise of the transformer surface with respect to the surrounding air. (See *Chapter 4, Thermal Models* section for details on other thermal models).
Equation (or variable name) = Trise, Units=Celsius

User Data Button	Input/Output field

User Data	
Trise	0
Winding fill %	100.0
Tlevel	0
Total Weight	61.67m
Copper Loss	0
Core Loss	0
Bac(max)	100.0k
Bac	0
Output Power	0
Calculator	4.000
Gap	1.000m
Lmag	-1.000

Winding fill % - Indicates the percentage of the window area that is used by the design. The algorithm calculates the build of all the windings and their respective insulation. The window fill % equals the total build divided by the window height times 100. (See information at the end of this section).
Equation (or variable name) = Kfill

Tlevel (integer) - This input variable sets the thermal model level used by Magnetics Designer.
Equation (or variable name) = Tlevel, Default=0

Total weight - The total weight of the magnetic device, including both the core and copper weights.
Equation (or variable name) = CopperWt + CoreWt, Units = pounds

Copper Loss - This is the power loss due to copper losses, including proximity loss.

Core Loss - This is the power loss due to core losses.

Bac(max): Bac(max) is a design constraint which limits the maximum AC flux excursion to a value which may be less than the optimum flux excursion. The program will select the optimum flux excursion which results in an acceptable temperature rise. If the constraint is less than the optimum, the operating flux density will be reduced to the value allowed by the constraint.

Bac - The AC flux density.
Equation = Bac

Output Power - This is the summation of the power (Iac * Vavg) for each winding except for the first winding.
Equation =
Pout = 0
for(winding=0;winding < Nmax;winding = winding+1)
  dp = Iac[winding] * Vavg[winding]
  Pout = Pout + isSecondary(winding) * dp

Core weight - This field shows the core weight. This entry is useful for checking whether Magnetics Designer has changed core geometries without having to view the core screen.
Equation = CoreWt, Units = pounds

Efficiency - The percent power delivered by the design.
Equation = 100 $*$ (1.0 - (Pcu + Pcore) / Pout)

Calculator - A sample button that is useful for making temporary mathematical calculations.
Equation = 2+2

Gap (floating point) - This input entry allows you to change the core gap. It is equal to the round trip gap length associated with either a ground center post or spacers. If the center post has been machined to create an air gap, the core gap is equal to the length of the air gap. If spacers are used, the gap length is equal to 2 times the thickness of the spacer.
Equation = gap, Units = cm

See "Getting The Voltages Right", later in this chapter, for more information on Min. Turns and Round Coef.

Max Strands (integer) - This input variable sets the maximum number of strands of wire allowed for each winding.
Equation (or variable name) = Nsmax, Default = 2

Lmag - The magnetizing inductance.
Equation - Lmag

Min. Turns (integer) - This input parameter sets the minimum number of turns allowed for all windings. It is used to decrease quantizing granularity.
Equation = MinTurns, Default=1

Round Coef. (floating point) - This input parameter adjusts the turns quantizing. The default, .99, forces the winding voltage to be greater than .99 times the Volts Avg Specified. You can set it to .5 for best accuracy, but the voltage may be less than the Volts Avg Specified. The behavior is the same for the inductor, except that the inductance calculation is affected rather than the winding voltage.
Equation = Kround, Default=.99

Winding pitch (floating point) - This input parameter adjusts the winding pitch. The value is the number of wire widths.
Equation = pitch, Default=1

Primary Turns (integer) - The number of turns on the primary winding.

Idens (max) - This is the maximum allowed current density for any winding. This constraint will override the design optimization algorithm and increase the wire size, if required.

Bp(max) - This is a design constraint which limits the peak flux density. In general, if this parameter is not specified, the program will limit the maximum flux density to less than 80% of Bsat. In general, the program will use the lower constraint (either the default or the specified Bp(max).

Window Fill
The Window Fill % is an indicator of how full the bobbin is at any time. It is calculated based on the current build divided by the usable height of the window. Since the window fill factor is calculated based on build rather than a window utilization factor, the window is actually full when the fill factor approaches 100 %.

Due to the way that layers are counted by the build algorithm, it may be possible (but not recommended) to physically construct an inductor where Magnetics Designer predicted a fill factor larger than 100%. The build algorithm assumes that layers are wound sequentially and that insulation is placed between each successive layer. Therefore, fractional layers count as full

layers in the cumulative build calculation. Furthermore, the algorithm does not allow small windings to fall into the gaps between larger windings.

In reality, when there is no insulation between windings, smaller windings will often fall in the cracks of larger windings, or two fractional layer windings may be wound on the same layer. Thus, Magnetics Designer may predict that such a design would not fit when, in fact, it does. Changing high current windings to foil or changing single strand windings to multiple strand windings will often improve the window utilization and minimize these types of problems.

Lead termination methods may affect the window fill factor. In general, Magnetics Designer assumes that no window space is required to exit from the bobbin unless the Adjust Margins for a Bobbin box is checked. This assumption is reasonably correct for cores such as E cores where leads exit easily from the bobbin on the ends outside of the core. For other cores such as Pot cores and PQ cores with closed ended bobbins, some of the end space must be allocated for lead exit. Furthermore, in high current cases where heavy leads must be soldered to foil, bulges in the coil where the wires exit may interfere with the core. These issues require the use of good judgement based upon engineering experience in order to determine what fraction of the window is actually usable.

For information about equation and button editing, see the "Editing and Adding Your Own Equations", section, later in this chapter.

Notice that there are additional buttons in the User Data area, e.g. Vdrop2, Ploss, Vterminal, and Jn. If you add a new entry to the winding spreadsheet, a corresponding button will appear in the User Data area. It will have the same equation as the new winding spreadsheet entry, and will display the value which corresponds to the last winding. You may change the equations for the winding spreadsheet entries or the User Data buttons. They are independent. Button modifications will only be saved if the design is saved, and will stay for the remainder of the current session. Button modifications will become global for all designs when you edit the user.equ file.

Customizing the User Data Buttons

Magnetics Designer allows you to add, delete, and resequence the user data buttons which appear within the Transformer and Inductor screens.

To add a new button:

- Select the Add Buttons function in the Edit menu.

For information about equation and button editing, see the "Editing and Adding Your Own Equations", section, later in this chapter.

- Make the desired selections and enter the button name in the Button Label field.

- Click on the Next button.

- Enter the equation and the required variables.

- Click on the Next button and follow the instructions.

- When you've finished, click on the Finish button to dismiss the dialog.

You can also control the sequence of the buttons in the User Data area. For example, to move a button in the list within the Transformer screen:

- Select the Arrange Transformer Buttons function in the Edit menu.

- Select the desired button name.

Notice that the "Trise" entry has moved down one position in the list.

- Click on the "Move down" button in order to move the selected button so that it appears one position lower in the User Data area.

- Click on the OK button.

The User Data buttons in the Transformer screen now appear in the order which you've just defined.

User Configurable Data Fields

The functions in this dialog allow you to sequence the user data buttons in any order.

The User Data area provides access to a wide variety of input variables and output results. The unique thing about the User Data items is that they are COMPLETELY CUSTOMIZABLE. Each button may contain a single variable, an equation, or a set of equations. The User button dialog for a particular field is accessed by clicking on the button. For example, to see the dialog and equation for Trise, click on the Trise button.

Click here to display the User Button dialog for Trise.
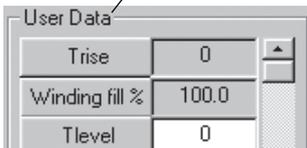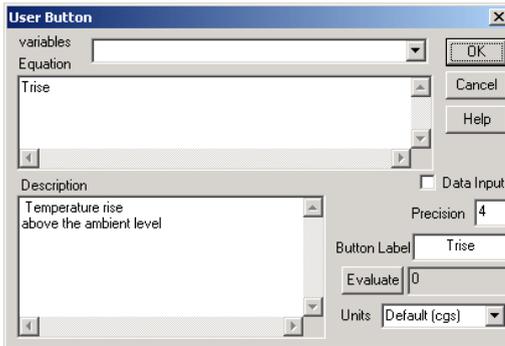
The User Button dialog, shown above right, contains a pop-up with a list of program variables at the top. The complete list, along with definitions, can be found in Appendix B. Virtually every internal variable, core parameter, and output calculation is exposed for your use. Several flags (half wave, secondary or primary, etc.) are available to allow you to monitor program settings. A series of special functions (getGauge, isPrimary,

windingArea, etc.) are also available to allow you to obtain winding related parameters and internal program calculations.

The Equation field contains the variable or equation(s) that are processed and displayed by the button.

The Description field contains a brief explanation of what's going on. The button label contains the text displayed in the button shown in the User Data area.

The Units pop-up contains a list of units that the value can utilize (be converted to) if it initially uses one in the approved list (See the next section).

The Data Input check box signifies to the program that the value in the field next to the button will be used as an input to the program or another button listed below this button. (Buttons are processed in the order in which they are listed, starting at the top). Therefore, if this box is checked, the equation can consist of a single variable name that will be assigned the entered value. Some examples of buttons used as input to the program are Max Strands, Tlevel, Min. Turns, and Round Coefficient.

Editing and Adding your own Equations

You can change the contents of any button shown in the User Data area directly in the program. The changes, if valid, can be used immediately. However, the changes will not be available in future sessions unless you un-check "Use Current Equations" in the Options tab before reloading the file. If the box is checked, the global button definition found in User.Equ, located in the Magnetics Designer directory, will be used for the default button equations. It is loaded along with the program. Care should be taken when editing this file. The syntax used in USER.EQU is as follows:

The variable names used in equations are case sensitive.

_**begin [button][token]** - Begins a new block of information, button for a new equation, token for a new token (constant).

_end - Ends a block; nesting buttons is not allowed.

For buttons, the following keywords are used:
_tab - The dialog tab where the button will be located. The value is defined as a bit-wise sum; core = 1, transformer = 2, inductor = 4, core and transformer = 6, wire = 8. The tab keyword is optional. The default value is 15.

_name - The name that goes in the User Data button shown on the Design Info screen.

_equation - An equation which is evaluated for each recalculation (click the Apply button). The equation capabilities are defined in the next section.

_description - Optional words to give some meaning to what's going on in the button.

_input TRUE | FALSE - This is an optional flag that causes the equation(s) to be evaluated prior to a recalculation or Apply. The result is that the data entered into the button field can be used as an input to the program or another button. The default value is FALSE.

_units - This is optional. All calculations are done in cgs units. However, the results can be modified by one of the unit modifiers (See the User.Equ file) if the final units are understood. For example, if your result is in cm^2, then clicking in^2 will cause the appropriate conversion. If your equation has calculated something like g/cm^2, then you will need to provide the conversion within your equation to get g/in^2.

A listing of which unit options (window or magnetic) control which parameters can be found in the on-line help.

The dialog below shows one of the default buttons (for Efficiency) in the Transformer screen's User Data area, along with its corresponding entry in the USER.EQU file.
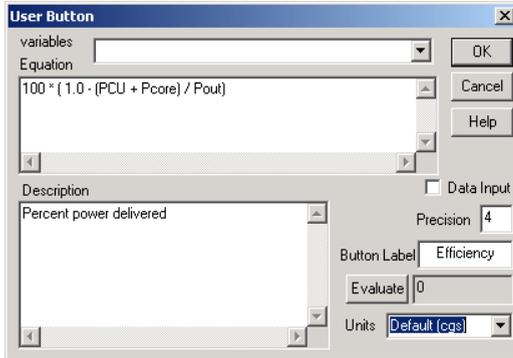
_begin button
_tab 2
_name Efficiency
_description Percent power delivered
_equation
100 * (1.0 - (Pcu + Pcore) / Pout)
_end

An example of a new button that you could create is shown below, along with the required USER.EQU text (Comments follow the // symbols).
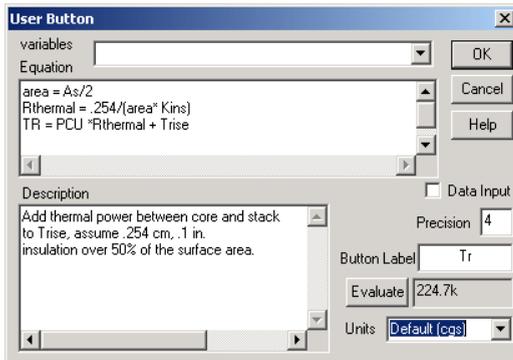
_begin button
// for transformers
_tab 2
// name in button
_name Tr
_description
 Add thermal drop between core and stack
to Trise...
_equation
area = As/2
Rthermal = .254/(area* Kins)
Tr = Pcu * Rthermal + Trise
_end

You may also click on the Calculator button in the User Data area of the Transformer or Inductor screens to enter or edit equations.

User data buttons that are simple variables used for data input and output should not be edited. You may, however, edit the equations for IR Drop, Copper Loss, Loaded Voltage, and Current Density, by simply double-clicking on the "key" icons in the User Data area. Similarly, you may also edit the equations for any user data buttons which you have created.

Equation Capabilities

The equation parser in Magnetics Designer is extremely powerful. It allows you to enter a variety of complex relationships including Mathematical, If-Then-Else, and For-Next expressions. The expressions can contain any variable displayed in the User Data Button dialog, algebraic, transcendental, and trigonometric operations, plus a variety of math functions. You can also sum various quantities from each winding. Each button may contain several equations. They will be executed in the order in which they are listed. Buttons are also executed in the order in which they are listed, so if a button contains an input variable which is used in another button, then the input variable button should proceed the button that uses it.

Formats

Math Equations: *Variable=Expression or Expression*

If-Then-Else: *Expression* ? *Expression* : *Expression* **or**   *Variable* = *Expression* ? *Expression* : *Expression*
If *Expression* is true, then *Expression* else *Expression*. Spaces should be included before and after the "?" and ":" symbols. The Expression can use a greater than ">" or less than "<" test. An equal test is not allowed.

Expressions may consist of any combination of variables, functions, or operators.

For-Next: *for(initial value ; test ; end condition) equations*
All the equations following the For-Next statement, until the end of the equation list, are executed in the for loop.

Examples
Math Equations
$100 * (1.0 - (Pcu + Pcore) / Pout)$ *(Efficiency)*
$Myvar = cos(log(Ac)) - Acmin + Bac^{Cost}$

Flag: If mean cross sectional area is greater than...
$Ac > AcMin ? 5 : .1$

My Temperature Calculation1
Kins $*$ (1.0 - (Pcu + Pcore) / Pout)
Temperature Calculation2
Kcond $*$ (1.0 - (Pcu + Pcore) / Pout)
Summation of all of the winding capacitances
for(winding = 0 ; winding < Nmax ; winding = winding+1)
   Cs(winding) = Cs(winding) + 2p
Summation of Iac $*$ Vavg for each winding, except for the first winding
Pout = 0
for(winding=0 ; winding < Nmax ; winding = winding+1)
   dp = Iac(winding) $*$ Vavg(winding)
   Pout = Pout + isSecondary(winding) $*$ dp

Math Functions

Function	Symbol	Description	Function	Symbol	Description
abs(x)	|x|	absolute value	exp(x)	e^x	exponential
acos(x)	$\cos^{-1}(x)$	(result in radians)	ln(x)	ln(x)	log base e
acosh(x)	$\cosh^{-1}(x)$	(result in radians)	log(x)	log(x)	log base 10
asin(x)	$\sin^{-1}(x)$	(result in radians)	sin(x)	sin (x)	(x in radians)
asinh(x)	$\sinh^{-1}(x)$	(result in radians)	sinh(x)	sinh(x)	(x in radians)
atan(x)	$\tan^{-1}(x)$	(result in radians)	sqrt(x)	$x^{1/2}$	square root
atanh(x)	$\tanh^{-1}(x)$	(result in radians)	sgn(x)	sgn(x)	signum, ± 1
cos(x)	cos(x)	(x in radians)	tan(x)	tan(x)	(x in radians)
cosh(x)	cosh (x)	(x in radians)	tanh(x)	tanh(x)	(x in radians)

The following operations and constants are defined:
+   -   *   /   ^   and unary -
(addition, subtraction, multiplication, division, raise to the power of, and unary minus).

If the argument of log, ln, or sqrt becomes less than zero, or if a divisor becomes zero, or if the argument of log or ln becomes zero, the resulting value will be limited.

Note: Do not use a plus sign (+) in front of positive numbers, as this will be interpreted as an addition operation. An error message similar to "**Parse tree build failed**" may result if Magnetics Designer can not understand your equation.

Getting the Voltages Right

There is virtually no limit to the length or complexity of the expressions that can be entered.

In some cases, the voltages on a secondary may not be exactly what you have specified. Magnetics Designer treats the primary and lowest voltage secondary with special care. It will always try to calculate a turns ratio that achieves the Volts Avg Spec. for these two windings. Other windings may be less than or greater than the specified value due to quantizing of the turns ratio.

Two parameters in the User Data area are available for adjusting the turns ratio quantizing behavior of Magnetics Designer. Min. Turns is used to set the smallest number of turns that Magnetics Designer will assign to any winding. For example, a 1 turn 5 volt

| User Data	
Core weight	0
Efficiency	0
Calculator	0
Gap	2.500m
Max Strands	2
Lmag	0
Min. Turns	1
Round Coef.	0.9900
Winding pitch	1.000
Primary Turns	0
Idens(max)	10.00k
Bp(max)	100.0k

winding can make it difficult to achieve 12Volts on another winding. In this case, Min. Turns can be set to 2 to allow more accuracy on the higher voltage windings. The second parameter is called Round Coef. It is used to adjust how the turns are rounded. You can set the value to .5 for the best accuracy, but the resulting voltages may be lower than the Volts Avg Specified. Setting the value to .99 forces the actual voltages to be greater than .99 times the Volts Avg Specified.

Increasing Accuracy of the Loaded Voltage

In some cases, the calculated Loaded Voltage is lower than the Volts Avg. Specified value due to the IR drops on the primary and secondary. You may be able to increase the accuracy of the Loaded Voltage by adjusting the number of primary turns. The Primary Turns value in the user data field can help. It shows the number of turns which the primary would need to have in order to cause the secondary voltage to be equal to the Volts Avg. Specified under loaded conditions. The initial value is only for informational purposes. To cause the turns on the primary (as shown in the spreadsheet) to be set to this value, we must edit the button equation.

• Click on the Primary Turns button in the User Data area.

The ShapeFactor default is 1.0, which represents a square wave. If you are working with different types of waveforms, you will have to enter the ShapeFactor here.

User Button

variables

Equation

```
shapeFactor = 1.0
vIRin = shapeFactor * Iac(0)*Rac(0)
vIRout= shapeFactor * Iac(1)*Rac(1)
N(1) * (Vspec(0) - vIRin) / (Vspec(1) + vIRout) + .5
```

OK   Cancel   Help

☐ Data Input

Description

```
Adjust turns for loading
Assumes winding 0 is the primary...
and winding 1 the secondary to compenstate
you can set N[0] = ... and press apply
several times to get an "automatic" calculation
```

Precision 4

Button Label Primary Turns

Evaluate 1.000e+100

Units Default (cgs)

Notice that the equation for the Primary Turns value is:
N(1) * (Vspec(0) - vIRin) / (Vspec(1) + vIRout) + .5

This value is calculated by the program and appears independently of the Turns (integer) value which is shown in the winding spreadsheet for the primary winding. In order to force (rounded to the nearest integer) the primary turns value in the spreadsheet to the calculated Primary Turns value in the user

N(winding #) refers to the winding number. N(0) is the number of turns in the primary winding.

We're entering a value of 90; the calculated Primary Turns value was 89.65, as shown on the prior page.

data buttons, add "N(0)=" to the button equation, e.g.
N(0)=N(1)*(Vspec(0)-vIRin)/(Vspec(1)+vIRout)+ .5

- Then close the dialog and click on the Apply button a few times in order to make sure that the recursive change propagates through the design.

This yields an automatic calculation in one iteration. **Note**: You may not see a difference between the calculated Turns and the Primary Turns value for small numbers of turns or small IR drops. If you prefer to enter a specific Turns value and force it to be used in the calculations, you can enter the value after the last line of the Primary Turns equation, e.g.

shapeFactor = 1.0
vIRin = shapeFactor * Iac(0)*Rac(0)
vIRout= shapeFactor * Iac(1)*Rac(1)
N(0) = N(1) * (Vspec(0) - vIRin) / (Vspec(1) + vIRout) + .5
90

Magnetics Designer assumes that winding 0 (zero) is the primary winding. If another winding is the primary winding, e.g. winding 1, you'll need to edit the Loaded Voltage and Primary Turns equations.

- Double-click on the "Key" icon beside the Loaded Voltage entry within the transformer winding spreadsheet.

Loaded Voltage
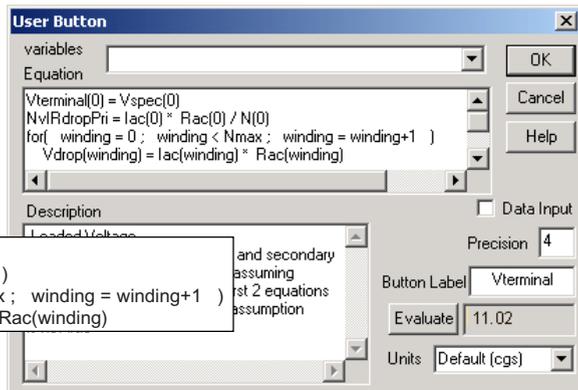
Vterminal(1) = Vspec(1)
NvIRdropPri = Iac(1) * Rac(1) / N(1)
for(winding = 0 ; winding < Nmax ; winding = winding+1)
    Vdrop(winding) = Iac(winding) * Rac(winding)

- Change the equation to reference the primary winding, e.g. winding 1, by changing all occurrences of "(0)" to "(1)."

The Inductor Screen

Magnetics Designer is specifically oriented towards designing tightly coupled energy transfer (inductors) devices where little energy is stored in the core or gap. Typical applications of the program include low frequency power inductors, switching regulator filter inductors, and flyback transformers.

The optional design constraints are handled in a manner similar to the transformer constraints.

A description of each of the entries on the inductor screens follows:

Edt Winding #1 (Volt-Sec): Edt is the volt-seconds applied in one polarity over one complete cycle of the fundamental frequency to the 1st winding. For example, if a 50 kHz square wave with an amplitude of 30 Vpk is applied, then:

$$Edt = \frac{Vpk}{2f} = \frac{30}{(2)(50 \times 10^3)} = 0.3 \times 10^{-3}\, volts - sec$$

Frequency, Waveform (Sine/Square), Bp(max), Bac(max), Max Idens, Trise(max), Kwindow(%), and Flux Swing are all discussed in the Transformer screen section.

Current Peak Specified: This specifies the maximum current for which the inductor must not saturate. It is usually larger than the DC component which is added to the peak AC component. Failure to correctly specify the peak current may result in a design which will saturate at an unacceptably low current.

DC Current and AC Current are discussed in the Transformer screen section.

Minimum Inductance: This is the specification of the desired inductance at the rated load current.

Lmin Actual: This is the inductance of the first winding. It is

calculated by the program as parameters are changed by the user. It accounts for the properties of the core and gap, including flux fringing.

Lmax (zero current): This is the inductance at no current.

Primary/Secondary: If all windings have current flowing simultaneously in the same direction (with respect to the start of the winding) then all windings will be called primaries. For example, a coupled inductor used on a multiple output converter has only primaries. If current flows in one winding part of the time and in the other windings the remainder of the time, the first winding will be identified as a primary and the other windings will be identified as secondaries. A flyback transformer is a case in which the input winding should be identified as a primary and the remainder of the windings should be identified as secondaries. Failure to properly identify winding types may result in incorrect peak flux density calculations.

The rest of the parameters on the Inductor's winding spreadsheet area are all discussed in the Transformer screen section.

Optional Design Constraints

The design constrainst are listed in the User Data area.

The design constraints are set well above the actual limits for the core (100K for Bac and Bpk, and 10K for current density). Bpk can be set to any value, but its value is internally limited in the program to Bsat.

Optional design constraints are allowed on the Inductor screen to provide the flexibility necessary to satisfy the needs of more advanced users. The optional design constraints will override the built-in design and analysis algorithms whenever the design choice exceeds the constraint.

For example, the inductor design algorithm chooses the maximum flux density and the maximum current density based on the allowed temperature rise and the optimum ratio of core loss to copper loss. However, it may be desired to have a

significantly more efficient design. One way of achieving this result is to constrain the AC flux density and the current density to significantly lower values than those allowed by the program. The result of such a decision would be a somewhat larger inductor with very low losses. Reduction of the temperature rise constraint would have a similar effect.

The winding spreadsheet area gives you the flexibility to select and adjust various wire and insulation options. The program then calculates the window fill and performance based on the additional information.

For example, if you choose to have layer insulation, the thickness for each required layer of insulation is counted in the window fill. Also, as the build of the 1st winding increases, all subsequent windings have a slightly longer mean length per turn, and therefore higher winding resistance.

For inductors, Magnetics Designer assumes the primaries all have currents flowing in the same direction, and will therefore reinforce their proximity fields. Magnetics Designer will increase their AC resistance as though they were part of a single inductor with a lot of layers. Moreover, the program assumes the secondary conducts at a different time so there is no correction for interleaving primaries and secondaries.

When end margins are specified, the window areas associated with the ends of the bobbin or coil form are no longer available as winding space. Therefore, if end margins are added after all of the other data has been entered, the window fill may change, the number of layers for each winding may change, and the DC and AC resistance of each winding may increase.

When optional design data (at the top of the inductor screen) is changed, all of the calculated data will be updated as required. This constant updating keeps the inductor designer informed of the impact of the added constraints.

The Bobbin Screen

The Bobbin screen, shown below, serves three functions:
1. Provides a graphical aid to view the winding stack.
2. Defines the bobbin geometry.
3. Shows the magnetic field in the winding stack.

The short lines in the field map represent the current on the high field intensity side of the conductor, the field intensity is given by the gray scale, where black is strong, white is weak.
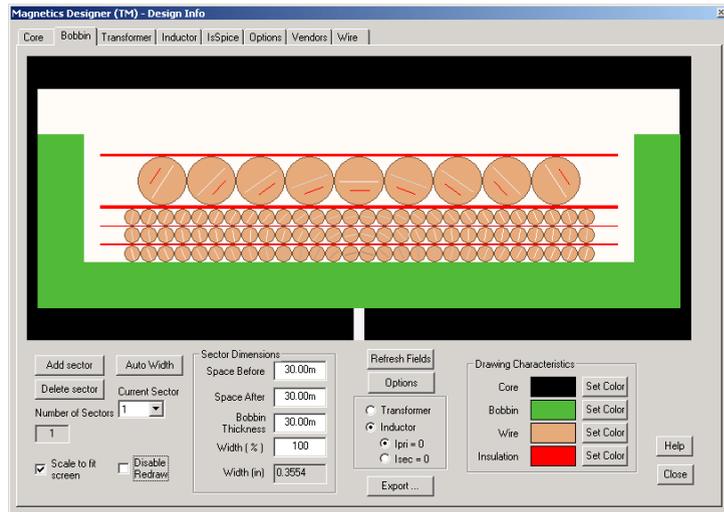

Viewing the Winding Stack

To view the winding stack, you must first initialize the Transformer or Inductor screen by pressing the appropriate tab. Then press the Bobbin tab. By default, the bobbin graphic will fill as much of the drawing region as possible while maintaining the correct aspect ratio. A small portion of the core is shown to maintain perspective. For solenoid or barrel windings, we assume symmetry across the bottom of the drawing and only show half of the stack. Toroidal windings begin at the mid-right side and are wound counter clockwise. If the sector dimensions are null, the winding continues over the last winding. A small pitch gap is allowed for the wire to hop

Default for toroids shows second layer continuing counterclockwise.
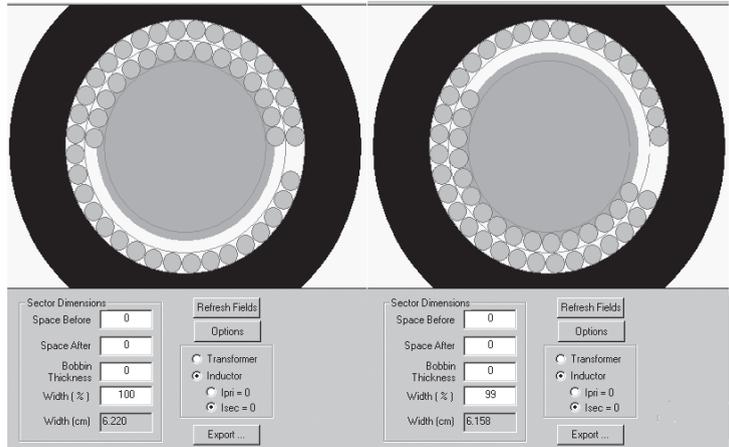
Any sector width that is not 100% causes layers to be wound back and forth.

 If there are any sector dimensions, then the winding will go back and forth.

Left, default for toroids shows second layer continuing counterclockwise. Right, any sector width that is not 100% causes layers to be wound back and forth.

Toroids show "insulation" for 45% of the area in the center in order to allow room for a shuttle. If you are using a machine to wind the toroid, you should keep wire out of this area. Setting the kWindow % to 55 will keep the program from using this area in the automatic design phase (check New and click the Apply button). Hand wound toroids can use this reserved area.

As an aid to the field solution, we show adjacent windings without any pitch. Windings on the opposite side would be offset by 1/2 the winding pitch. Margins are measured after pitch is taken into account, so there may appear to be more "air" in the stack than is the actual case.

Winding stacks which use many turns may re-draw slowly. The "Disable Redraw" check box prevents the drawing from updating. Typically, you would check this button when filling out data in the Bobbin screen which changes the bobbin

geometry. Turning off the "Scale to fit screen" check box will shrink or enlarge the drawing to its actual size so that you can get a real world size perspective. There is insufficient mechanical data to draw the entire envelope, so only the winding stack is shown accurately.

Drawing characteristics can be used to adjust element colors to your choosing. The Export button lets you write DXF files. You can choose to selectively include drawing elements depending upon the use of the DXF file. For example, magnetic field solvers run faster without insulation in the drawing.

Defining Bobbin Geometry

A bobbin contains at least one sector, and one sector is the default setting. For toroids, the bobbin dimensions are null, since toroids do not use a physical bobbin. Solenoid or barrel-wound devices usually have a bobbin. The bobbin default dimensions are set to .03 inches (.762mm). This default scheme makes the Magnetics Designer version 4.x core libraries different than earlier libraries because the older libraries included a bobbin dimension with the geometry parameters.

Sectors are numbered sequentially beginning with 1. The first sector is on the left side of the drawing, with subsequent sectors drawn in order from left to right. The "Add sector" button will clone the current sector into a new sector. Typically you would fill out the sector dimensions, then press "Add sector" for as many sectors as you plan to use. "Auto Width" divides the available space equally between sectors. In order to edit an individual sector's dimensions, you must first select the desired sector using the "Current Sector" drop down list box. You can then change the space before, space after and width percentage. The actual width will be shown below in the units which you have chosen in the options screen. When you change dimensions after a design has been made, you should return to the transformer or inductor screen and press Apply to update the calculations.

The "Delete sector" button will remove the currently selected sector. You will not be allowed to delete sectors that are being used in the Transformer/Inductor screens. To delete a sector that is in use, you must first remove all references to that sector in the Sectors entry of the spread sheet. Conversely, you can't enter a sector to the spreadsheet until it is defined in the Bobbin screen. The number of sectors are shown in the Bobbin screen. A legal sector exists from 1 through the number shown.

Since defaults for barrel-wound bobbins are different than toroids, you will be asked whether or not to change the existing bobbin definition if you change the basic core type. This typically occurs inadvertently when core browsing, and you should probably elect to leave things as they are. You can always go back and change the bobbin, but if you delete your work, then it must be recovered from a prior saved copy.

The build reported in the Transformer and Inductor screens is the build for the winding's sector. The winding fill percentage is the largest sector fill. It's up to you to divide the sector width in proportion to the power utilization in each sector. High frequency and quantizing effects may make it necessary to change the sector width after a design has been done. The visual feedback in the Bobbin screen should give you a good idea of what to do.

Showing the Magnetic Fields in the Winding Stack
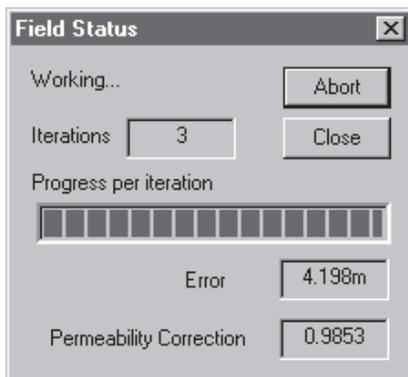
*(**Note**: This operation cannot be performed on toroids in version 4.x of Magnetics Designer.)*
Pressing the "Refresh Fields" button in the Bobbin screen is the same a pressing the "Apply using fields" button in the Transformer or Inductor screen. An iterative turn-by-turn computation is made. The field solution is only useful when skin effect and proximity losses have important contributions to the copper loss. While the computations are being made, a progress dialog is displayed. It tells you

whether the computer is working on the calculation or it has finished. The iteration number is shown, and a progress bar show the progress within the iteration. The error term is a composite error whose limit is set within the Options dialog. When the error is reduced below the options limit, the job is done. A permeability correction is shown. It accounts for a permeability reduction which occurs in long gaps. In some cases, the solution time may be longer than you want, so an abort button is provided in order to terminate the calculation. The computation time is proportional to the total number of turns raised to a power that is less than 2. For planar and foil windings, the foils are chopped into squares, each being a turn, so there can be a lot of turns and it takes a longer time for foils than for wires.

The IsSpice Screen
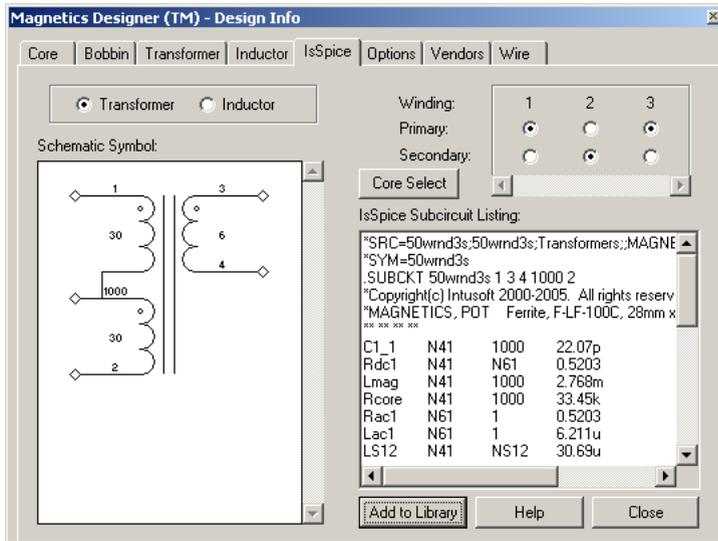
The IsSpice screen contains five key areas. The Transformer/ Inductor radio buttons are used to select which type of magnetic device you want to model. The Schematic Symbol area provides a preview of the transformer or inductor symbol. Included are values for the Start and Finish ID numbers and the number of turns per winding. The Winding: area (top right) is used to

configure the symbol. You can click the radio buttons, whose Winding number corresponds to the winding number shown in the Winding Spreadsheet area, in order to move a winding from one side of the symbol to the other.

If several windings are split in parallel (their ID numbers are the same), their associated radio buttons will move together as a group. Only one coil section will be shown for the parallel windings case. Series winding splits and center-tapped windings will show an additional pin if the windings are on the same side of the core symbol. If the windings are separated on both sides of the core symbol, one side will have the connection point while the other will show a continuation (sideways T) symbol with the same ID number.

The Core Select button allows you to choose how you will model the B-H Loop shape. Choose between linear (default), powdered, atan, sigmoid, log, exp, and user defined.

The last area contains the IsSpice Subcircuit Listing. This is a text field. You can type into the field, paste into the field (<Ctrl>+V), and cut text (<Ctrl>+X) out of the field. This is convenient, as it allows you to modify and document the netlist before saving it. You can also copy the netlist out of the dialog and paste it directly into your IsSpice circuit file. This bypasses the library creation process listed below, but allows you to quickly evaluate the model before saving it to a file.

To create a SPICE model:

• First, generate a valid design. Then switch to the IsSpice tab from the Transformer or Inductor tab.

Note that changes in the model resulting from the changes in other screens (Options: data precision, for example) will not appear in the model until you return to the Transformer or Inductor tab. Also the IsSpice model is regenerated each time you transition from the Transformer or Inductor tab to the IsSpice tab.

The linear core model generated by Magnetics Designer is compatible with most SPICE simulators. Its uses primarily SPICE 2G.6 syntax, except for its use of node names (instead of node numbers) and negative capacitor values. The nonlinear core models use B-element expressions which is used by

Intusoft's IsSpice4 program but other SPICE simulators might use slightly different syntax.

• When you are satisfied with the symbol and netlist generated in the preview window then press the Add to Library button.

• Fill in the transformer model name, schematic symbol name, subcircuit file and select the symbol format.

• Click on OK.

Add to Library

Transformer Model Name:

MyTran

Schematic Symbol Format:

SpiceNet 7.6

Schematic Symbol File Name:

MySym   .SYM

Subcircuit Library File Name:

MyLib   .LIB

OK   Cancel
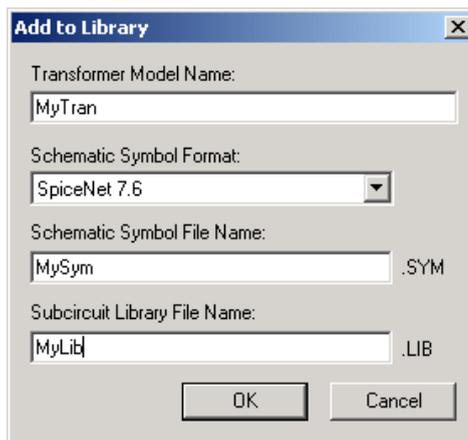
If you do not have ICAP/4 Windows, you will be able to specify where to save the SpiceNet symbol and spice library netlist, and you are done.

If you have ICAP/4 Windows a copy of the library and symbol will be saved in the c:\spice8\MagSpice folder. A warning dialog will appear describing the steps necessary to add a model to the ICAP part database.

Magnetics

Please close any opened symbols in SpiceNet before proceeding.

Then SpiceNet will show your symbol, you need to save it.
Then the Library Manager will show your netlist which you also need to save.
Then rebuild the data base from the library manager.

Finally, place your new model on a schematic using the SpiceNet part browser.

OK
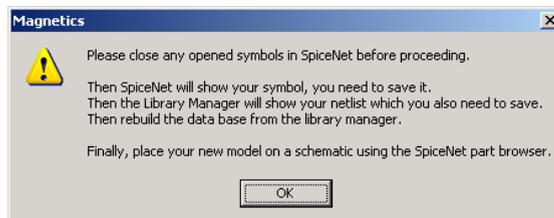
• First make sure that the ICAP/4 Windows program is not running.

- Use <ALT>+<TAB> to switch to the Symbol Name dialog if it is hidden underneath other windows.

- Select OK to save the symbol in the c:\spice8\sn\symbols\XFMRS.sym symbol file.

- You can also save the symbol to your own compound symbol library.

ICAP/4 users: If you copy the netlist into your circuit file, make sure to place it before the *SPICE_NET line.
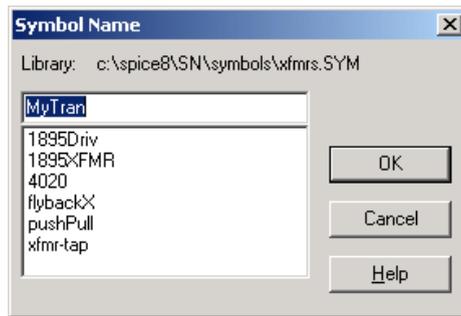
The IsSpice model structure is discussed in Chapter 4.
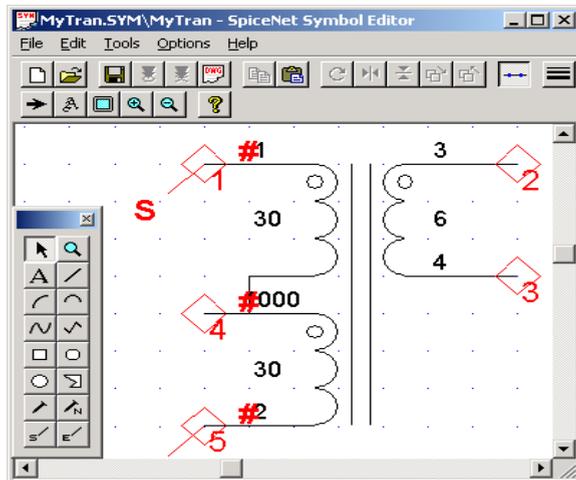
- In the new Model dialog, select an existing .lib file, or type a new lib name.

New Model

Select an existing library or
enter a name for a new library

OK

Cancel

xfmrs.lib

TRIAC.LIB
user.Lib
VACUUM.LIB
XFMR.LIB
xfmrs.lib

Enter the new
model name

MyTran
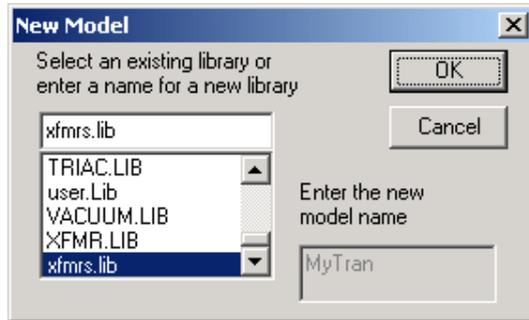
• Compile the part database.

To make an OrCAD or Protel schematic symbol
• Run the ISSYM.EXE program from the DOS prompt.

C:> **issym** <Intusoft symbol filename> <Orcad ascii filename>
Example: issym ec35.sym ec35.asc

A file symbol_name.Asc will be produced. This file is in the
OrCAD SDT format, which can be imported into OrCAD SDT,
OrCAD Capture, and Protel's Schematic[3]. The resulting file will
be the ASCII representation of the Intusoft symbol in the OrCAD
SDT format.

•   To complete the .Asc text file, place the following lines at
     the top of the file. You may use any text editor.

     {De-Compiled Library}

     PREFIX
     END

The Options Screen

The Options screen is used to change the units of different
parameters and to change various program defaults.

Note: When opening designs which were created using a prior Magnetics Designer version, check the "Use Current Equations" check box before loading the file.
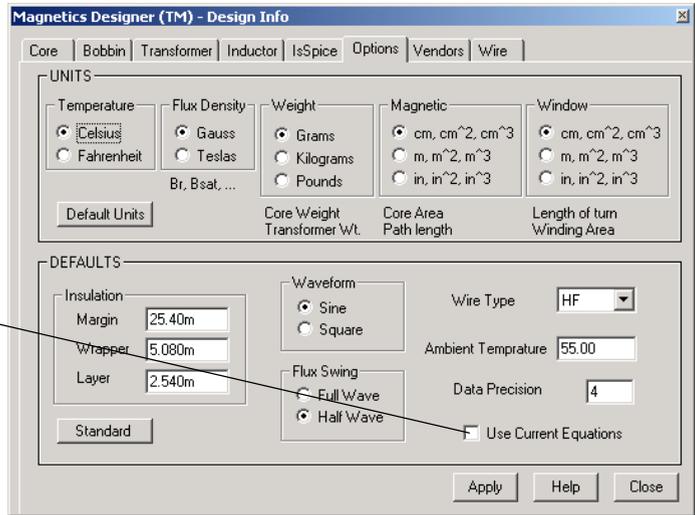
The following table lists the Unit types and the program items to which they apply:

Unit	Core Screen	Transformer/Inductor screen
Temperature		Trise(max)
Flux Density	Br, Bsat, B1	Bp(max), Bac(max)
Weight	CoreWt	
Magnetic	Ap, Ac, As, MPL	Max Idens
Window	Ap, Vol, Acmin, Min gap,	Insulation items, Wire width,
	ID, Hw, Lw, MLT	Wire height

User Data Fields Note: The units in the Options screens do not apply to the User Data fields in the Transformer and Inductor screens. Since these items can be controlled by the user, they are afforded their own unit pop-up, which is available by clicking on the User Data button.

The Insulation defaults apply to the values listed in the Winding Spreadsheet area in the Transformer and Inductor screens.

The Waveform and Flux Swing defaults apply to the values listed at the top of the Transformer and Inductor screens.

The Wire type default applies to the Wire type field in the Winding Spreadsheet area in the Transformer and Inductor screens. Any new wire types you add will appear in the pop-up, and may be selected as the default.

The Ambient temperature is the temperature of the air surrounding the transformer. It is used in the calculation of the different thermal models.

Data precision is the number of decimal places used in the Magnetics Designer display. It is not the number of digits used in the calculation process; however, Standard resets all of the default values back to those which are shipped with the program.

Number of elements in ½ turn:
The fields are computed by dividing each wire turn into a number of segments. Since the field equations are cosine symmetric, we only need to find the field for ½ turn and double the result. More accuracy may result in increasing this number; however, it doesn't do much if the wire diameter is lager than the current element length.

Number of current regions:
When the skin depth is sufficiently small, a discrete number of regions represent the current in the wire. The regions are located parallel to the magnetic field, one skin depth inside the equivalent square wire. Half of the elements are on one side of the wire and the other half are on the opposite side. A red line is drawn on the high field side between the regions.

Far Dia:
When the distance away from the wire is large, the division into regions doesn't affect the field. The Far Dia sets a threshold for using a single current region. It's measured in wire diameters of the wire producing the field.

Rel Tol:
A tolerance estimate used to halt the iteration. Its current value displayed as the Error term in the Field Status dialog.

Max Iterations:
Halts the iteration before the Rel Tol value is reached.

Simple Model:
Computes fields as though the core is not present. When unchecked, the core is simulated using a geometrical shadowing algorithm. The computational work is less; however, quantizing errors are more severe. Current elements that are shadowed are far away and don't contribute very much to the local field so the results using either method is generally within 10% except for inductors with small gaps.

Use B and L:
Computes fields using the Bennet and Larson model instead of the field simulation. This box can be checked on or off by pressing the green/red LED button in the Transformer or Inductor tab without opening this Options dialog.

Gap Location:
Locates the center of any air gap as a percent or the center-leg length. The default, 50, places the gap in the center.

Gap Coefficient:
The default, .5, is used for a single gap and .5 if the gap is divided between the center-leg and the outside-leg of the core. Dividing the gap will reduce the gap field in half. No contribution to copper loss is credited to the outer-leg gap so that gap induced copper loss will be reduced by the square of the gap field, which is a factor of 4.

Use this value for gap flux density enter 0 for MD computed:

Allows you to override the automatic gap flux density calculation and add your own value in user flux units. MD accounts for the higher flux in the core when the wire is not wound uniformly around the entire magnetic path length. Moreover, the tendency

for flux to concentrate close to the surface is also simulated so that computing a value to enter here is tricky. A small value, like 1u, will eliminate gap loss so you can get a clearer picture of what's going on.

The Vendors Screen

The Vendor screen contains a database of transformer manufacturers, core manufacturers, core distributors, and wire manufacturers. You can change or delete any entry and add any desired vendor to the database. Any additions, changes, or deletions you make are immediately saved once you exit the particular (Add, Change, or Delete) dialog. You do not have to exit Magnetics Designer to save the changes.

To add a new vendor to the list:

•   Click on the New button. Select the desired category.

•   Enter the desired data. Select Save if you wish to save the entered data and add another vendor. Select Close if you

want to stop adding to the database. If you have not saved the new vendor, you will be prompted to do so before the dialog is closed.

To change a vendor entry:

- Click on the Change button. Select the category you wish to edit. Select the name of the vendor whose information you wish to change.

- Enter or change the desired data. Select Save if you wish to save the entered data and make more changes. Select Close if you want to stop changing the database. If you have not saved the changes, you will be prompted to do so before the dialog is closed.

To delete a vendor:

- Click on the Delete button. Select the category from which you wish to delete a vendor.

- Click on the name of the vendor you would like to delete. Select Delete if you wish to delete the highlighted vendor and delete other vendors. Select Close if you want to stop deleting names. If a vendor is highlighted, you will be asked if you want to delete the vendor from the database.

The Wire Screen
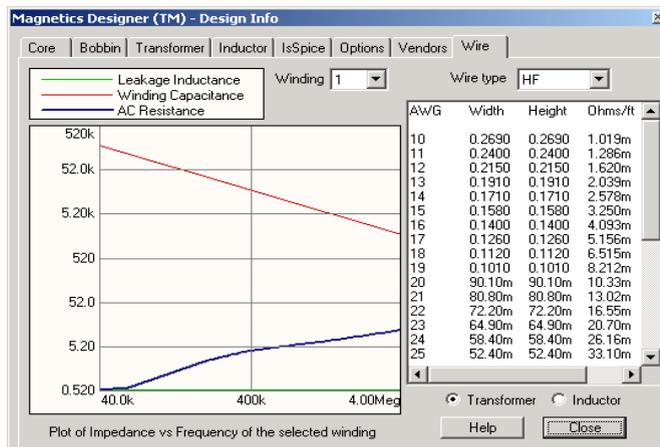
The Wire screen contains two separate functions. The graph on the left is used to view the impedance changes over frequency for the AC resistance, leakage inductance, and winding capacitance for each winding in your design. You can see the different graphs for the different windings by selecting the desired winding from the Winding pop-up to the right of the graph legend.

The graph provides a great deal of insight into the losses you can expect as the harmonics of your waveforms increase beyond the fundamental (See *Chapter 4*, *AC Resistance for Square Wave Excitation*).

The chart on the right is used to view the AWG or equivalent gauge (for European wire), dimensions, Ohms/foot, and area for the different types of wire available. You may have to scroll the chart to see the area column.

The wire characteristics shown in the chart MAY NOT be the same as those of the wire whose impedance is shown in the graph. The chart is ONLY controlled by the Wire Type displayed in the pop-up above the chart.

For Foil, Magnetics Designer will create a table of equivalent gauges which are based on the thicknesses listed in the foil wire file. The width is the window length, while the height is the thickness. For PCB traces, Magnetics Designer will create a table of equivalent gauges. The limits of the table will depend on the settings in the wire file and the characteristics of your design. The width is the minimum width (highest gauge) being set by the minimum trace width shown in the pcb wire file. The characteristics of foil and pcb traces will change, depending on the currently selected geometry.

Generating Reports

To generate a complete performance report for your magnetic device:

- First, construct a valid design. You must have done at least one Apply (Apply button in the Transformer or Inductor screen) so that all parameters are initialized.

- Pull down the Reports menu under the Magnetics title bar and select either Transformer Summary or Inductor Summary.

A report will be generated in the main window behind the Design Info screen (tabbed dialog). You can click the Toggle Design Info button or move the Design Info window to see the report completely.

To generate a winding sheet for your magnetic device:

- First, construct a valid design. You must have done at least one Apply (Apply button in the Transformer or Inductor screen) so that all parameters are initialized.

- Pull down the Reports menu under the Magnetics title bar, and select either Transformer Winding Sheet or Inductor Winding Sheet.

```
newmag.mag - Magnetics                                              _ □ ×
File  Edit  View  Reports  Help

 D  ⌷ ⊟   ⊞⌷ ⊜   ⊡ ?

TRANSFORMER PERFORMANCE SUMMARY
Design Name:                               Designer:
Date/Time:      11/07/02 13:15:04          Project:  newmag.mag
Notes:

TRANSFORMER DESCRIPTION
Core Family:  POT    Ferrite              Core Weight (Grams):        40.00
Geometry:                  28mm x 23mm    Total Gap (cm):             50.00m
Material Name:             F-LF-100C      Spacer Thickness (cm):      25.00m
Manufacturer:              MAGNETICS      Window Fill (%):            83.92

CORE DESCRIPTION
Eff. Core Area (cm^2):     1.280          Min. Core Area (cm^2):      0.9580
Winding Length (cm):       1.650          Winding Height (cm):        0.4855
Avail. Window (cm^2):      0.8011         Area Product (cm^4):        1.025
Min. Core Gap (cm):        450.0u         Volume (cm^3):              6.320
Inside Diameter (cm):      1.264          Surface Area (cm^2):        31.98
Mean Length Turn (cm):     5.496          Winding Shape:              Round
Max. Permeability:         2.500k         Max. B, linear u (Gauss):   1.800k
Sat. Flux Density (Gauss): 3.450k         Res. Flux Density (Gauss):  1.850k
Mean Mag. Path Len. (cm):  4.930

TRANSFORMER PERFORMANCE DATA
Flux Swing Type:           half wave      Input Waveform:             sine
Output Power (Watts):      31.35          Magnetizing Ind. (Henry):   1.279m
Pk. Flux Density (Gauss):  541.1          Core Loss (Watts):          36.84m
AC Flux Density (Gauss):   162.8          Copper Loss (Watts):        1.124
Ambient Temp. (deg C):     55.00          Core AwAc (cm^4):           1.025
Temp. Rise (deg C):        25.77          Frequency (Hertz):          220.0k
Volts/Turn:                1.833

For Help, press F1                                              NUM
```

You can adjust the size of the main window to see the entire report, if your monitor allows.

To save a report to disk:

- Select the desired report from the Reports menu.

- Select the Save Report function from the file menu. You will be prompted for the directory in which to save your report.

All reports are saved in ASCII text files which can be edited with any text editor. Tabs are converted to spaces so all columns will line up if you use a fixed size font like Courier.

Copying Report Data

To copy a report to the Windows system clipboard:

- Click in the report window. Select the Select All function from the Edit menu. Press <Ctrl>+C, or select Copy from the Edit menu.

You may now go to your other program and paste in the text from the report. To see the report window, you may have to turn off the Design Info dialog. To do this, uncheck the Design Info menu item in the View menu.

Core Database

Core Database

Explanations of the cores in the database are available in the on-line help.

The heart of Magnetics Designer is the database of core information. The information in this database is used to describe the materials and geometries of the cores you will use to design transformers and inductors.

To facilitate the management of this large amount of information, the database is distributed as an Excel file called mtl.xls, which is located in the Magnetics Designer directory. The contents of the Excel file are divided into separate sheets. The Material sheet holds data which describes the B-H and power loss characteristics of a core. The Geometry sheet holds data which describes the geometry of the core and bobbin. The Core Loss and Permeability sheets contain calculators which are used to determine material data parameters.

The output of the core database spreadsheet is two separate files, Mtl.Lib and Geo.Lib, which Magnetics Designer uses to construct the transformer or inductor. These files hold the data from the Material and Geometry sheets, respectively. Both files are comma delimited ASCII text files.

Opening the Core Database

The core database file, mtl.xls, is located in the Magnetics Directory. To open this file, either

• Click on the "Material Database" icon in the Magnetics Designer program group, or

• Double-click on the file "mtl.xls" located in c:\spice8\mags\ (default location).

• Click on the Enable Macros tab.

The Core Database Dialog

When the database file, mtl.xls, is opened, the Core Database dialog (shown below) will be displayed.
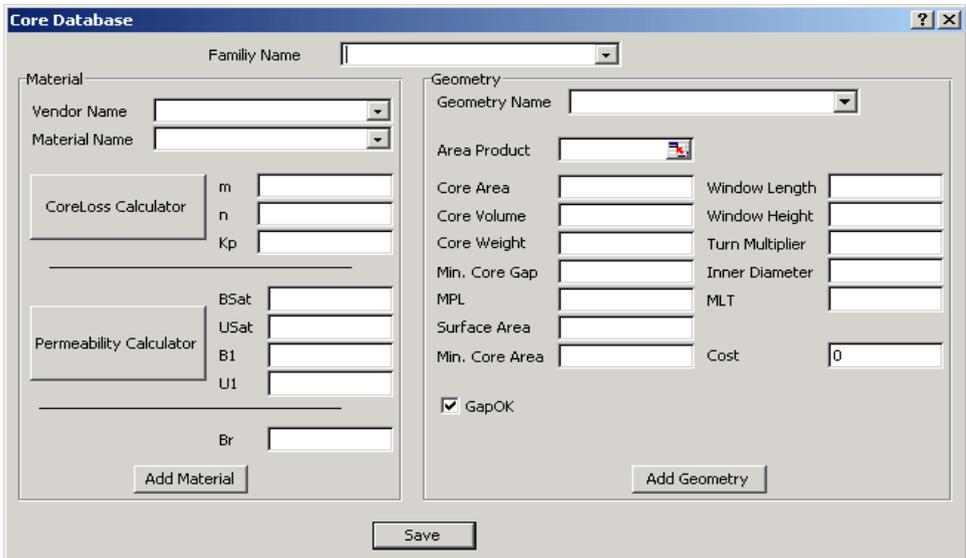
The dialog is divided into two main sections which represents the material and geometry parameters which are stored in the Material and Geometry sheets, respectively. The names of the

entries in the dialog correspond to the names you will see in later sections of this chapter. These names also appear at the top of their respective sheets.

The only data item which appears outside of the material and geometry sections is the Family Name. This entry is used as the relational key which links materials and geometries. **This entry must be filled in before any other entry is filled**.

The Save button dismisses the dialog and creates new library files, Mtl.lib and Geo.lib. The Add button adds the new Core characteristics for a material or geometry to the core database.

Adding a New Material or Geometry

A new material, or geometry, can be added by typing completely new entries, or by selecting an existing entry and modifying it. If you choose to modify an existing material or geometry entry in the database, you **MUST** change the Material or Geometry Name in order to prevent the duplication of parts. In either case, the entries should be completed in the order described below.

• Select a Family Name or enter a new one.

If you are entering a new material,

• Select a Vendor name or enter a new one.

• Enter a unique Material and/or Geometry name.

As mentioned in the first paragraph, this name must be unique in order to prevent duplication. For more information, please refer to the *Material Sheet* and *Geometry Sheet* sections.

• Enter the core's material and/or geometry characteristics.

• Click the Add Material and/or Add Geometry buttons.

If you add a new Family Name for a material, or geometry, you must enter a corresponding geometry or material with the same Family Name before you can create new library files for Magnetics Designer.

Deleting Material or Geometry Entries

To delete a database entry:

•   Dismiss the Core Database dialog by pressing the Escape key, or by selecting the Save button.

•   Activate the sheet, Material or Geometry, which contains the entry(s) you wish to deleted.

•   Using the procedures which are described in the Microsoft Excel documentation delete the desired entry.

All data which has not been distributed by Intusoft will appear at the bottom of a sheet. A red line will mark the end of the data which has been supplied by Intusoft.

If you delete a material or geometry, and the deletion removes the last reference to a Family Name, you must delete all corresponding geometries or materials which have the same Family Name.

Closing the Core Database

After selecting the Save button, the Core Database dialog will create new library files for Magnetics Designer, and will leave the spreadsheet open.

To close the database:

•   Select the Exit function from Excel's File menu.

Material Sheet

The Material Sheet of the Core database is used to store information that pertains to the material characteristics (B-H and power loss) of the core.

	A	B	C	D	E	F	G	H	I	J	K
1	Family Name	Vendor Name	Material Name	m	n	Kp	Bsat	Br	U1	B1	Usat
2	Cut C 1mil Shell	MAGNETICS	Orthonol	1.26	1.37	5.24E-11	14800	15000	14000	11000	755
3	Cut C 1mil Shell	MAGNETICS	Permalloy 80	1.492	1.86	4.16E-14	7700	6200	25000	5000	1670
4	Cut C 1mil Simple	MAGNETICS	Orthonol	1.26	1.37	5.24E-11	14800	15000	14000	11000	755
5	Cut C 1mil Simple	MAGNETICS	Permalloy 80	1.492	1.86	4.16E-14	7700	6200	25000	5000	1670
6	Cut C 2mil Shell	MAGNETICS	Orthonol	1.4	1.28	5.58E-11	15000	15000	14000	11000	756
7	Cut C 2mil Shell	MAGNETICS	Permalloy 80	1.79	1.52	6.03E-14	7400	6200	25000	5000	1670
8	Cut C 2mil Shell	MAGNETICS	Supermendur	0.91	1.31	2.88E-09	21000	21000	30000	19000	117
9	Cut C 2mil Simple	MAGNETICS	Orthonol	1.4	1.28	5.58E-11	15000	15000	14000	11000	756
10	Cut C 2mil Simple	MAGNETICS	Permalloy 80	1.79	1.52	6.03E-14	7400	6200	25000	5000	1670
11	Cut C 2mil Simple	MAGNETICS	Supermendur	0.91	1.31	2.88E-09	21000	21000	30000	19000	117
12	Cut C 4mil Shell	MAGNETICS	Supermendur	1.25	1.39	1.93E-10	21000	21000	30000	19000	117

Each line of this sheet represents a new core material. Each column represents a core characteristic. Each core material will generally have multiple geometries associated with it. These geometries will have the same Family Name, and will be located on the Geometry sheet.

The following sections describe each entry in the Material sheet, and the steps necessary to determine the correct value.

Family Name

The family name is used as the relational operator that links the material and geometry. For each Family Name, there must be a material in the Material sheet and a geometry, or set of geometries, which have the same Family Name. This entry cannot exceed a length of 31 characters. The actual limit on the length of this name will depend on the display settings of your computer. The name should be as descriptive and short as possible.

An example of a good family is "Toroid MPP 125u." This family name describes the 125µ MPP material, and the set of toroidal geometries which are available for that core material. The

name must include the character string "toroid" or "tape wound" for Magnetics Designer to understand that the core is a toroid.

Vendor Name

This column represents the name of the core material manufacturer. The length limitations of this column are the same as those of the Family Name. The following table lists some reasonable entries for this column.

Actual Name	Entered Name
Arnold Engineering	Arnold
Ferroxcube	Ferroxcube
Thomas & Skinner	Thom & Skin

Material Name

All vendors have naming conventions which suit their product line. Unfortunately, these naming conventions are not universal. Therefore, it is likely that different vendors will manufacture the same materials and use different names.

In order to improve the accuracy of Magnetics Designer, characterize each material for specific regions of use. For instance, although power loss curves are provided for a set of frequencies, there is no way to accurately model the characteristics over the entire frequency range. Therefore, the material is characterized over smaller frequency ranges in order to improve the accuracy of the power loss calculation. Similar techniques are used to account for temperature effects. Both of these topics are covered further in later sections.

Any name can be used to represent the material. The name should be descriptive enough to clearly signify the region of optimal use, but should not exceed the string length limitation.

Some examples of good Material Names are;

Material Name	Region of use
3F310K50K_100C	10kHz-50kHz at 100°C
3C85-HF-25C	Below 100kHz (LF) at 25°C

m, **n**, **and Kp**

The three core loss coefficients must be calculated from the manufacturer's loss curves. The general equation for core loss as a function of frequency, flux density, and core volume is given below.

$$Pcore = VolKpB^n f^m$$

where Pcore is the core loss, in watts, Vol is the volume of core material, in cm³, B is the peak AC flux density, in Gauss, f is the operating frequency, in Hz, Kp is the core loss multiplier, n is the exponent of B, and m is the exponent of f.

Typically, core loss is plotted as a series of constant frequency curves on log-log paper, where each plot is a straight line. To demonstrate how the above equation plots as a straight line, take the log of both sides of the loss equation:

$$LOG(Pcore) = LOG(Kp) + nLOG(B) + mLOG(f)$$

If frequency is held constant, and the core losses are calculated for two different flux densities, B1 and B2, two equations can be written and simultaneously solved for n as follows:

$$LOG(P1) = LOG(Kp) + nLOG(B1) + mLOG(f0)$$

$$LOG(P2) = LOG(Kp) + nLOG(B2) + mLOG(f0)$$

Subtracting the second equation from the first equation and solving for n gives :

$$n = \frac{(LOG(P1) - LOG(P2))}{(LOG(B1) - LOG(B2))}$$

Likewise, flux density can be held constant, and two equations for core loss as a function of two different frequencies can be written. When the two equations are subtracted, solving for m gives:

$$m = \frac{(LOG(P1) - LOG(P2))}{(LOG(f1) - LOG(f2))}$$

Knowing both m and n, it is easy to solve for Kp using the original equation:

$$Kp = \frac{P1}{B_1^n f_1^m}$$

The Core Loss calculator uses linear regression to calculate coefficients that minimize the sum of the errors squared. Therefore, using the core loss calculator will generally result in more accurate estimates than calculating the losses from 3 data points. Even better predictions can be obtained if the estimates are performed with data values which are near the operating frequency and flux density. For example, if you will be designing transformers which operate at 100 kHz and approximately 1000 Gauss, then only use data points from 50 kHz to 200 kHz and 500 to 2000 Gauss.

The Permeability calculator can be used to compute and enter Bsat, Usat, B1, and U1.

Bsat

Manufacturers typically specify saturation flux density at 25°C and 10 to 15 Oersted. However, in most cases it would be unwise to design a transformer that operates near this specified value.

As shown in the figure to the left, when the flux density approaches Bsat, the permeability (and thus the magnetizing inductance) drops off very rapidly. Furthermore, at elevated temperatures, Bsat will be significantly lower than the 25°C value. Therefore, in the interest of generating a conservative design, it is worthwhile to choose Bsat at a magnetizing force on the order of 1 Oersted at the maximum operating temperature. For example, consider J material (Magnetics) which has a specified Bsat of 4300 Gauss at 15 Oersted. Extrapolating the B-T curve for 100°C and 1 Oersted, the flux density is approximately 2400 Gauss. Furthermore, referring to the permeability versus flux density curve, at 2400 Gauss and 100°C the permeability is approximately 2000, which is approximately 1/3 of the 25°C 3000 Gauss value.

$\mu_{sat}=db/dh(Bsat)$

Bsat

B1 — $\mu_1=db/dh(B1)$

Br
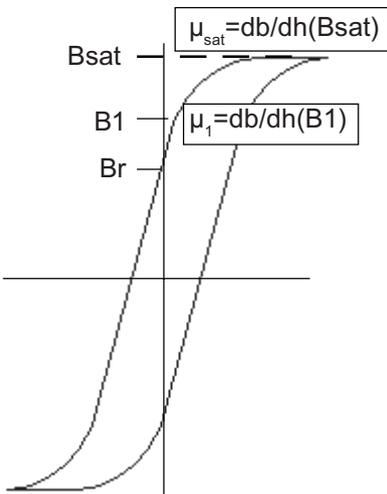
It is recommended that the saturation flux density, Bsat, is the 1 Oersted, 100°C flux density value from the B-H loop curve. For lower operating temperatures, a somewhat larger value can be chosen. However, this is a decision which must be made by the designer. It is not unusual in the case of a forward converter transformer (where there is a DC offset in the flux density which is equal to Br) for designers to use a maximum magnetizing force as high as 2 Oersteds as the design limit. Generally, in these cases, there is a modest gap which reduces the effective residual flux density and stabilizes the magnetizing inductance. However, the designer should be aware that during a large positive line transient, the additional volt-seconds applied to the primary may cause the core to saturate, depending upon the speed of the control loop and current limiting circuits.

Br
The residual flux density can usually be determined in one of three ways. Sometimes the data sheet simply lists Br. Alternately, if there is a B-H curve, Br is the flux density to which the flux returns when the magnetizing force is zero Oersted. Sometimes only a coercive force (Hc) is specified. In this case, Br is approximately equal to Hc times the relative permeability of the material (Hc is the magnetizing force which is necessary to return the flux density to zero).

U1
The permeability often varies with temperature, flux density, and frequency. Magnetics Designer uses the permeability as well as the core gap to calculate the magnetizing inductance. You should review the various curves and select an average value which best corresponds to the expected operating conditions.

In order for Magnetics Designer to properly model the core saturation characteristics, the permeability should approximately equal the slope of the B-H loop for flux values below B1. Often the permeability of the core is specified under a small signal condition which results in a permeability value considerably lower than the B-H loop slope. However, in most cases the inductance is primarily controlled by the length of the gap rather

than the permeability of the core. The only impact of a poor estimate of permeability is reduced accuracy in the magnetizing inductance calculation as the core begins to saturate.

Other materials, such as powdered iron or powdered molypermalloy, have very low initial permeability (from 10 to 200). In this case, a gap is not necessarily required, and the accuracy of the inductance prediction can be no better than the accuracy of the permeability. Furthermore, permeability often varies significantly with AC flux density. Therefore, it may be wise to generate several different data sets for different AC flux densities, where the permeability as well as the core loss coefficients are appropriately adjusted.

If the permeability resulting from the minimum gap is greater than μ_{max}, then the gap shown in the Transformer/Inductor screen will be adjusted upward.

If a B-H loop curve is not provided, a good estimate of B1 is .75 times Bsat.

B1
B1 is the flux density where the slope of the B-H loop starts to decrease. As the DC bias is increased above this value, inductance will decrease. B1 is one of four data points which are used by Magnetics Designer to curve fit an equation which represents the B-H loop of the material. This data is usually extracted from the manufacturer's data sheet.

When the manufacturer supplies a graph of permeability as a function of DC bias, the Permeability calculator should be used to determine the B-H characteristics. The calculator uses a linear regression algorithm to calculate the best possible coefficients which describe the B-H loop (B1, µ1, Bsat, µsat) using data from the permeability versus DC bias graph.

The algorithm assumes that permeability is essentially constant for any magnetizing force less than H1. That is, the B-H relationship is linear (B=µH). For values of H which are greater than H1, the permeability exponentially approaches one. That is,

$$\mu(H) = K_1\left(e^{-K2(H-H1)}\right) + 1$$

These assumptions are usually reasonably accurate for powdered iron and powdered molypermalloy cores. Some inaccuracy will result when the flux density is very high, because a significant percentage of flux linkages occur outside of the core material. Therefore, inductance calculations will have significant errors because the effective area and the magnetic path length of the core do not correctly define the magnetic circuit.

Saturation Permeability
Usat is the permeability of the material at the defined value of Bsat. If Bsat is defined at H = 1 Oersted, then Usat is the slope of the B-H loop at 1 Oersted.

For ferrite materials, the saturated permeability is usually between 20 and 100. If a B-H loop is not available, choose something on the order of 50.

If the material characteristics are described by a permeability versus DC bias curve rather than a conventional B-H curve, use the permeability calculator to calculate Bsat. When predicted by the linear regression algorithm, Bsat is defined as the flux density where the permeability has declined to 10% of its initial value.

Geometry Sheet

The Geometry Sheet of the core database is used to store information that pertains to a core's geometric characteristics.

	A	B	C	D	E	F	G	H	
1	Family Name	Geometry Name	Area Product	Core Area	Core Volume	Core Weight	Bobbin Length	Bobbin Height	Tur
2	Cut C 1mil Shell	MC1606-001S	0.19588	0.323	1.539095	13.445	1.27	0.4775	
3	Cut C 1mil Shell	MC0001-001S	0.26048	0.323	1.64084	14.334	1.27	0.635	
4	Cut C 1mil Shell	MC1582-001S	0.39032	0.484	2.45872	21.479	1.27	0.635	
5	Cut C 1mil Shell	MC0143-001S	0.52016	0.645	4.09575	35.78	1.27	0.635	
6	Cut C 1mil Shell	MC0003-001S	0.73387	0.728	4.62644	40.416	1.5875	0.635	
7	Cut C 1mil Shell	MC0004-001S	0.91028	0.645	5.324475	46.514	2.2225	0.635	
8	Cut C 1mil Shell	MC1169-001S	1.17097	0.968	7.37616	64.438	1.905	0.635	
9	Cut C 1mil Shell	MC0007-001S	1.694	0.847	7.52136	65.706	2.54	0.7874	
10	Cut C 1mil Shell	MC1586-001S	1.85384	0.645	6.7596	59.051	3.0175	0.9525	
11	Cut C 1mil Shell	MC1200-001S	2.34193	0.968	9.2202	80.547	2.54	0.9525	
12	Cut C 1mil Shell	MC1571-001S	2.7822	0.968	10.14464	88.623	3.0175	0.9525	
13	Cut C 1mil Shell	MC1703-001S	3.12096	0.645	8.1915	71.56	3.81	1.27	

mtl.xls

Dialog1 / Materials Library \ Geometry Library / CoreLoss / Permeability /

The rows of the sheet represent different core material geometries. The columns represent data elements which describe the geometric representation. Each core geometry must have a core material whose Family Name is the same.

A geometric representation includes core and bobbin dimensions. Therefore, you will need access to core and bobbin data. In most cases, manufacturers supply data sheets which contain both core and bobbin geometry data. In some cases, many cores are listed together in a table, and bobbin data is listed elsewhere. It is also possible that a core manufacturer may not supply bobbins. In such a case, coil forms can be constructed from fiberglass tubing, or bobbins can be purchased from other suppliers.

Toroidal cores have no bobbin or air gap. This requires special consideration when entering the core geometry data. In the following sections, and in the examples listed at the end of the chapter, special notice is given for any core geometries that require special calculations.

Family Name

As explained in the Material section, this entry is used as a relational operator to link the Material and Geometry libraries. There must be a material and at least one geometry entry for every Family Name. The name should be less than 31 characters. Although the length of the string can be 31 characters, most screens will not allow all of the characters to be displayed. The Family Name should be as descriptive and short as possible.

Geometry Name

The core may be given any suitable, <u>unique</u> name to distinguish it from other core geometries within its Family Name. In general, cores are given names which are fairly uniform across the industry. For example, a 7mm x 4 mm pot core can be purchased from many different vendors.

Duplication of geometry names is allowed as long as the Geometry Name belongs to a different Family Name.

Area Product

The area product is automatically calculated by multiplying the effective core area and the effective window area. The effective window area is calculated by multiplying the bobbin height and length.

This parameter is used as a measure of the power handling capability of a core. When the library file, Geo.lib, is created, all cores are sorted according to Family Name and Area Product. This allows Magnetics Designer to quickly search for the best core.

Effective Core Area

Most vendors list the effective core area on the data sheet. Sometimes the data is in square centimeters; sometimes it is in square inches. **The effective core area must be entered in square centimeters.**

Tape-wound cores such as cut C cores list the gross area of the core. The effective area must be calculated using stacking factors which vary as a function of the tape thickness. Therefore, when working with tape-wound cores, a separate entry will be required for each foil thickness.

Core Volume
The core volume is used by Magnetics Designer to calculate core losses. Core losses are directly proportional to volume. Sometimes core losses are specified with respect to weight. Since weight is directly proportional to volume, either system is valid. However, **Magnetics Designer requires data to be entered in cgs units**.

Core loss coefficients are derived from curves which are expressed in watts per volume. The volume entered here and the volume used to calculate the Core Loss coefficients must be expressed in cm^3.

Core Weight
The core weight is used to estimate the weight of the final inductor or transformer. The weight of the core should be entered in grams. Magnetics Designer will calculate the weight of the final core by summing the core weight, provided here, and the copper weight, calculated from the winding information. You can include any additional weight by altering the equation for the Weight User Defined Button. See the *User Data Input/ Output Fields* section for more information.

Window Length
The window length is the maximum winding length for a single layer winding, assuming there is no bobbin. This dimension is typically listed in the data sheet. The window length, in conjunction with the bobbin data generated by Magnetics Designer will determine the area allowed for winding.

For toroidal cores, the window length is the perimeter of the inner portion of the core.

$$L_b = \frac{A_{win}}{H_b}$$
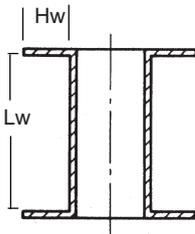
Window Height
The window height is the distance from the center post or leg of the core to the outside edge of the core window. For standard bobbins, this dimension will be listed on the data sheet. For toroidal cores, the height is the window area divided by the window length. The window area is generally specified in the product documentation.

Turn Multiplier
The turn multiplier is used to calculate the length of a single turn on the first layer, and is based on the value of the bobbin's inside diameter. If the core has a circular center post, the multiplier should be 3.14. If the bobbin is rectangular, the core is a toroid, or the bobbin has an irregular shape, the multiplier should be 4.

Minimum Core Gap
The minimum core gap is the effective gap due to surface roughness between the two mating surfaces of a core. The minimum gap can be calculated based on the inductance factor, Al, the permeability at the specified condition for Al, the Area of the core, and the magnetic path length using the following equation:

$$gap = \frac{.4\pi Acore \times 10^{-2}}{Al} - \frac{lcore}{\mu r}$$

The permeability for this equation is determined from the test conditions which were used to determine Al. For instance, all Magnetics® data for Al, except where noted, is measured at 5G and 25°C. Using the μ vs. B graph for 25°C, the permeability can be determined.

For example, a 2020 PQ core, made from P material, has an Al of 2.41 Henries/1000 turns (5 Gauss AC at 25°C), a lcore of 4.54 cm, an Acore of .62 cm², and a permeability of 2600 (at 25°C and 5 Gauss). Using the above equation, find the gap.

$$gap = .4\pi(.62)\frac{10^{-2}}{2.41} - \frac{4.54}{2600} = 1.49 \times 10^{-3}\, cm$$

Magnetic Path Length (MPL)

The magnetic path length is usually specified near the beginning of the data sheet. If the path length is not given, it can be approximated by calculating the average round trip distance for the various flux paths. The magnetic path length is used to calculate the reluctance of the core so that the magnetizing inductance can be predicted. Magnetics Designer automatically calculates the effective Br when there is a gap based on the gap length, core relative permeability, and the magnetic path length.

Inside Diameter

ID is provided on the manufacturer data sheet.

The inside diameter, in conjunction with the bobbin information entered into Magnetics Designer, is used to calculate the length of a turn on the first layer. For round bobbins, the inside diameter is equal to the diameter of the core center post. For rectangular bobbins, the diameter is defined as the length of a single turn divided by 4.

For toroidal cores, the inside diameter (ID_b) is a constant which is 1/4 of the length of a turn on the first layer.

$$ID_b = \frac{\left(H + \left(\frac{OD - ID}{2}\right)\right)}{2}$$

Surface Area

The surface area of the finished transformer is used to predict the temperature rise. A conservative estimate of surface area can be obtained by drawing a box or cylinder around the transformer and finding the surface area of that simpler shape. In general, irregularities in the surface of the transformer will increase the total surface area, and therefore result in a lower temperature rise than that which was predicted by the simpler model.

Manufacturers sometimes provide a curve which predicts the temperature rise versus power dissipation. This curve can be used to calculate the equivalent surface area using the following equation:
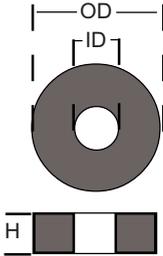
$$A_{surf} = \frac{(710 P_{diss})}{T_{rise}}$$

where A_{surf} is the surface area, P_{diss} is the power dissipation, and T_{rise} is the temperature rise.

For toroidal cores, the surface area can be estimated using the following formula:

$$A_{surf} = \frac{\pi}{2} Dia^2 + \pi\ Dia\ Ht \quad \text{where}$$

$$Dia = OD + 0.275\ ID$$

$$Ht = H + 0.55\ ID$$

and H is the height of the toroid, OD is the outer diameter, and ID is the inner diameter. See the figure to the left.

MLT
MLT is the mean length per turn assuming the window is completely filled with wire. This parameter is usually listed on the data sheet for commercial bobbins, or may be approximated by calculating the length of a turn which is located at the layer where the window is half full of wire. MLT is only used in the core selection algorithm. In the resistance prediction, the actual wire length is used based on the inside diameter of the bobbin plus any build due to from windings and insulation.

For toroidal cores, MLT is the mean length per turn assuming the window is completely filled with wire. The toroid is considered to be completely filled when 55% of the inside diameter (ID) is full of wire. The mean length per turn is approximated by

$$MLT = OD - 0.316\ ID + 2\ H$$

Minimum Core Area
Certain cores have sections which have less cross-sectional area than the effective core area. For example, the center post of a pot core has less cross-sectional area than the outside part of the core. To prevent the core from saturating, the minimum

area is used to calculate the peak flux density. Typically, the minimum cross-sectional area is specified on the data sheet. Sometimes, you may have to calculate the cross-sectional area of the part of the core that appears to be the smallest.

For toroidal cores, the minimum core area is equal to the effective core area.

Gap OK
This flag signifies that it is OK to insert a gap into the core in order to adjust the inductance value. For most cores, this value will be set to 1. Cores that cannot be gapped, such as toroids, the values will be set to 0.

Cost
This database entry currently serves to disable core geometries. When this entry is set to a value equal to or greater than 1, the core will be bypassed by the core selection algorithm. At this time, all Cost fields are set to 0.

Gapped Core Data

The characteristics of gapped cores are not entered directly into the database. Various manufacturers make gapped cores for some geometry types. In other cases, the core can be machined in order to achieve the desired gap. In any case, the data entered into the database should represent an ungapped material and geometry.

Gapped Cores are taken into account automatically by Magnetics Designer whenever GapOK is checked in the Core Database dialog. When GapOK is checked, Magnetics Designer will insert a gap in order to satisfy the desired specifications which have been entered into the Transformer or Inductor screens. The gap is reported through the User Defined Buttons. (See the *User Data Input/Output Fields* section for more information.)

Once Magnetics Designer has determined the appropriate gap, the value can be used to select the correct part from the manufacturer, or to machine the core to the correct dimensions.

If you make a core family using pre-gapped cores, then make sure gapOK is set to FALSE. You should place all cores having the same permeability in the same family. You will have to compare results using different permeability in order to find the smallest core. It works better to let Magnetics Designer calculate the gap and then change to the nearest pre-gapped core. Incidentally, cores with a single gap in their centerleg will have higher AC losses than cores with gaps distributed in both the centerleg and outer leg of the core.

Core Loss Calculator

The Core Loss Calculator is an Excel macro that uses linear regression to calculate the coefficients of the core power loss equation, Kp, m, and n from

$$Pcore = VolKpB^n f^m$$

A table consisting of three columns, B (flux density in Gauss), f (frequency in Hertz), and P_L (power loss in watts/cm^3) is used as the input to the linear regression formula. The data values used in this table are obtained from the manufacturer's data sheets and generally appear as a log-log graph of B versus P_L per volume for constant frequencies.

When entering the data extracted from the graphs, it is very important to use cgs units.

The (ERRORS^2) parameter and the calculated core loss (Pcalc) are displayed as feedback of the error involved in the calculation of the core loss coefficient. It is desirable to have the (ERRORS^2) parameter approach 0. In some cases, it may be necessary to adjust the data derived from the graph in order to minimize the error term.

Entering Data
At least three independent data points must be entered before the calculator can estimate the coefficients correctly. All three columns must be filled in for all three points. Up to 9 data points may be entered.

CORE LOSS CALCULATOR

To enter data:

- Click the mouse in the cell representing the data point to be entered.

- Enter the number using standard numerical syntax.

- Press the tab key or the enter key to advance to the next cell.

The Calculate button is used to perform the calculation. If the data is satisfactory, i.e. (ERRORS^2) ≈ 0, The Apply button can be used to add the calculated data to the Core Database dialog and quit the calculator. The Cancel button clears the calculator and returns to the Core Database dialog, without entering new data into the Material library.

Permeability Calculator

The Permeability Calculator is an Excel macro that is used to obtain the coefficients that approximate a core's B-H characteristics.

A two column table is used to enter the magnetizing force in Oersteds and the percentage of the relative permeability at the specified magnetizing force. The data for this table is usually presented in the manufacturer's data book as a linear-log graph of %μr versus H (in Oersteds). When entering data from the graph, it is important to use Oersteds.

As feedback of the error involved in the estimation of the data, the (ERRORS^2) and calculated % of μr are displayed. It is desirable for the (ERRORS^2) to approach zero. In some cases, it may be necessary to adjust the data derived from the graph in order to minimize the error term.

The output parameters of this calculator are displayed at the top of the calculator. The first four parameters (u1, B1, usat, and Bsat) are the coefficients used to describe the B-H characteristics of the material as a function of DC bias. Four additional parameters (K1, K2, A1, H1) are displayed and used in conjunction with the previous constants to define equations which predict flux density and permeability as a function of DC bias using the following equation (for B >B1 and H>H1):

$$\mu(H) = K_1 K_2 e^{-K2(H-H1)} + 1 \quad \text{or} \quad \mu(H) = A1\, e^{-K2H} + 1$$

$$B(H) = B_1 + K_1\left(1 - e^{-K2(H-H1)}\right) + \left(H - H_1\right)$$

Entering Data
Two parameters (H and % of u(0)) must be entered on each line. Three independent data points must be entered in order to calculate the coefficients. Up to 9 points can be entered.

To enter data:

- Click the mouse in the cell representing the data point to be entered.

- Enter the number using standard numerical syntax.

- Press the tab or enter key to advance to the next cell.

The Calculate button is used to perform the calculation. If the data is satisfactory, i.e.(ERRORS^2) $\approx$ 0, the Apply button can be used to add the calculated data to the Core Database dialog and quit the calculator. The Cancel button clears the calculator and returns to the Core Database dialog without entering new data.

Entering a New Pot Core

The data for this section is extracted for the Magnetics F type material from the 1992 Magnetics Ferrite Core data book. The core parameters will be entered for a design that will operate at 40kHz and 100°C. The data we will enter is shown in the following dialog. All units must be entered in cgs.

Entering a Family Name
The Family Name drop box located at the top of the Data Entry dialog is used to select an existing Family Name or to enter a new Family Name. The Family Name should reflect the type of core material that will be entered.

To enter a new Family Name:

• Place the mouse pointer over the Family Name Drop Box.

• Click the left mouse button.

• Type "Pot Core Example", without the quote marks, into the Drop Box.

Entering a Vendor Name
The material we are entering is from a vendor that already exists in the database. Therefore, we will simply type the name already used.

• Place your mouse pointer over the Drop Box.

• Click the left mouse button.

• Type "MAGNETICS", without quote marks.

Entering a Material Name
In order to optimize the accuracy of the calculations performed within Magnetics Designer, material data should be entered as close to the intended design operating conditions as possible. The material name entered should be descriptive enough to recognize the proper region of use for the material. In this example we will select data to optimize a Magnetics' F material for a frequency of 40kHz and a core temperature of 100°C.

Core Database

Family Name: Pot Core Example

Material

Vendor Name: MAGNETICS
Material Name: F2550K_100C

CoreLoss Calculator
m: 1.67988
n: 2.75802
Kp: 4.05E-18

BSat: 3400
USat: 140
Permeability Calculator
B1: 1700
U1: 2600

Br: 1800

Add Material

Geometry

Geometry Name: 26x16A

Area Product: 0.3863156318

Core Area: 0.931
Core Volume: 3.5
Core Weight: 20
Min. Core Gap: 0.589
MPL: 3.76
Surface Area: 22.721
Min. Core Area: 0.751

Window Length: 0.9931
Window Height: 0.41783
Turn Multiplier: 3.14
Inner Diameter: 1.28
MLT: 5.242
Cost: 0

☑ GapOK

Add Geometry

Save

However, since the data is provided for 25k and 50k and not 40k we will create a material for this frequency range and give it a name of F25-50K_100C.

• Place the mouse pointer over the Material Name Drop Box.

• Click the left mouse button.

• Type F2550K_100C into the Drop Box.

Entering the Core Loss Coefficients

The core loss coefficients are derived from the Core Loss versus Flux Density curves given by the core manufacturer. Our choice of core is the Magnetics F material. The Core Loss graph for this example yields the following data points:

B	**f**	**Power**
150	25000	0.0001
800	25000	0.01
200	50000	0.0007
1000	50000	0.06

Since all units must be cgs, the Power Loss/ Volume must be entered as watts/cm³.

• Activate the Core Loss calculator by clicking on the Calculator button located to the left of the m, n, and Kp coefficients.

• Click on the first box in the upper left of the white data entry area of the Core Loss Calculator.

• Enter the Flux density in Gauss, 150, as provided in the table given above.

• Press the tab key to advance to the frequency entry field.

• Enter 25000 for the frequency and press the Tab key to advance to the power loss entry field.

• Enter the power loss in Watts/cm^3, .0001, as provided in the table.

• Press the Enter key.

• Repeat the above steps until all of the data from the table has been entered.

• When all the data has been entered, press the Calculate button.

The coefficients will be calculated and displayed in the dialog.

- Click the Apply button to enter the values and return to the Core Database dialog.

Typically, the final values received from the Core Loss calculator will depend on the interpretation of the Core Loss graph. All numbers will be equally valid if the error term, (ERROR^2), is kept as low as possible.

For the data given above, the final values for the core loss coefficients are:

m = 1.67987595
n = 2.75801955
Kp = 4.0529E-18

In some cases, here will be information about power loss as a function of temperature. Typically, this information is minimal at best, and is usually given for only one bias and one frequency. Therefore, the extrapolation of the Core Loss graph to other operating temperatures is virtually impossible.

Now that the core loss coefficients have been defined, we will enter the DC bias information of the core. This is done by entering the values for Bsat, Br, μ1, B1, and μsat. It is best to examine the data given and choose values that, as in the case of the core loss parameters, match the design operating conditions. These values can be determined by interpreting the B-H loop or by using the Permeability calculator. Since the appropriate μ vs. H graph is not present in the Magnetics data book for this material, we will focus on the interpretation of the B-H loop.

Bsat
When provided, this parameter is generally given by manufacturers at 25°C and in the vicinity of 10-15 Oersteds. For the Magnetics F material, we are given 4900 @ 15 oersted, 25°C. This is not the most appropriate value to use when designing a transformer. As discussed in previous sections, the

best value to use is the 1 Oersted, 100°C value extracted by interpreting the B-H loops provided. The value for Bsat at 1 Oersted, 100°C is 3400 Gauss.

• Enter 3400 in the Bsat edit field in the Data Entry dialog.

Usat
The saturation permeability can be determined as the slope of the B-H loop at Bsat. From this, μsat is determined to be 140.

• Enter 140 in the Usat edit field in the Data Entry dialog.

B1
B1 is the flux density where the slope of the B-H loop starts to decrease. In other words, it's the point where the magnetizing permeability (and hence the magnetizing inductance) diverges from linearity. From the B-H loop, this value is determined to be 1700 Gauss.

• Enter 1700 in the B1 edit field in the Data Entry dialog.

U1
The permeability at B1 is defined as the slope of the B-H loop below B1. From the B-H loop, this is determined to be 2600.

• Enter 2600 in the U1 edit field in the Data Entry dialog.

Br
The residual flux density can be read directly from the data sheet, if provided, interpreted from the B-H loop provided as the point were H is 0, or calculated as Hc (the coercive force) times the relative permeability. Since we are given the B-H loop, we can read it directly as 1800 Gauss.

• Enter 1800 in the Br edit field in the Data Entry dialog.

Adding the Material to the database
With all of the entries for the Material filled in and the appropriate Family Name entered or selected, we can add the material to the database.

• Click the Add Material button

The material entries will be added to the Material sheet and the entire database will be saved.

Geometric Information
Each Family Name must have a Material and Geometry database entry. In most cases, the Family Name will have several Materials, each describing a specific operating range, and a set of core geometries that apply to the Materials. For the new Pot Core we just entered, we will enter one of several geometries that apply to the material we have chosen.

Geometry Name
Any descriptive name that identifies the core geometry can be used. For this example, we will be entering the data for the 26mm x 16mm ungapped core geometry from Magnetics. For this geometry, we will use 26x16A as the Geometry Name.

• Place your mouse pointer over the Geometry Name Drop Box.

• Click the left mouse button.

• Enter "26x16A", without the quote marks, into the Geometry name Drop Box.

The Area Product
This value is calculated by the Core Database dialog as the product of the effective core area and the usable bobbin window area of the core. It is typically given as WaAc in the manufacturer's data book. This parameter is calculated by multiplying the entered core area, the bobbin height, and the bobbin length. This entry will be filled in only after all appropriate entries have been completed.

Entering the Core Area
The effective Core area is given by the manufacturer as .931 cm^2.

• Enter .931 into the Data Entry dialog for Core Area.

Core Volume (Vol)
The core volume is given by the manufacturer as 3.5cm³.

• Enter 3.5 into the Data Entry dialog for Core Volume.

Core Weight (CoreWt)
The weight of the core is given as 20 grams per set. The core comes in a two piece set, so the entire core weight is 20 grams.

• Enter 20 into the Data Entry dialog for Core Weight.

Min. Core Gap (MinGap)
The minimum possible gap is determined using the following formula:

$$gap = \frac{.4\pi Acore \times 10^{-2}}{Al} - \frac{lcore}{\mu r}$$

where Acore = .931, Al =6350 , MLP = 3.76, and μ=2500 . From the Magnetics data book, the Al for the F type 2616 ungapped core is given as 6350 @5Gauss and 25°C. Thus, the minimum effective gap is 0.589cm.

• Enter .589 into the Data Entry dialog for Min. Core Gap.

MPL
MPL, the magnetic path length, is given by the manufacturer as 3.76cm.

• Enter 3.76 into the Data Entry dialog for MPL.

As (Core & Bobbin)
The surface area of a Pot core can be calculated by assuming that the final product is a cylinder with a height equal to the two halves of the core plus any gap, and a diameter equal to the

diameter of the core. The formula for the surface area of a cylinder is

$$A_{surf} = 2 * \pi\, r^2 + \pi\, D\, H$$

From the dimensions provided by the manufacturer, D=2.52cm, r=1.26cm and H=1.61cm

$$A_{surf} = 2 * \pi\, (1.26)^2 + \pi\, (2.52)(1.61) = 22.721$$

Thus, the final surface area is 22.721cm^2.

When determining bobbin data, use the single sector bobbin geometry.

• Enter 22.721 for the Surface Area of the core.

Min Core Area (Amin)
The minimum core cross sectional area given by the manufacturer is .751cm^2.

• Enter .751 into the Data Entry dailog for Min. Core Area.

Window Length (Lw)
The length of the window is given in the Magnetics data book as 1.102cm.

• Enter 1.102 for the Window Length in cm.

Window Height (Hw)
The window height is calculated from the data in the Magnetics data book as 0.4865cm.

• Enter 0.4865 for the Window Height, in cm.

Turn Multiplier (Bobbin)
For round bobbins, this parameter must be set to 3.14.

• Enter 3.14 for the Turn Mult. in the Data Entry dialog.

Inner Diameter (ID)
The inside diameter of the POT core is the diameter provided, and is 1.148cm.

• Enter 1.148 for the Bobbin ID in the Data Entry dialog.

MLT
The mean length per turn (average length of turn) is given as
.173ft. Multiply this by 0.3048 to obtain the MLT in meters,
which is .05242.

• Enter 5.242 for the MLT in cm.

GapOK
The GapOK parameter determines if a core gap can be inserted
by Magnetics Designer. For Pot cores, this parameter should
be checked. By default, this parameter is checked and should
not be changed.

After your design is complete, the Gap variable in Magnetics
Designer can be used to select the correct part from your
vendor's selection of gapped cores, or to machine the core to
the specified gap.

Cost
The current version of Magnetics Designer does not process
the Cost parameter. It should be left at its default value of 0.

Adding the new Geometry
At this point, we can add the newly entered geometry data to the
database by clicking the Add Geometry button.

• Click the Add Geometry button.

Creating the Library files
Now that both the material and geometry have been added to
the database, we can create a new set of libraries, Mtl.Lib and
Geo.Lib, for Magnetics Designer.

• Click the Save button.

The done button will create the Mtl.Lib file and Geo.Lib file with
all the data sorted correctly for Magnetics Designer. After the
dialog is dismissed, the database file, Mtl.Xls, will be saved and
Excel will remain open, allowing you to go to the next example.

Entering a New Toroid Core

The data for this section is extracted for the Magnetics MPP 60µ material from the 1992 Magnetics Powder Core data book. The core parameters will be entered for a design that will operate at 40kHz and 25°C.

This example will demonstrate how to derive the toroid values so that Magnetics Designer will correctly calculate the results for toroidal cores. The data we will enter is shown in the following dialog. All units must be entered in cgs.

Family Name
The family name is chosen to correspond to the characteristics of the material. In order to avoid conflicts with current materials, enter "Toroid MPP60 Example" for the Family name.

• Place your mouse pointer over the Family Name Drop Box.

• Click the left mouse button.

• Type "Toroid MPP60 Example", without the quotes.

Vendor Name
A new vendor's name can be entered into the Drop box using the techniques described above.

• Place your mouse pointer over the Vendor Name Drop Box.

• Click the left mouse button.

• Type "MAGNETICS", without quote marks.

Material Name
In order to optimize accuracy of the calculations performed within Magnetics Designer, material data should be entered as close to the intended design operating conditions as possible. The material name entered should be descriptive enough to

recognize the proper region of use. In this example, we will select data to optimize for a frequency of 40kHz and a core temperature of 25°C. However, since data is provided for 10k and 50k and not 40k we will create a material for this frequency range and name it 10K50K_25C.

• Place the mouse pointer over the Material Name Drop Box.

Core Database

Familiy Name   Toroid MPP 60u

Material

Vendor Name   MAGNETICS

Material Name   10K50K_25C

CoreLoss Calculator		
	m	1.39889
	n	2.32657
	Kp	4.39E-12

Permeability Calculator		
	BSat	6596.83
	USat	6.900
	B1	1473.1
	U1	60.0

Br   100

Add Material

Geometry

Geometry Name   55181

Area Product   0.0008381301

Core Area	0.0286	Window Length	0.4615
Core Volume	0.061	Window Height	0.0635
Core Weight	0.244	Turn Multiplier	4
Min. Core Gap	1E-7	Inner Diameter	0.247
MPL	1.06	MLT	1.242
Surface Area	1.3078		
Min. Core Area	0.0285	Cost	0

☑ GapOK

Add Geometry

Save

• Click the left mouse button.

• Type 10K50K_25C into the Drop Box.

Core Loss Coefficients
The core loss coefficients are derived from the Core Loss versus Flux Density graphs provided by the manufacturer. Our core selection is the Magnetics MPP60 material. The Core Loss graph yields the following data points:

B	f	Power
200	10000	.3593
400	10000	1.711
200	20000	1.2832
500	20000	10.266
200	50000	3.422
400	50000	17.110

Since all units must be cgs, the Power Loss/Volume must be entered as watts/cm3.

•   Activate the Core Loss calculator by clicking on the Calculator button located to the left of the m, n, and Kp coefficients.

•   Click on the first box in the upper left of the white data entry area of the Core Loss Calculator.

•   Enter the Flux density in Gauss, 200, as provided in the table given above.

•   Press the tab key to advance to the frequency entry field.

•   Enter 20000 for the frequency and press the tab key to advance to the power loss entry field.

•   Enter the power loss in Watts/cm^3, 0.3593, as provided in the table.

•   Press the return key and then the left arrow key to advance to the beginning of the next line.

•   Repeat the above steps until all of the data from the table has been entered.

•   When all the data has been entered, press the Calculate button.

The core loss coefficients will be calculated and displayed at the top of the calculator. The error term should be very close to zero to indicate a good fit.

- Click the Apply button to enter the values and return to the Core Database dialog.

If the error term is not close to zero, you may adjust the values entered into the table to provide the best error value. Since most vendors provide a log-log graph with low resolution, there is some play in the selected set of numbers.

Let's calculate the values for Bsat, Usat, B1, and U1 from the Percent Permeability versus DC magnetizing force graph provided by the manufacturer. We can do this via the Permeability Calculator.

- Click on the Calculator button directly to the left of the Permeability variables, Bsat, Usat, B1 and U1.

The Permeability calculator will be displayed. The first step is to enter the zero bias permeability of the material, $\mu(0)$. For MPP60 material, this value is given as 60.

- Place the mouse pointer over the white entry area next to the u(0) entry.

- Click the left mouse button and type 60.

Now we will enter data points representing the Permeability vs. DC Bias of the material.

- Enter the following numbers into the white area of the calculator. Remember to enter the magnetizing force (H) in Oersteds.

H	% of u(0)
10	100
40	87
80	63
100	50
200	15

- When you have finished entering the data, click the Calculate button.

The parameters will be calculated and displayed at the top of the calculator. The error term should be as close to zero as possible for the data to approximate the B-H loop correctly.

- Click the Apply button to apply the values and return to the Data Entry dialog.

If the error term is not close to zero, you may adjust the values entered into the table to provide the best error value. Since most vendors provide a semilog graph with low resolution there is some play in the selected set of numbers.

The values for µsat, Bsat, µ1, and B1 have been calculated and entered into the Data Entry dialog. The remaining parameter, Br, is found by interpreting the B-H loop provided by the manufacturer. It is the Flux density value when the magnetizing force approaches 0. For the 60µ material at 25°C, this value is 100 Gauss.

- Enter 100 for the Br value in the Core Database dialog.

To add the material to the database:

- Click the Add Material button.

The new material will be added to the Core database and the database file will be saved.

Geometrical Data
The geometrical data for the toroid given by the manufacturer's data sheet is not entered directly into the Core Database dialog. The following sections describe the data translations which are necessary to create the proper toroid geometry database entries.

Family Name

The Geometry library sheet will require a Core Family entry to link the entered geometry with a material. When entering geometries and materials together there is no special need to change the value already selected. However, if you were to enter this geometry for several material types, i.e. MPP147, MPP125 and so on, you would want to enter the geometry data once and simply change the selected Core Family from the Drop Box before selecting the Add button.

• Do not change the Core Family Drop Box.

Geometry Name

The part number for the μ = 60 MPP toroid is 55181. This is an adequate name to describe the geometry, and makes ordering the final part a bit easier. However, this name is already used by a MPP60 part in the Core Database. Therefore, we will enter 55181A.

• Place your mouse pointer over the Geometry Name Drop Box.

• Click the left mouse button.

• Type "55181A", without the quotes, into the Drop Box.

WaAc

This parameter is calculated by the program by multiplying the effective core area by the bobbin height and the bobbin length. This field should be left blank.

Acore

The effective area of the toroid core is given by the manufacturer as $0.0285cm^2$.

• Enter 0.0285 for the Core Area parameter.

Core Volume

The core database must be in cgs units. Therefore, it is important to enter the volume in cm^3. The volume can be calculated by dividing the core weight in grams by the density in grams/cm^3, or by subtracting the calculated volume of the cylinder defining the toroid's hole from the cylinder defined by the outer diameter of the toroid. Here we will use the weight and density. The weight for the 55181 toroid is given as .26. However, Magnetics weight data for the 1992 data book is provided for the 125µ material. To obtain the weight of the 60µ material, you must multiply the given weight by the multiplying factor provided on the inside back cover.

• Obtain the weight for the MPP60 by multiplying .26 by .94 to obtain .244 gm.

• Divide the calculated weight, .244 grams, by the density of the MPP60 material, which is 7.896gm/cm^3.

• Enter 0.031 for the volume of the core.

The volume can also be calculated by subtracting the cylindrical volume which is defined by ID and H from the cylindrical volume defined by OD and H.

Core Weight

As calculated on the previous page, the weight for the Magnetics® databook provides only the MPP125 weight. The weight for the MPP60 must be calculated using the scaling factors provided on the inside front cover of the manual.

• Enter .244 grams as the weight of the MPP60 core.

Minimum Gap

Since the toroid is made of one piece of material, it has no physical air gap.

• Enter 1E-7 for the effective air gap.
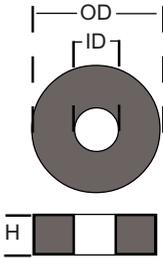
Surface Area

The surface area of the toroid is estimated by the formulas in the Geometry Library section. The value of surface area is calculated as:

$$A_{surf} = \frac{\pi}{2} Dia^2 + \pi\ Dia\ Ht$$

where,

$$Dia = OD + 0.275\ ID$$

$$Ht = H + 0.55\ ID$$

giving,

$$Dia = .521 + 0.275 * .193 = 0.5741$$
$$Ht = 0.33 + 0.56 * 0.193 = 0.4381$$

$$A_{surf} = \pi/2 * 0.5741^2 + \pi * 0.5741 * 0.4381 = 1.3078$$

• Enter 1.3078 for the Core surface Area.

Minimum Core Area

For the toroid, the minimum core area is equal to the effective core area. Hence, this value is read directly from the manufacturer's data sheet and is given as $0.0285cm^2$.

• Enter 0.0285 for the Min Core Area parameter.

MPL

This parameter is given by the manufacturer as 1.060cm.

• Enter 1.060 for MPL.

Window Length
The window length is calculated assuming the first layer is wound along the perimeter of the inner diameter (ID) of the torroid.

$$Lw = 3.14159*ID$$

The inner diameter is given as 0.193cm which makes the window length 0.6063cm.

• Enter 0.6063 for Lw.

Window Height
The window height is the window area divided by the calculated window length:

$$Hw = Awin/Lw$$

Units must be in cgs. Multiply by 5.07x10E-6 to convert from circular mils to cm².

The window area can be calculated using the finished dimensions listed in the databook. The final value becomes 0.02654cm.

• Enter 0.02654 for Hw.

Core ID
The inside diameter (ID_b) is a constant defined as 1/4 of the length of a turn on the first layer, assuming the wire is wound directly on the core. A single turn becomes:

This is not the ID which is provided on the manufacturer data sheet.

$$ID_b = ((2*Ht)+(2*((OD-ID)/2)))/4 = 0.247$$

• Enter 0.247 for the ID parameter.

MLT
The mean length per turn for a toroid is calculated assuming 55% of the ID is filled with wire. This value is approximated by the following equation:

$$MLT = OD - 0.316\ ID + 2H = 1.2420$$

•   Enter 1.242 for the MLT parameter.

Turn Multiplier
The Turn Multiplier is used to calculate a single turn around the bobbin. The turn multiplier for toroids should be set to 4.

•   Enter 4 for the Turn Multiplier parameter.

Gap OK
A toroid does not have a gap, so this value should be set to 0 by unchecking the box.

Cost
Currently, this database entry is used only to disable core geometries from being selected. At this point, the entry should be left equal to 0.

Now that the core geometry data has been entered, we can add it to the core database.

• Click the Add Geometry button.

The new core geometry will be added to the core database and the database will be saved. To write out new library files, Mtl.Lib and Geo.Lib for Magnetics Designer, simply click the Save button.

• Click the Save button.

If you wish to exit the dialog without creating new library files, press the Esc key.

Wire Tables

All wire descriptions are located in separate ASCII text files located in the Magnetics Designer directory. All files provided as part of Magnetics Designer end in a .W extension. Any user defined files must end in an extension given below.

Round wire	.RW
Square wire	.SW
Foil	.FW
PCB	.PW

With the exception of the Foil (foil.w) and PCB (pcb.w) files explained at the end of this section, all files have the same format as

```
Short Name,Long Name,# of entries,First
entry,Kwire,
gauge,height,width,copper area
...
```

There are two sections to the file. The first section consists of the first line, and is used to describe the contents of the file. The items in this line are described below.

Short Name
The short name is used by Magnetics Designer internally. It is the name that appears in the various list boxes that allow you to choose wires. This item is not currently used by Magnetics Designer.

Long Name
This name is used by Magnetics Designer when a long, more descriptive name is required, such as when reports are printed. This item is not currently used by Magnetics Designer.

# of entries
This is the number of wire entries in the table.

First entry
This is the gauge of the first wire in the table.

Kwire
This is the wire utilization factor. It is equal to the ratio of bare copper area, A_{wire}, to the rectangular area used by 1 turn of the a wire, A_r.

$$Kwire = A_{wire}/A_r$$

The remaining lines in the wire description file describe each of the wire sizes that can be selected. Each wire size is listed on a separate line in the following format:

```
gauge,height,width,copper area
```

All of the entries are described below.

Gauge
This is the standard AWG number for the wire to be described.

Bare
Copper

Height
This represents the height, H, of the rectangular area that encloses the wire. This height should include any insulation, as show to the left.

H

Width
This represents the width, W, of the rectangular area that encloses the wire. This width should include any insulation, as shown to the left.

W

Insulation

Copper Area
This represents the area of bare copper found in the wire.
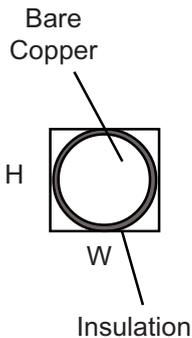
Example

As an example, we will enter the data for Formvar wire. The data is taken from the New England Electric Wire Corp. data book, dated 10/94. The finished file is shown below.

```
NEF,New England Corp. Formvar,2,8,.764
8,.335,.335,.084
9,.299.299,.066
```

Since a Formvar wire table is provided with Magnetics Designer, we could choose to add to the existing file or create a new file. For this example, we will choose the latter.

- Use a standard text editor and open a new file.

- On the first line, enter the short and long names for this wire type as "NEF,New England Corp. Formvar", without the quotes.

Although these two entries are not currently used, Magnetics Designer will require some text as a place holder.

The next two entries will depend on the wire data we enter into this wire table. For the sake of simplicity, we will enter only two wire sizes starting with the 8 gauge wire.

- Type "2,8", without the quotes, directly after the long name previously entered.

Now we will enter the wire utilization factor for the table. We calculate this by dividing the area of the copper by the rectangular area of the window used by 1 turn of fully insulated wire.

Kwire = Awire/Ar

Kwire = $\pi(dia*2.54/2)^2/((OD_{nom})*2.54)^2$

Kwire = $\pi(.1285*2.54/2)^2/(.1305*2.54)^2$

Kwire = 0.762

- Add ",0.764" to the end of the first line (without the quotes).

We have completed the file description line. We can now enter the lines describing the wires for our table.

- Add a new line to the file.

The wire description lines are quite simple. Start by entering the gauge of the wire.

- On the new line, enter "8," without the quotes.

The next two parameters are the height and width that describe the rectangular area that the fully insulated wire will occupy. For a round wire, this is simply the outer diameter of the insulated wire. Our data is given in inches, so we must convert to cm before entering the data.

- Enter ".335,.335," without the quotes.

The final entry for the wire description line is the bare copper area. This is not given in the data sheet. However, the bare copper diameter is and can be used to calculate the area. Remember to convert the diameter from inches to cm.

- Enter ".084" without the quotes.

The first line is complete. To complete the file, enter the data for the second wire table entry on a separate line.

- Enter "9,.299,.299,.066"

The final step is to save the file. The file must be saved in the Magnetics Designer directory with an extension defined by the table given at the beginning of this section. Since our wire is round, the extension will be .RW. To complete the example,

- Select the Save function in your text editor.

- Locate the Magnetics Designer directory.

- Save the file with the name NF.RW.

Foil Table
The contents of the Foil file are self explanatory. An example is shown below.

```
Foil Wire Thickness = 2.5cm/in
50m
20m
5m
2m
1m
.1m
```

The first entry is a conversion factor used by Magnetics designer to convert the table units into the cgs units required by Magnetics Designer. If you are entering dimensions in cgs units, this number should be set to 1. If you choose to enter dimensions in any other unit, the proper scaling factor to cgs should be entered. Each line after the first is the thickness of the foil that is to be made available to Magnetics Designer.

Any additional foil description files must have a .FW extension as explained at the beginning of this section. The name of the file will be used internally by Magnetics Designer.

PCB Table
The contents of the PCB file are self explanatory. An example is shown below.

```
PCB Thickness = 2.5cm/in
Thickness of copper = .0033
Minimum trace width = .0150
Minimum trace spacing = .0100
PWB Thickness = .1250
```

The first entry is a conversion factor used by Magnetics designer to convert the table units into the cgs units. If you are entering dimensions in cgs units, this number should be set to 1. If you chose to enter dimensions in any other unit, the proper scaling factor to cgs should be entered. The remaining lines are self explanatory.

A separate file will be required for each PCB characterization. The file should be saved as a standard ASCII text file and located in the Magnetics Designer directory. The file must have the .PW extension, as explained at the beginning of this section. The name for the PWB file will be used internally by Magnetics Designer.

WIRE TABLES

Magnetics Design & Applications

The Magnetics Design Process

The purpose of this section is to provide designers with the necessary background to effectively use the Magnetics Designer program. Various topics are reviewed, ranging from magnetic design equations to basic transformer construction. Several design examples illustrate how to convert circuit design data to magnetic design requirements.

The transformer and inductor design process is a series of design and analysis cycles. First, a core is chosen, and then the number of turns and the wire sizes are selected, based on the desired electrical specifications, temperature rise, and flux and current densities. Flux and current density are then varied to achieve the desired performance, while minimizing weight. Typically, the process ends when the designer cannot achieve any further performance improvement or weight reduction.

This process is well suited to computer aided design. By describing the physical and electrical properties of the magnetic devices in the form of equations and core data constants, the iterative design process can be automated. The remainder of this chapter will discuss the basic magnetic equations and design algorithms as implemented in Magnetics Designer.

Fundamental Magnetic Design Equations

The units displayed by Magnetics Designer can be changed in the Options screen.

Transformer behavior is generally described by three fundamental equations: Ampere's Law, Faraday's Law, and Lenz's Law. These three equations, coupled with the core's geometry, material characteristics, and the various conductors' electrical characteristics, may be used to derive most of the necessary equations for analyzing transformer and inductor designs.

The CGS system has been consistently used in the equations throughout the manual in order to avoid confusion. However, Magnetics Designer's Options screen allows you to work with other units in the program. All of the variables used in these equations are listed and defined in *Appendix 2*.

Ampere's Law

$$Hl = .4\pi \ NI \qquad\qquad 4\text{-}1$$

If the path is broken into k segments of length l_k and there are j windings, each having n_j turns and I_j amps, Ampere's law can be expressed as follows:

$$\sum_{k=1}^{m} H_k l_k = .4\pi \ \sum_{j=1}^{m} N_j I_j \qquad\qquad 4\text{-}2$$

This form of the equation will be useful when deriving an expression for reluctance in the following section. Note that the field intensity, H, is related to the flux density, B, by the permeability of the magnetic medium. That is,

$$\frac{B}{H} = \mu \ \ or \ \frac{dB}{dH} = \mu \qquad\qquad 4\text{-}3$$

Faraday's Law

$$e = N\frac{d\Phi}{dt}x10^{-8} = NAc\frac{dB}{dt}x10^{-8} \qquad\qquad 4\text{-}4A$$

The instantaneous voltage across a winding of N turns is proportional to the rate of change of flux lines (or flux density). This equation is typically used to determine the number of turns for each winding, based on the core area (Ac), maximum desired flux density, and the desired voltage. If one were to integrate the above equation over a half cycle, then the average voltage (over the half cycle) can be expressed as a function of the peak AC flux excursion by the following equation:

$$Vave = 4\ N\ Ac\ f\ Bac\ x10^{-8} \qquad\qquad \text{4-4B}$$

Vave is the conventional definition used to describe the average voltage of an AC waveform. That is, Vave is the average of the rectified AC waveform over a full cycle. Mathematically,

$$Vave = \frac{\int_{0}^{T} |v(t)|\, dt}{T}$$

where T is the period of one complete cycle.

B-H Loop of Magnetic Materials

When flux lines are confined to a magnetic material, there exists a relationship between flux density (B) and magnetic field intensity (H) which can best be expressed in a graphical form called a B-H loop, as shown below.

Typical B-H loop

As the magnetic field intensity (H) increases, the flux density also increases. At a certain level, called the saturation flux density, the flux density begins to increase much more slowly as a function of H. After driving the core into saturation, when the magnetic field intensity is reduced to 0, the flux density does not return to zero. Instead, the flux density returns to a level defined as the residual flux density. In effect, the material has a memory which retains magnetic information. A negative value of H (called the coercive force (Hc)) must be applied in order to return the flux density to zero.

If a transformer is driven in only one polarity (for example, a forward converter) and allowed to reset itself back to Br, the relationship between B and H will be described by the minor loop shown in the B-H loop figure. The peak flux density (Bp) can then be described by the following equation:

$$Bp = Br + 2Bac$$

where *Br* is the residual flux density and Bac is the peak value of the AC flux density.

The incremental permeability of the material is defined as the slope of the B-H loop for a given operating point. Typically, the incremental permeability falls off rapidly as the flux density approaches the saturation level of the material.

Magnetic materials usually have a permeability which is thousands of times the permeability of free space ($4\pi \times 10^{-9}$ Henry/cm). In fact, most plots of permeability are actually the relative permeability of the material, i.e. the ratio of the permeability of the material divided by the permeability of free space.

The figure below shows a typical plot of the relative permeability of a ferrite material as a function of AC flux density. Permeability also varies as a function of the DC magnetizing force (H). Generally, below a certain DC magnetizing force, the incremental permeability is reasonably constant. Above that level, the permeability linearly decreases to 1 at a very high magnetizing force.

**Incremental
Permeability vs
AC Flux Density**
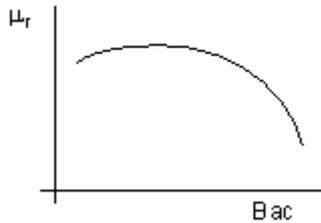
When a gap of nonmagnetic material is introduced into the magnetic path, the B-H loop is changed as shown in the figure below. In general, the slope (relative permeability) and the residual flux density are decreased. Since the permeability of a nonmagnetic material (in this case, the air gap) doesn't change appreciably with increasing flux density, the saturated flux density of the gapped core does not change appreciably from that of the ungapped core.

**B-H Loop of a
Gapped Core**
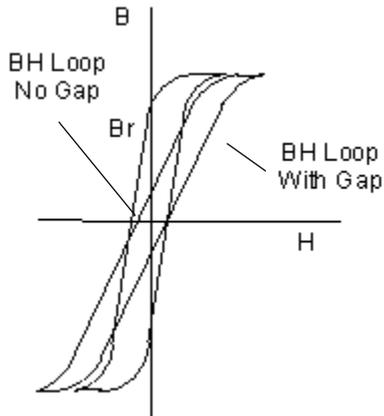
Assuming the air gap is small (no appreciable fringing of the flux lines), the equivalent residual flux density of the gap/core combination can be calculated as shown below:

$$Br(eq) = \frac{Br}{1 + \dfrac{lg\ uc}{lc}}$$

Lenz's Law

4-5

$$e = L\frac{di}{dt}$$

Lenz's Law is used primarily in circuit analysis to determine the relationship between the voltage and current of an inductor. Since voltage is proportional to both rate of change of flux (eq. 4-4) and rate of change of current (eq. 4-5), there is an implied relationship that flux lines are proportional to current.

Resistivity of Copper

The resistivity of a material is a basic characteristic which can be used to calculate the resistance of a conductor constructed from that material. In general, resistivity varies as a function of temperature. The following equation expresses the resistivity of copper as a function of temperature (in degrees C).

$$Kr = rho + rhoTc * T$$

4-6

The default for Copper is,
    rho = 1.59×10^{-6} and rhoTC = 6.77×10^{-9}
You can change to Aluminium in User.equ by using,
    rho = 2.41×10^{-6} and rhoTC = 1×10^{-8}

Core Loss Equation

$$Pcore = Kp\ Bac^{n}\ f^{m}\ Vol$$

4-7

The core loss equation is a curve fit of measured data. It is generally only accurate over a modest range of frequencies (from 10 kHz to 100 kHz). These curves are usually plotted as a family of straight lines on log-log graph paper where each line is associated with a particular frequency.

High Frequency AC Resistance

As the operating frequency increases, the effective resistance of the transformer or inductor windings increases. This change is because of a reduction in the penetration depth of electrons in the conductor. Instead of being evenly distributed throughout the conductor, electrons are forced to the surface by the magnetic field. When windings are in proximity to one another, the magnetic field is modified. Bennet and Larson [48] solve Maxwell's equations for layer wound solenoids; their work can be extended to get the solution on a per layer or per turn basis in the presence of a magnetic field. If Fr is the ratio of AC to DC resistance at some frequency, f, then:

$$Fr = x\left[F1 + 2\,\frac{H_1 H_2}{Hi^2}\,F3 \right]$$

4-8

$$x = \frac{h\sqrt{Fl}}{Dp}$$

$$Dp = \sqrt{\frac{\rho}{\pi\,\mu_0\,\mu_r\,f}}$$

The term F3 can be approximated by:
F3 = (sinh(x)-sin(x))/(cosh(x)+cos(x))

While

$$F1 = (sinh(2*x) + sin(2*x))/(cosh(2*x) - cos(2*x)))$$

H1 and H2 are the field strengths on either side of the wire. Hi is the field produced by the wire itself. The "wire" is converted into a rectangular sheet to simplify evaluation of the boundary conditions. These equations are the same as Jongsma [1], however they allow us to express Fr in terms of the magnetic field. If we let H1 = H2 = Nisum/(Lw) and let I approach zero, the power loss is then I*I*Fr*Rdc so that the proximity loss defined when I = 0 is

$$P(I=0) = 2Rdc \, x \left[\frac{Nisum \; w \; pitch}{N \; Lw} \right]^2 F3 \qquad 4.8.1$$

This formula allows us to compute eddy current losses in shield windings, whether they are foil or wound.

The way air gaps are handled using field predictions is to introduce a sheet of ampere-turns around the gap, just under the core surface. Surface currents aren't used unless there is a gap since they produce no field in the stack. When there is a gap, it turns out that a "negative" surface current winding can be added at the gap which is computationally more efficient than introducing surface currents everywhere except for the gap. The surface current is introduced as follows:

$$(NI)_s = -Kg \; \mu_{eff} \; \frac{g}{Lm} NI$$

Notice that for transformers, SNI is small 0 so that the gap usually has little effect (more on this later). The constant Kg accounts for the field bunching near the surface caused by proximity to the windings.

The surface current in each phantom turn is made proportional to μ_{eff} times H(x), rather than NI/Lm, measured at the center of the core under the surface winding, thus accounting for Kg. Unfortunately, this procedure is unable to converge reliably to measure μ_{eff}. If we know μ_{eff}, then the field generated by the

surface winding provides a good estimate for the Fr of each turn. The problem in calculating μ_{eff} is related to describing the flux inside the core. The flux tends to be higher near the winding surface when the MMF is not distributed uniformly around the core. Since this MD release is focused on AC wire losses, we haven't explored field solutions inside the core. An empirical formula is being used to account for the reduction in permeability for long gaps.

There are 2 methods used in Magnetics Designer to compute the fields in the winding stack. The first approach computes the magnetic fields based on an estimation similar to the conventional approach described by Dauhajre [24] which constructs the field from the core outward for solenoid windings and sideways across the length of the bobbin for sector wound configurations. The former approach gives good results for a single sector; however, the latter approach is in error for thin side-by-side sectors. Fields in the winding stack are influenced by neighboring currents, causing the field to be centered about the sector. The algorithms used in Magnetics Designer account for the sector shapes in distributing the fields. The method for automatic design uses this method because it is fast enough to direct the program to a good optimization.

The second method uses the same equations to predict AC losses, but it makes a magnetic field estimate using the following equation:

$$\overrightarrow{dH} = \frac{\overrightarrow{idl} \times \overrightarrow{r}}{4 \pi r^3} \qquad\qquad 4.8.2$$

An iterative solution is required because the current distribution in the wires affects the field in nearby conductors. The red lines in the field map represent the current on the high field intensity side of the conductor, the field intensity is given by the gray scale, where black is strong, white is weak. The solution is basically a quasi-static solution of Maxwell's equations. The winding stack magnetic field can be estimated without solving for the fields within the core by assuming that the core shields

most of the field that penetrate the core. Including the phantom surface current winding accounts for the gap fringe fields. This solution is too lengthy to be used for optimization so it is enabled afterward when the user presses the "apply using fields" in the Transformer/Inductor screen or "Refresh Fields" button in the Bobbin screen. For inductors that have secondary as well as primary windings, we assume that the primary and secondary conduction is independent. The fields are computed with primaries conducting and again with secondaries conducting. The affects are combined using superposition.

AC Resistance for Square Wave Excitation

Magnetics Designer allows you to calculate the resistance for both sine and pulse shaped current waveforms. In general, the resistance, for a sine wave shape will produce the least resistance while square waves will produce the worst due to the harmonic content. The pulse selection allows you to specify a duty ratio and current rise time. Square waves are specified by selecting 50% duty ratio and 0 rise time. Selecting a small non-zero rise time will frequently reduce dissipation enough to allow a more aggressive design. Other arbitrary shapes (trapezoidal, sawtooth, etc.) will normally produce results that fall between sine and square. The following discussion for square waves can be adapted to any wave shape by using the appropriate Fourier series for that shape.

Sine wave design switched to a Square wave shape

The AC resistance value for a square wave is calculated below. Let Rac be a single value composite resistance that looks like the following:

$$Ploss = I1^2*R1 + I3^2*R3 + I5^2*R5 + ... = Irms^2*Rac \quad 4\text{-}8a$$

Square wave optimized design

where I1/R1, I3/R3, I5/R5, ... are the current/resistance values at F, 3F, 5F, F is the fundamental frequency as stated in the transformer screen, and Irms is the RMS value (Iac-rms) of the AC components. This formulation is actually performed by squaring the current series and taking the average value. All of

the cross products integrate to zero, leaving the result in equation 4-8a. The total includes the DC component which is waveform independent and is user defined.

To understand the way this is handled without a sine/square switch, we assume that a single Rac value is calculated for the fundamental, and is applied to all harmonics. The result is defined by:

$$Ploss = (I1^2 * R1 + I3^2 * R1 + I5^2 * R1 + ...) = R1 * ((I1^2 + I3^2 + I5^2 + ...) \quad \text{4-8B}$$

and since $I3^2 = (I1/3)^2, I5^2 = (I1/5)^2,...$
$Ploss = R1 * (I1^2 + I1^2/9 + I1^2/25 + ...)$
$\qquad = I1^2 * R1 * (1 + 1/9 + 1/25 + 1/49 + ...)$

Finally, equation 4-8C shows what Magnetics Designer reports when not accounting for variations in resistance at various harmonics. Rac is constant with frequency.

$$Ploss = 1.2287 \, I1^2 * R1 \qquad\qquad\qquad\qquad \text{4-8C}$$

If we actually compute a different R for each frequency, we can solve for Rac.

$Ploss = I1^2 * R1 + I3^2 * R3 + I5^2 * R5 + ...$
$\qquad = I1^2 * R1 + I1^2 * R3/9 + I1^2 * R5/25 + ...$
$\qquad = I1^2 * (R1 + R3/9 + R5/25 + ... Rn/(n*n) + ...) \qquad \text{4-8D}$

Equation 4-8D accounts for variations in resistance with frequency. If we let Ploss in equation 4-8D

$$= Irms^2 * Racsq = I1^2 * (R1+R3/9+R5/25+ ... Rn/(n*n)+...) \quad \text{4-8E}$$

and Ploss in eq 2.0 $= Irms^2 * Rac1 = 1.2287 \, I1^2 * R1 \qquad$ 4-8F
and divide 4-8E by 4-8F, we get

$$Racsq/Rac1 = (R1 + R3/9 + R5/25+ ... Rn/(n*n)+...) / (1.2287*R1) \quad \text{4-8G}$$

Notice that all I1 and Irms terms cancel and Rac1 = R1 in our original assumption; then

Racsq = (R1+R3/9+R5/25+... Rn/(n∗n) + ...) / (1.2287)   4-8H

Now let R1 = Kr1 such that R1 = kR1∗Rdc, then

Racsq = (Kr1 ∗ Rdc + Kr3 ∗ Rdc/9 + Kr5 ∗ Rdc/25 + ... Krn ∗ Rdc/(n∗n) + ...) / (1.2287)
    = Rdc ∗ (Kr1 + kr3/9 + Kr5/25 + ... Krn/(n∗n) + ...) / (1.2287)   4-8I

Equation 4-8I is the exact solution to the Rac problem that is implemented after the optimization process (See New function) is performed. Magnetics Designer iterates through the 99th harmonic.

When designs are optimized for sine waves and used with square waves, it is possible to get significantly higher AC losses. Working the other way around usually produces good designs for both sine and square wave signals.

Derived Equations

Many useful magnetic design equations can be derived from the basic equations which are described in the previous sections. Some equations calculate inductance, winding resistance, or specific copper loss. Others predict the required core area product or the weight. The following sections will derive and summarize some of the more useful expressions which are necessary to design or optimize a transformer or inductor.

Inductance of a Winding

Equations 4-2 through 4-5 can be combined to derive an expression for inductance. Start with equations 4-4 and 4-5

$$e = L\frac{di}{dt} = N\frac{d\Phi}{dt} \times 10^{-8}$$

Rearrange the terms to solve for L as follows:

$$L = N \frac{d\Phi}{di} \times 10^{-8}$$

4-9

Derive an expression for di from equation 4-2 (assuming a single winding, but a multiple element path).

$$di = \frac{\sum\limits_{k=1}^{m} l_k \, dH_k}{.4\pi \, N}$$

Substitute for di in equation 4-9

$$L = .4\pi \, N^2 \left(\frac{d\Phi \times 10^{-8}}{\sum\limits_{k=1}^{m} l_k \, dH_k} \right)$$

$$L = \frac{.4\pi \, N^2 \times 10^{-8}}{R}$$

4-10

where

$$R = \sum\limits_{k=1}^{m} \frac{l_k \, dH_k}{d\Phi} = \sum\limits_{k=1}^{m} \frac{l_k \, dH_k}{A_k \, dB_k}$$

$$R = \sum\limits_{k=1}^{m} \frac{l_k}{A_k \, \mu_k}$$

4-11

Bmax in a Gapped Inductor with a Defined Peak Current

Since a magnetic path may be composed of several gaps and several core segments, an expression can be derived to find the flux density in any desired core section. It is assumed that the section of interest has a cross-sectional area of Ac. Start with equation 4-2:

$$\sum_{k=1}^{m} H_k\, l_k = .4\pi \sum_{j=1}^{n} N_j\, Ipk_j \qquad \text{4-2}$$

Solve equation 4-3 for H and substitute into equation 4-2 as shown below:

$$\sum_{k=1}^{m} \frac{B_k\, l_k}{\mu_k} = .4\pi \sum_{j=1}^{n} N_j\, Ipk_j$$

However, the flux density in one segment of the magnetic path is equal to the number of flux lines divided by the area of that segment. Therefore, substitute for Bk:

$$\sum_{k=1}^{m} \frac{\Phi\, l_k}{A_k\, \mu_k} = .4\pi \sum_{j=1}^{n} N_j\, Ipk_j$$

Assuming that leakage flux is negligible, the total number of flux lines is the same in all segments, and may therefore be moved outside of the summation.

$$\Phi \sum_{k=1}^{m} \frac{l_k}{A_k\, \mu_k} = .4\pi \sum_{j=1}^{n} N_j\, Ipk_j$$

Furthermore, the summation on the left side of the equation is equal to the reluctance of the magnetic path. Therefore,

$$\Phi\, R = .4\pi \sum_{j=l}^{n} N_j\, Ipk_j$$

Use the relationship $\Phi = Bpk\ Ac$ and solve for Bpk:

$$Bpk\ Ac\ R = .4\pi\ \sum_{j=1}^{n} N_j\ Ipk_j$$

$$Bpk = \frac{.4\pi\ \sum_{j=1}^{n} N_j\ Ipk_j}{Ac\ R}$$

$$Bpk = \frac{.4\pi\ Np\ \sum_{j=1}^{n} T_j\ Ipk_j}{Ac\ R} \qquad \text{4-12}$$

DC Resistance of a Winding

The low frequency resistance of a winding is related to the resistivity (as a function of temperature, Kr), the length, and the cross-sectional area of the conductor as follows:

$$Rdc = \frac{Kr\left(T\right) lwire}{Awire}$$

In the case of a transformer or inductor, it is more useful to think in terms of the number of turns and the mean length per turn (MLTj) than the length of the wire. Therefore, the resistance equation for the jth winding becomes:

$$R_j = \frac{Kr\left(T\right) MLT_j\, N_j}{Awire_j} \qquad \text{4-13}$$

Note that the MLTj becomes progressively longer as windings are added to the bobbin. That is, the first winding will have a lower MLTj than the last winding.

Window Utilization

Part of the power handling capability of a core is related to how much copper can be put in the available winding space. The following equations use two window utilization factors to relate window area to turns ratios, RMS current, primary turns, and current density.

Current density is defined as the ratio of RMS current (IRMS) to the bare copper cross-sectional area (Awire). Solving for Awire gives:

$$Awire = \frac{Irms}{J}$$

4-14

In general, the cross-sectional area used by a single turn of magnet wire is a rectangular area (Ar) which is considerably larger than the cross-sectional area of the bare copper. For example, the outside diameter of a standard magnet wire is larger than the bare copper by twice the thickness of the insulating film. Furthermore, when two round wires are wound side-by-side, each wire consumes a square area with sides which are equal to the outside diameter of the wire. Therefore, each particular wire type will have a wire fill factor, Kwire, which is equal to the ratio of the bare copper area to the rectangular area used by the wire.

$$Kwire = \frac{Awire}{Ar}$$

4-15

Most windings require many turns. As more turns are put in the winding area, it becomes difficult to keep the wire tightly spaced. As a result, another winding factor, Kw, must be introduced. The amount of window area, A_j, required to handle N_j turns of a wire with a uniform current density for all windings is:

$$A_j = N_j \, Ar_j = \frac{N_j \, Awire_j}{K_w K wire} = \frac{N_j \, Irms_j}{K_w \, Kwire \, J}$$

The total required winding space (Abob) to handle n windings is then

$$Abob = \sum_{j=1}^{n} A_j = \sum_{j=1}^{n} \frac{N_j \, Awire_j}{K_w \, Kwire}$$

$$Abob = \sum_{j=1}^{n} \left(\frac{N_j \, Irms_j}{K_w \, Kwire \, J} \right) \qquad \text{4-16A}$$

If this equation is normalized by factoring the primary turns, Np, outside of the summation, then

$$Abob = Np \sum_{j=1}^{n} \left(\frac{T_j \, Irms_j}{K_w \, Kwire \, J} \right) \qquad \text{4-16B}$$

Copper Loss

The total copper loss is the sum of the i²R losses for all of the windings.

$$Pcu = \sum_{j=1}^{n} \left(Irms_j{}^2 \, R_j \right)$$

Substitute for Rj using equation 4-13:

$$Pcu = \sum_{j=1}^{n} \left(Irms_j{}^2 \, \frac{Kr \, (T) \, MLT_j \, N_j}{Awire_j} \right)$$

Replace Irms with (J x Awire) and simplify to get the following expression:

$$Pcu = J^2 \sum_{j=1}^{n} \left(Awire_j \, Kr \, (T) \, MLT_j \, N_j \right)$$

Replace MLTj with the MLT of the bobbin and rearrange terms:

$$Pcu = J^2 \, Kr\,(T) \; MLT \; \sum_{j=l}^{n} Awire_j \, N_j \qquad \text{4-17}$$

But from equation 4-16A,

$$\sum_{j=1}^{n} N_j \, Awire_j = Abob \; K_w \; Kwire$$

Substitute the above expression into equation 4-17 to get

$$Pcu = J^2 \, Kr\,(T) \; MLT \; Kwire \; K_w \; Abob \qquad \text{4-18}$$

Equation 4-18 is used for the Core Browser.

Equation 4-18 is significant in that it relates current density to copper loss. Therefore, one could solve the equation for J to achieve a specific power loss for a given core winding area independent of the actual RMS current or the number of turns.

Transformer and Inductor Core Utilization

For both transformers and inductors, there are two specific types of designs: core loss limited design and flux saturation limited design. In the transformer case, there is only one equation that determines the necessary core area.

$$Ac = \frac{edt \times 10^8}{dB \; Np} = \frac{edt \times 10^8}{2 \; Bac \; Np} \qquad \text{4-19}$$

Although it is not particularly useful by itself, this equation, when combined with equation 4-16A, becomes one of the basic core selection equations. In the core loss limited case, the trick will be to select the optimum flux density. The saturation limited case is simple in that one only needs to select a reasonable percentage (about 80 percent) of Bsat.

Equation 4-19 works equally well for the loss limited case for inductors. However, once a DC bias is introduced, it becomes

likely that the core will saturate long before the core losses become excessive. In the saturation limited case, equation 4-12 is rearranged to find the core area as follows:

$$Ac = \frac{.4\pi \, Np \ \sum_{j=1}^{n} T_j \, Ipk_j}{Bpk \ R}$$

4-20

Half Turns

Cores with center legs have a physical capability for ½ turn increments. Half turn windings only link flux in ½ of the core, which results in a very high leakage inductance. Magnetics Designer does not support half turns because of the poor power conversion performance which results from the added leakage inductance. Future versions will address the problem of multiple magnetic paths that arise in "integrated" magnetic structures.

Area Product

A common method for rating the relative power handling of cores is called the area product. The area product is the window area times the core cross-sectional area. Here a further refinement of that rating is proposed. The area product is the effective area times the usable window area. First, the area product equation for a transformer will be derived.

Equation 4-16B gives the usable winding area and equation 4-19 gives the necessary core area for a transformer. Multiply Abob times Ac to get the area product.

$$AwAc1 = \left(\frac{Np}{K_w \ Kwire \ J} \sum_{j=1}^{n} T_j \ Irms_j \right) \left(\frac{edt \times 10^8}{2 \ Bac \ Np} \right)$$

$$AwAc1 = \frac{edt \left(\sum_{j=1}^{n} T_j \ Irms_j \right) \times 10^8}{2 \ K_w \ Kwire \ J \ Bac}$$

4-21

Once the electrical requirements and the appropriate J and Bac selections have been made, equation 4-21 can be used to calculate the area product and select a core.

When an inductor design is core loss limited, equation 4-21 may be used to select the core. However, when the design is saturation limited, a different equation must be derived. In this case, equations 4-16B and 4-20 are combined.

$$AwAc2 = \left(\frac{Np \ \sum_{j=1}^{n} T_j \ Irms_j}{K_w \ Kwire \ J} \right) \left(\frac{.4\pi \ Np \ \sum_{j=1}^{n} T_j \ Ipk_j}{Bpk \ R} \right)$$

$$AwAc2 = \left(\frac{.4\pi \ N^2 p}{R} \right) \left(\frac{\sum_{j=1}^{n} T_j \ Irms_j \ \sum_{j=1}^{n} T_j \ Ipk_j}{K_w \ Kwire \ J \ Bpk} \right)$$

$$AwAc2 = \frac{Lp\left(\sum_{j=1}^{n} T_j\, Irms_j\right)\left(\sum_{j=1}^{n} T_j\, Ipk_j\right)x10^8}{K_w\, Kwire\, J\, Bpk} \qquad \text{4-22}$$

Equation 4-22 is particularly useful since all of the required inputs are inductor design parameters which should already be known at the start of the design.

Optimum Ratio of Core Losses to Copper Losses

It has been shown by Bill Muldoon (Ref. 2) that for core loss limited designs, there exists an optimum ratio, r, of core loss to copper loss (ignoring high frequency AC resistance effects) which minimizes the total power dissipation. This ratio will vary with material type as a function of the exponent of B (n) in the core loss equation.

$$r = \frac{Pcore}{Pcu} = \frac{2}{n} \qquad \text{4-23}$$

In general, the total power dissipation does not change very much as the ratio varies away from the optimum value. However, as a design starting point, one may as well begin with the optimum ratio. If the ratio of Pcore to Pcu is r, then the Pcu is related to Ptot by the following equations:

Ptot = Pcu + Pcore

$$Ptot = \left(1 + r\right)Pcu$$

$$Pcu = \frac{Ptot}{\left(1 + r\right)} \qquad \text{4-24}$$

Likewise, an equation for Pcore as a function of r and Ptot can be derived:

$$Pcore = Ptot\,\frac{r}{\left(1 + r\right)} \qquad \text{4-25}$$

Magnetics Designer initially tries to derive a design that satisfies eq. 4-23. Then it proceeds to optimize the design such that the minimum power loss is obtained. This solution may or may not have a copper-to-core ratio of 2/n, as stated in equation 4-23.

There are 2 factors that invalidate the optimum ratio calculation. First, when operating at high frequency, there is likely to be a 1 or 2-turn winding. Incrementing or decrementing the turns causes very large changes in core loss, making it impossible to get to the optimum ratio. Secondly, the AC losses in the stack at high frequencies tend to favor NOT filling the window. Filling the window is implicit in the derivation of equation 4-23.

Core Gaps

The magnetic field induced when windings are split.

It is convenient to set the magnetizing inductance of a transformer by inserting an air gap. When this is done, flux is no longer confined to the core. Flux between the core halves will begin to fringe as the gap is increased so that the effective gap area will be larger than the physical cross section. The fringing flux creates several problems:

1. For laminated cores, some flux passes normal to the lamination which results in increased eddy current losses.
2. Flux will intercept windings transversely, thereby causing eddy current losses in the winding.
3. As gap length increases, fringing increases its effective area.

Magnetics Designer accounts for gap fringing when calculating the effective gap area used in permeability computations. The resulting area multiplier is made available via the User Data fields using the Kgap function. Eq. 4-26 calculates the ratio of effective area to core area according to Stephens[11] as follows:

4-26

$$Kgap(lg) = 1 + \frac{lg}{\sqrt{Ac}} \log\left(\frac{2 \times lw}{lg + 1\mu}\right)$$

where lg is the gap length in cm, lw is the window length in cm and Ac is the core cross section in cm². Even this formula breaks down for large gaps so that Magnetics Designer uses an empirical correction to better estimate Inductance for large gaps.

According to Partridge [17], gap loss in laminated cores is:

$$Pg = 17 \times 10^{-10} \times lg \times d \times \mu \times t \times f^{.5} \times Bm^2 \qquad 4\text{-}27$$

where d is the lamination width in cm and t is the lamination thickness in cm.

Magnetics Designer does not incorporate this estimate in the power loss calculations, however, you can add this loss to the Total Power Loss field equation in the User Data area.

Core gaps cause significant problems for high frequency designs. These problems can be virtually eliminated by using low permeability core materials so that the gap is effectively distributed along the magnetic path. The eddy current loss is proportional to the square of the magnetic field and the field is inversely proportional to the number of gap segments. Going from one gap to 2 reduces the leakage field in each by 2 and the loss from each by 1/4.

Eddy current losses can also be minimized by keeping the winding away from the gap. Severns [12] places the acceptable distance at twice the air gap length.

Series splitting is a Magnetics Designer feature which is activated by pressing the Split button while holding down the control key. Otherwise, the Split button will produce a parallel split.

Skin Effects, Proximity Effects and Split Windings

The resistance of a conductor increases at high frequency because the magnetic flux forces currents away from each other, toward the edge of the conductor. For round conductors, current is effectively carried in an annulus whose thickness is the skin depth. As windings are built into layers, the proximity

to each other further crowds the current and increases the resistance even more. Since the current crowding is caused by the magnetic field intensity, winding arrangements that reduce either the size of the conductor or the magnetic field intensity will reduce these effects and improve transformer efficiency.

The figure below compares the field intensities for a transformer whose primary is split, half on each side of the secondary. Notice that the field intensity of both secondary and primary is reduced by a factor of 2. In this case, the wire sizes and currents did not change since the primary was connected in series. It may not be practical to split windings that have only a few turns, such as a low voltage secondary. In these cases, the winding may be split and connected in parallel. Parallel splitting reduces both the wire size and current density; however, currents may not be shared evenly.
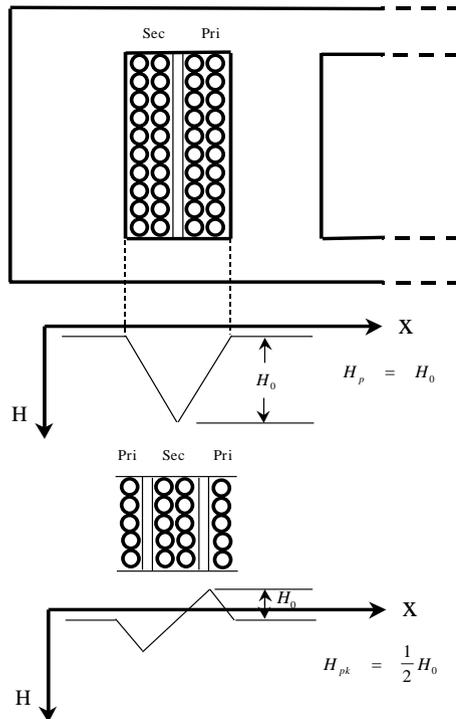
Notice that you get the maximum pay off for odd splits, because the winding that is sandwiched between the split winding has its magnetic field alternate from positive to negative. Splitting the inner winding will not achieve better results unless the outer winding is also split.

Magnetics Designer computes AC resistance based on an estimate of the magnetic fields in the winding stack. Using the "Apply using fields" button causes a more accurate calculation of these fields. All primaries are assumed to conduct the specified current at the same time. For transformers, the secondary current is assumed correlated with the primary current with reversed field polarity. Inductor primary and secondary currents are assumed uncorrelated. This fits the case of a simple inductor, primary only, or a flyback transformer. Forward converters should be designed using the transformer screen.

Leakage Inductance

Leakage inductance is modeled using the techniques described by Dauhajre [13]. In this paper, Dauhajre points out that the general problem is mathematically intractable, even for very simple geometries, because of the dependence of current distributions on a detailed knowledge of the flux field pattern. The underlying assumption that allows us to make an estimate without the use of a 3 dimensional field solver is that the current distribution can be accurately estimated. Once we know the currents, we can solve for the leakage inductance by evaluating the following integral:

We can find leakage flux, which is flux that isn't linked through

$$L_1 \ = \ \frac{\mu_0}{I_1^{\ 2}} \iiint H^2 dv$$

the core, as the region between windings. We then solve for the leakage using the previous equation. The magnetizing inductance can all be referred to a single winding if the leakage inductance is small compared to the magnetizing inductance. Moreover, if the leakage inductance between sectors is also large compared to the leakage inductance between adjacent windings, we can move the sector leakage to the outer windings. From a physical point of view, observing that the volume between barrel windings is smaller than the volume between sector windings validates these assumptions. This physical model is considerably more compact that the n-port mathematical model that requires n-squared terms that cannot be easily extracted. We connect the model using ideal transformers. It is convenient to cascade the windings so that the stray capacitance goes directly around the ideal transformer; thus avoiding singularities that could arise from negative capacitors.

See the Wire screen for a plot of the AC resistance.

This model results in the following equivalent circuit:
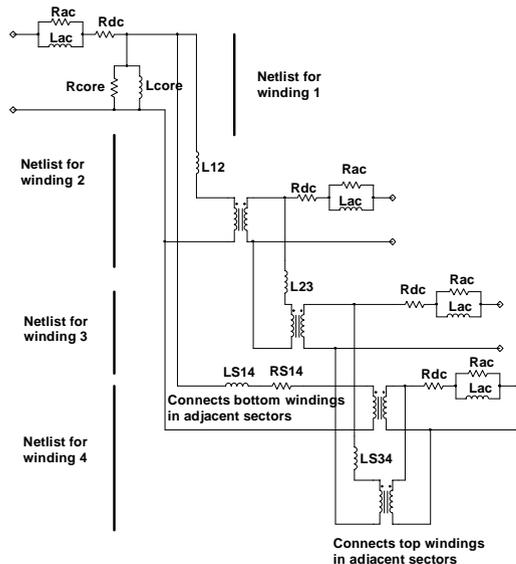
Winding Capacitance

The model of Collins [16] describes a technique that models winding capacitance based on energy conservation. This model has the disadvantage that its parameters change with different interconnect configurations. This is undesirable for computer simulation because there is no way of knowing the details of the user's application at the time the transformer or inductor is being modeled. Moreover, the circuit itself can switch topologies over a cycle of operation; for example, a full wave bridge rectifier will alternately ground opposite sides of the secondary.

The model of Collins accounted for specific solutions for an interconnect topology with a single capacitor. The model shown below uses 5 capacitors and avoids these problems by solving for capacitor values that account for all possible interconnect configurations
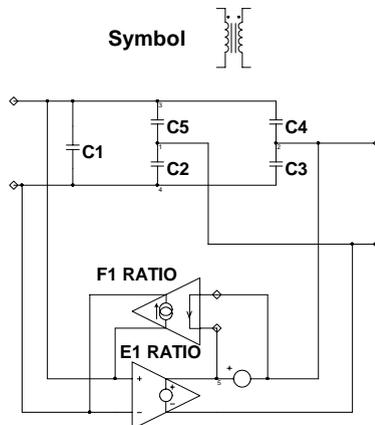
Equivalent Circuit for a transformer winding using a capacitor bridge to conserve energy

Magnetics Designer assumes that windings start on the left if the Start ID number is less than the Finish ID number. If the

Case 1: Finish and Start the winding on the same side.

Finish ID number is smaller, the winding starts on the right. Winding layers are assumed to reverse direction at the end of each layer. Magnetics Designer assumes that layers are completed either with wire or insulator; therefore, 2 windings can't occupy the same layer.
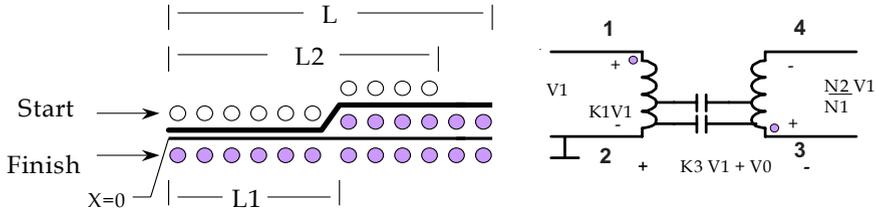
Shown next is a plot of the distance versus voltage along the windings (case 1). En0 and En1 are the energies obtained after integrating the interval 0 to L1 and L1 to L2, respectively.
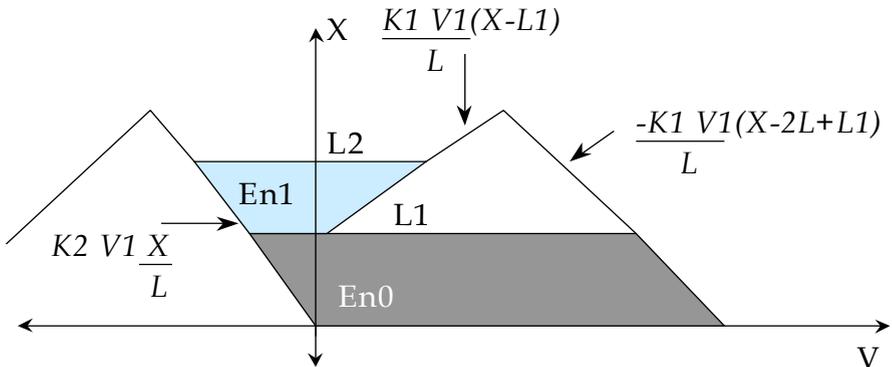
By adding the two energy distributions, En0 and En1, due to the different winding distribution from Start to Finish, we are able to calculate the capacitor values of the small signal capacitance representation by solving the following matrix:

V1 = 0	0	1	1	1	1	C1i		Cnext	
v(2-4)=0	1	0	A	B	1	C2		E(k3=-N2/N1)	
v(2-3)=0	1	A	0	1	C	C3	=	E(k3=0)	
v(1-3)=0	1	C	1	0	A	C4		E(K3=1)	
v(1-4)=0	1	1	B	A	0	C5		E(k3=1+N2/N1)	

where: $A = (N2/N1)^2$
$B = (1+N2/N1)^2$
$C = (1-N2/N1)^2$,   and $C1 = C1i + Cself$

The following figure illustrates the second case:

Case 2:
Finish and
Start the
winding on
opposite
sides.
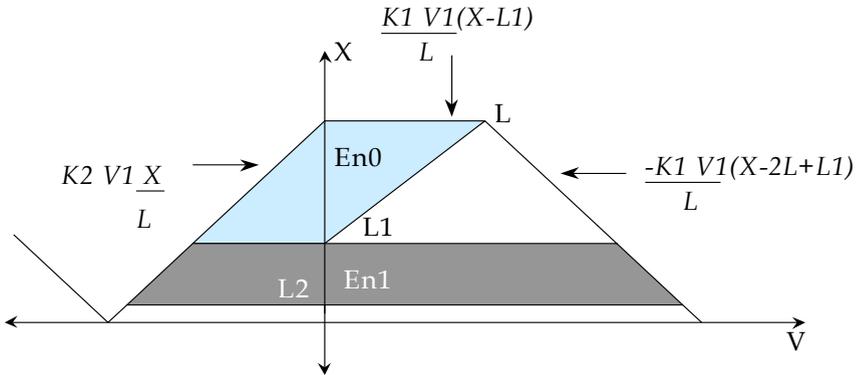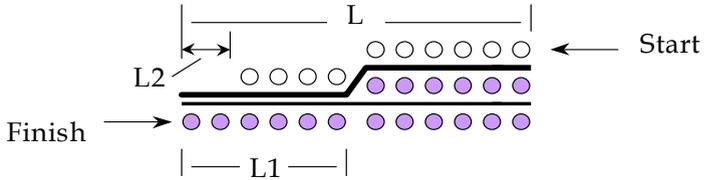
How IsSpice4 Models are Generated

The complete SPICE model combines the previous stray capacitance and leakage inductance models. The AC resistance is approximated using a single L-C parallel section. The impedance is fit to the AC resistance such that the loss is modeled at the operating frequency and 1/3 of the parasitic resonance. A plot of AC resistance is shown in the Wire screen for each winding. For all cases we have observed, the leakage inductance produces a much higher impedance than the AC resistance. This leads us to conclude that the effect of the AC

resistance will be to damp the resonance of the transformer, hence the importance of making the model accurate in the neighborhood of expected resonance. Again, the level of complexity to accurately model a second order effect must be weighed against its value. The resonant frequency using leakage inductance and winding capacitance represents a theoretical maximum. We reduce this frequency by 1/3 to align our AC resistance calculation more closely with expected circuit operation.

The ideal transformer accounts for the forward voltage transfer and reverse current transfer, and is modeled using a pair of IsSpice controlled sources. In the forward direction, the "primary" voltage is transferred to the secondary using a voltage controlled voltage source with its gain set to the turns ratio. In the reverse direction, a voltage controlled current source assures that current is reflected from the secondary to the primary by the turns ratio.

The DC and AC resistance equivalent circuits are each attached to their respective windings. The voltage source after the first winding is used to sense current for the feedback term in the ideal transformer model.

The core is modeled as a simple resistor in parallel with the magnetizing inductance. The resistance is set by the core loss equations at the operating frequency. A linear core model is used. References [14] and [15] illustrate techniques for making a non-linear saturable core model. The eddy current break is not sufficiently described in the core database, so its effect can't be modeled by the program. This effect can be modeled by adding a series R-C network across the magnetizing inductance, set to match manufacturer's data. This could add extra damping to the ringing observed when switching devices turn off while still conducting current.

Modeling added effects requires considerable computational resources, and shouldn't be done unless you depend on the non-linearities for an aspect of your design; for example, a "swinging" inductor may be used to extend the continuous conduction region of a power converter.

Thermal Models

The surface temperature rise above the ambient temperature of a magnetic device which is suspended in still air is dependent upon the amount of surface area and the power dissipation. The following equation (Ref. 2) provides a reasonably good estimate for the temperature rise.

$$\Delta T = \frac{710 Ptot}{Asurf} \qquad \text{4-26}$$

This equation only accounts for the convective heat loss from the surface of the magnetic device, and is used as the basis for the default thermal model Tlevel=0. The temperature rise from the surface to the hottest part of the magnetic device is not considered in this default model level. Thermal models 1 and 2 account for the internal temperature rise of the magnetic device.

Magnetic devices may depend on special cooling methods, such as fans, thermally conductive heat paths, oil filled containers, or water cooling to reduce the internal temperature. If special provisions are taken to remove heat, then you must modify the heat transfer coefficients using the User Data fields and equations to calculate your own temperature rise result. Adding your own equations to the User Data area of the transformer or inductor screen is described in *Chapter 2*, *User Data Input/Output Fields*.

Magnetics Designer includes 3 thermal models. The model levels can be changed by setting the Tlevel value in the User Data area. The values of the various thermal coefficients can also be viewed by accessing the desired variable from the User Data button dialog.

Thermal Model Level 0, Tlevel = 0
This is the default thermal model. The result, Trise, is the temperature rise, above ambient temperature, of the surface of

the magnetics device. The only method of heat transfer considered is convection from the core surface (surface area (As) through the convection coefficient Kconv.) Kconv (default value is 710) is the thermal resistance between the core surface and the mounting surface. This may be something other than air, but would then necessitate a change in the Kconv value.

Thermal Model Level 0
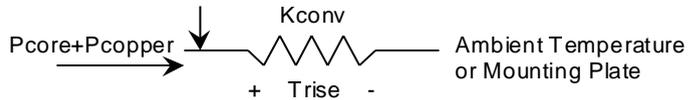
The convection rate equation governing this model is:

$$q = h(Ts - Ta)$$

where q = the total power divided by the surface area, h is the convection coefficient, Ts is the surface temperature, Ta is the ambient temperature.

Rearranging the convection rate equation and substituting the total power and surface area, we can obtain the following:

$$\Delta T = (Ts - Ta) = \frac{Ptotal}{Asurf \times h}$$

The convection coefficient governs the efficiency with which heat is transferred from the surface of the magnetics device. This coefficient can range anywhere from 0.5m to 2.5m (W/cm² C) for free convection, to 2.5m to 25.0m (W/cm² C) for forced convection. A common value is 1.4m (W/cm² C), which is approximately 710 (cm² C/W). Substituting this into the equation above, we get

$$\Delta T = (Ts - Ta) = 710 \frac{Ptotal}{Asurf}$$

Magnetics Designer allows access to the ambient temperature, Ta (in the Options screen), and the convection coefficient, Kconv (h = 1/Kconv). This allows great flexibility when describing the thermal characteristics of the environment in which the

magnetics device will finally be placed. The total power loss Ptotal, is computed as Pcore, the total core power loss plus Pcopper, the total copper power loss. The surface area is a function of the selected core geometry.

Thermal Model Level 1, Tlevel = 1
The result of this thermal model is the temperature rise, Trise from the stack hot spot to the ambient temperature or other mounting surface. Heat conduction from the wire stack through the core is incorporated. The insulation conduction coefficient Kins (Kins=2E-3) is used, in conjunction with the appropriate computed areas and copper power losses, to compute the temperature rise from the stack/core interface to the surface. This result is combined with the convection equation described in thermal model 0.

Thermal Model Level 1
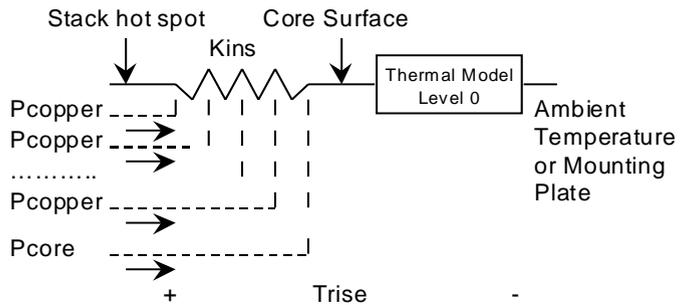
Thermal Model Level 2, Tlevel = 2
This thermal model is similar to level 1, with the exception that the temperature rise is from the internal core through the wire stack to the ambient temperature or other mounting surface. Since the interface between the core and stack is unknown, Magnetics Designer does not provide a user-definable thermal resistivity. However, using the User Data buttons and the Trise value, you can create your own equation similar to the one shown below.

Tcore = Trise + Kuser x Pcore
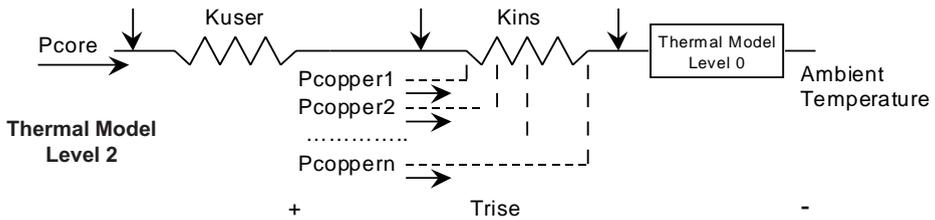
For the figure above, pcopper# is the number of the winding. The conduction coefficient, Kuser, is the thermal resistivity of the core-stack boundary. Remember, the Kuser x Pcore term is not part of the level 2 thermal model. The user should add an appropriate drop, depending on construction methods.

Level 1 is appropriate for cores with exposed surfaces, while level 2 works for toroids.

Core Selection Algorithm

Magnetics Designer will automatically select core and wire sizes based on electrical requirements written to the transformer or inductor screen. The following "pseudo code" illustrates the automated process used to obtain the initial design after entering the design requirements and clicking Apply for the first time.

While the design temperature rise is higher than specified
    If the core is not locked
        If it's the first pass, pick the smallest core based on low
            frequency copper loss
        Otherwise pick the next largest core in the family

    Select the current density and flux density
    Do until exit conditions (listed below)
        Calculate the turns for each winding
        Calculate the area available for each winding
        Do until the temperature is stable

            For each winding
                For each strand number
                    Calculate the build and resistance
                    Estimate AC losses
                    Save data for lowest loss configuration
                Select the best strand count
                Calculate the build parameters
            Calculate power loss

        Break out of this loop after 15 iterations (exit conditions)
        Adjust the current density to make the winding fill equal
            to the specification
        Adjust the flux density to make the core/copper loss ratio optimum
        Adjust the core/copper loss ratio for minimum total loss
        Evaluate special break conditions

    Do until exit condition
        For each winding
            Make wire smaller if power loss decreases
        Break out after 3 passes
        Adjust area per winding
        Readjust strand and build calculations

    If no more cores, break out of the loop

Notice that the inner loop looks for the best strand configuration as the build is calculated. This is only an estimate since the complete build information is needed in order to calculate the AC resistance. This results in slight errors which sometimes cause more strands to be selected than are optimum for high frequency designs. The errors are not significant, but it helps to reduce the maximum strand limit to see if the benefit of more strands is justified.

Although the optimum flux density and optimum current density are good design guidelines, certain conditions will cause the actual design generated by the program to be unacceptable. For example, consider a low power, low voltage, high current application. The algorithm might select a single turn of 10 AWG wire and a very small core. A single turn of large wire may not make good use of the bobbin area and therefore, it may be desirable to change the wire to foil. Alternately, when the current is very low, the smallest wire in the wire table may have too much cross-sectional area. Therefore, the window will be significantly overfilled.

Another problem which may result in a poor design occurs when standard magnet wire is specified for a high frequency design, and the AC resistance of the wire causes significantly higher losses than the cross-sectional area of the wire would imply. In this case, the designer should force more strands or in the last resort choose to use foil or Litz wire.

Generating the Design Requirements

Transformer and Inductor Design Requirements

An inductor or transformer design begins by converting system requirements to magnetic design requirements. For example, a power supply designer may tell a transformer manufacturer that he is designing a 100 kHz, 500 Watt switching regulator that has two isolated 15 Vdc outputs and a 100 Vdc input. Before the transformer designer can begin his job, he must gather more information than revealed by the DC input/output relationship and the frequency. The transformer designer must know the maximum volt-seconds that the transformer must sustain over a half cycle without saturating. He must determine the proper winding configurations: full-wave bridge, push-pull, or single ended. He is more interested in the RMS current that the windings must carry than the DC output current. He needs to know the ambient temperature and the acceptable temperature rise. If output cross-regulation is an issue, he needs to know the maximum acceptable winding resistance.

When the circuit designer doesn't properly specify requirements to the magnetics designer, the results can be disastrous for both parties. Therefore, the purpose of this section is to provide insight into the specification of magnetic design requirements so the designed component will satisfy the requirements and function in the circuit.

Magnetics Designer relieves the designer of much of the difficulty associated with this process. Electrical requirements are entered on the Transformer or Inductor screens while the program selects the core geometry and iterates the design. The designer then continues the optimization process, changes wire sizes and types, adjusts turns ratios, tries other winding configurations, etc., until the final design objectives are achieved.

The following sections will discuss each of the design parameters and indicate how the parameters are used by the software to generate the design and calculate its performance.

The Inductor Screen

Required Data Fields
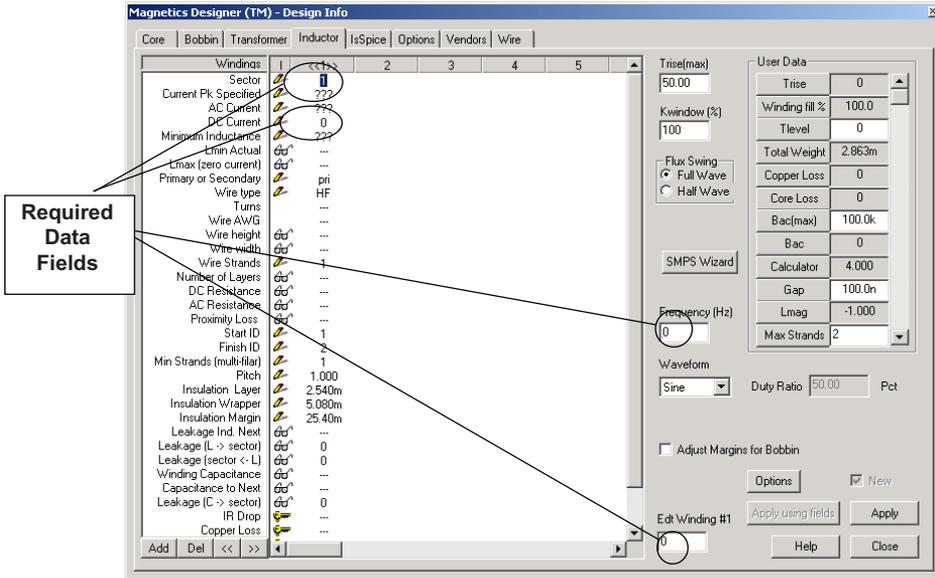
Note:
If you change the turns, make sure that you maintain the split ratio.

The figure above shows the initial Inductor screen. The screen is comprised of several components. Required data fields include the frequency, Edt (volt-seconds), specified current peak, AC current, and minimum inductance. They are indicated by the question marks "???" and must be supplied with a value. Some of these fields are located at the right of the dialog, while others are located inside the winding spreadsheet portion of the screen. The spreadsheet area is used to enter and review the information pertaining to each winding and to add, split, or move windings. The User Data area to the right is used to enter input variables and view calculated results.

The optional design constraints are shown at the right of the dialog and include the maximum AC flux excursion [Bac(max)], the maximum current density (Max Idens), and maximum flux density (Bp(max)), temperature rise (Trise(max)), and maximum window fill (Kwindow(%)).

You may override the internally calculated design constraints by entering values in the edit fields shown at the right of the screen. The wire type and ambient temperature defaults are set in the Options screen. When imposed, these constraints may override the internal design optimization algorithm. For example, if the program determines that the optimum current density is 500 A/cm^2 and the designer has specified 400 A/cm^2, the program uses 400 A/cm^2 to design the inductor. However, if the designer specified 600 A/cm^2, the program will use the optimum value of 500 A/cm^2.

The minimum inductance is the minimum acceptable inductance at the defined peak current. At lower current levels, inductance may increase above this specified value. If a winding description column is left blank, the program assumes that there are no additional windings.

With $V = L\dfrac{di}{dt}$

$\therefore \int V\,dt = \int L\,di$

and ΔI is equal to the current ripple which

equals $\dfrac{E\,dt}{L}$

To fully describe the inductor requirements, the designer must determine the maximum volt-seconds (Edt) that must be supported across winding 1 without overheating or saturating the core. Edt, in conjunction with the frequency, will be used to calculate the AC flux excursions and the core losses.

The peak current is used to calculate the maximum flux density. Therefore, the peak currents which are specified on the spreadsheet screen should be the combination of currents which result in the highest total ampere-turns. Typically, this combination will correspond to an overload or start-up situation. The combination of DC and AC current is used to calculate the total copper losses. In particular, the total copper losses (Pcu) can be found by the following equation:

$$Pcu = Idc^2 Rdc + Iac^2 Rac + P_{proximity}$$

where Rdc is the DC resistance of the winding and Rac is the AC resistance of the winding at the specified frequency. The DC current is the average current in the winding over a full cycle. The AC current is the RMS value of the original current without the DC current. Methods for calculating these parameters will be shown later in this section. Proximity loss is calculated for zero current windings that experience an AC magnetic field.

The Transformer Screen
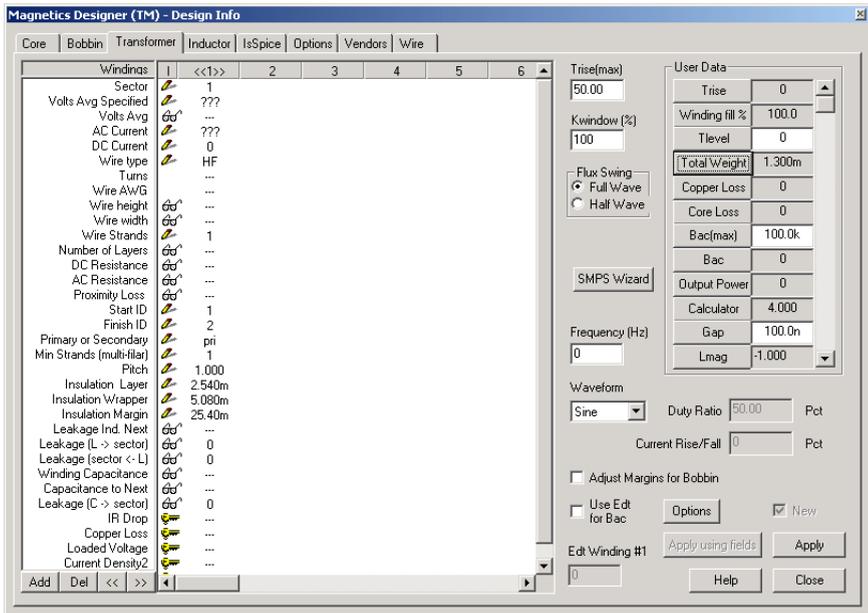
Note:
If you change the turns, make sure that you maintain the split ratio.

The Transformer screen, shown above, is very similar to the Inductor screen. The required data fields include the operating frequency of the design, and 3 parameters for each winding; average voltage, DC current, and AC current. Required fields are indicated by the presence of question marks "???" and must be supplied with a value. The spreadsheet area, in the middle of the screen, is used to enter and review the information which pertains to each winding and to add, split, or move windings. The User Data area to the right is used to access input variables and the calculated design results. The optional design constraints are also shown at the right of the dialog, and operate exactly like those found in the Inductor screen.

The Flux Swing radio button tells the program the type of flux swing that the transformer must be designed to handle. Full Wave means that the flux will be symmetrically driven in both directions. Half Wave indicates that the flux in the core will be

driven in one polarity and will be allowed to reset to the residual flux density in the other polarity.

The frequency must be declared so that the design can be performed and the AC resistance of the windings can be calculated at the specified frequency. Note: The core family and material must be selected in order to proceed with the design.

The Volts Avg Specified is the average voltage that the transformer terminals should have or generate. The value is used to calculate the number of turns required to operate at the desired flux density. The AC and DC currents are necessary in order to determine the current density and to calculate the copper losses.

To achieve a center tap winding configuration, enter two identical secondary windings and make the Finish ID number of the first winding equal to the Start ID number of the second winding.

Utilities for Determining Requirements

To properly design an inductor or transformer, it is very important that various requirements are properly specified. For example, if the waveform has a large DC component and a very small AC component, the copper losses associated with the high frequency AC resistance will not influence the design significantly. However, if there is a large component of AC current, the high frequency copper losses might be orders of magnitude larger than the DC losses. Therefore, it is important to separate the current into AC and DC components and to correctly calculate the magnitude of each component. Likewise, Magnetics Designer uses the average voltage across the first winding to calculate the peak flux density. Therefore, if you specify the RMS voltage instead of the average voltage, the program may select a larger core than necessary in order to satisfy bogus requirements.

Calculating DC and AC Currents

The average value of a complex waveform can be found by finding the integral of the equation and dividing the result by the period of the waveform. That is,

$$Iave = \int_0^T \frac{I(t)dt}{T}$$

4-1

The average (or DC) component of the half-wave rectified sine wave shown below is then

$$Idc = \int_0^{\frac{T}{2}} \frac{\sin(\omega t)dt}{T} = \frac{\left[-\frac{1}{\omega}\cos(\omega T)\right]_0^{\frac{T}{2}}}{T}$$

However, $\omega = \frac{2\pi}{T}$. Therefore,

$$Idc = \frac{-\frac{T}{2\pi}\left[\cos(\pi) - \cos(0)\right]}{T} = \frac{1}{\pi}$$

I(t)
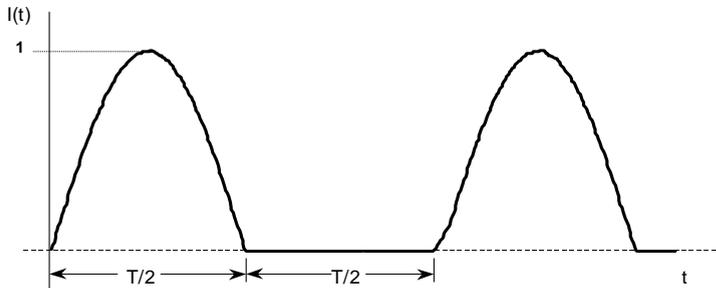
Half-Wave Rectified Sine Wave

The RMS value of a repetitive waveform can be determined by the following equation:

$$Irms \;=\; \sqrt{\dfrac{\displaystyle\int_{0}^{T} I(t)^2 dt}{T}} \qquad\qquad \text{4-2}$$

where I(T) is the current as a function of time and T is the period of one full repetition of the waveform. For example, it is possible to find the RMS value of the half-wave rectified waveform shown above using this method.

$$Irms \;=\; \sqrt{\dfrac{\displaystyle\int_{0}^{.5T} \sin^2(\omega t)\, dt}{T}}$$

$$Irms = \sqrt{\dfrac{\left[\dfrac{1}{2}t - \dfrac{1}{4\omega}\sin(2\omega t)\right]_{0}^{\frac{T}{2}}}{T}}$$

where $\omega = \dfrac{2\pi}{T}$ Therefore,

$$Irms = \sqrt{\dfrac{\left[\dfrac{1}{4}(T-0) - \dfrac{T}{8\pi}\left(\sin(2\pi) - \sin(0)\right)\right]}{T}}$$

Since sin(2π) and sin(0) are both equal to zero,

$$Irms \;=\; \dfrac{1}{2}$$

In general, any waveform can be separated into a DC component and an AC component. That is,

$$I(t) \;=\; Idc + Iac(t)$$

Once separated, the RMS value of the waveform can be found by taking the root-square-sum (RSS) of the DC and AC components. That is

$$Irms = \sqrt{I^2 dc - I^2 ac\,(rms)}$$

Likewise, if the RMS value and average value of the waveform are known, the RMS component of AC current can be calculated as follows:

$$Iac\,(rms) = \sqrt{I^2 rms - I^2 dc}$$

To illustrate how the above relationship was derived, consider the following argument. Any complex waveform can be expressed using a Fourier series. The series will have a DC component (perhaps 0) and a number of sine wave terms of various amplitudes and frequencies. For example, the Fourier series shown below can be used to represent the half-wave rectifier waveform which was shown previously.

$$I(t) = \frac{1}{\pi}\left[1 + \frac{\pi}{2}\cos\left(w_1 t\right) + \frac{2}{3}\cos\left(2w_1 t\right) - \frac{2}{15}\cos\left(4w_1 t\right) + \frac{2}{35}\cos\left(6w_1 t\right)^2 - \ldots\right]$$

According to Parseval's theorem (Ref. 5), the RMS value of this expression is the RSS (square root of the sum of the squares) of the RMS values of all terms. That is:

$$Irms = \frac{1}{\pi}\left[1^2 + \frac{1}{2}\left(\frac{\pi}{2}\right)^2 + \frac{1}{2}\left(\frac{2}{3}\right)^2 + \frac{1}{2}\left(\frac{2}{15}\right)^2 + \frac{1}{2}\left(\frac{2}{35}\right)^2 \ldots\right]$$

Irms = .49903

The above demonstration illustrates that except for minor numerical differences, either the Fourier series method or the direct integration method results in the same RMS value. In general, either method can be used to calculate the RMS current. Furthermore, since the DC current is simply the first term in the Fourier series, and the AC current is the RSS of all of the AC components, the relationship between Irms, Idc, and Iac has been verified.

Calculating Vavg, Vrms, and Edt

The relationship between voltage and flux was previously shown to be:

$$e = n \frac{d\Phi}{dt} \times 10^{-8}$$

This equation means that the voltage is proportional to the rate of change of flux in the magnetic path. If you are interested in flux, rather than voltage, the equation could be solved for Φ:

$$\Phi_1 - \Phi_0 = \int_0^{t1} \frac{edt \times 10^8}{N}$$

Simply stated, this equation says that the change in flux is proportional to the integral of voltage with respect to time. Edt is then defined as the integral of voltage with respect to time over a specific time interval.

For all magnetic components, the integral of voltage across any zero resistance winding must be zero as t approaches infinity. If this condition is violated, the flux will continue to increase in one polarity until the core saturated. Therefore, it is not appropriate to consider Edt over a full cycle since this parameter must be zero in the steady state. Instead, Edt is the integral of voltage in one polarity over a single cycle. For example, consider a 100 Vpk, 100 kHz square wave (shown on next page).

$$Edt = Vpk \left[\left(\frac{1}{2} \right) \left(\frac{1}{f} \right) \right] = \frac{Vpk}{2f}$$

$$Edt = \frac{(100V)}{(2)(100KHz)} = 5 \times 10^{-4} \, volt - \sec$$

If the waveform is duty cycle modulated, as shown in the half-wave rectified sine wave figure,

$$Edt = Vpk\left[D\left(\frac{1}{f}\right)\right] = \frac{DVpk}{f}$$

The average voltage may be calculated in a similar manner as the average current using the relationship

$$Vave = \frac{\int_0^T |V(t)| \, dt}{T}$$

4-3A

Note: The average voltage is calculated by integrating the absolute value of the voltage waveform with respect to time. If we don't take the absolute value of the voltage waveform, the average voltage would always be zero for an AC waveform.

If frequency and Edt are known, the average voltage can be calculated from the equation

$$Vave = 2 f \ Edt$$

4-3B

For example, if the frequency is 100 kHz, and Edt is 10 sec, then

$$Vave = 2(100k)(10 \times 10^{-6}) = 2 \ volts$$

Ipk

0

D Ipk
(1-D)

D Tsw   (1-D) Tsw
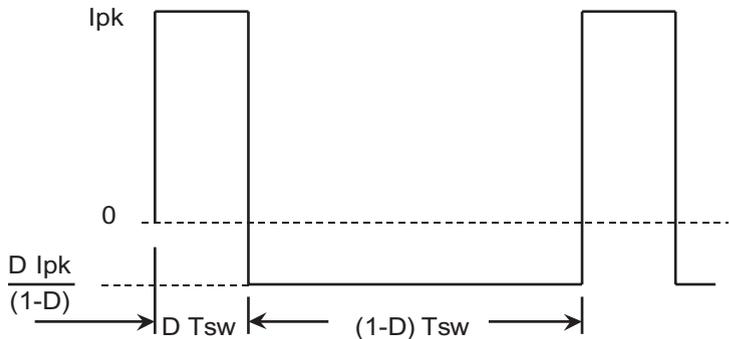
Duty Cycle Modulated Waveform

The RMS voltage may be calculated in the same manner as the RMS current. That is

$$Vrms = \sqrt{\int_0^T \frac{V^2(t)dt}{T}} \qquad \text{4-4}$$

Note: Unlike the current through a winding which can have both an AC and a DC component, the voltage across an inductor or transformer winding will never have a DC component since this will cause the core to saturate.

Requirements from Different Applications

The following sections will illustrate how to convert circuit/ waveform data to transformer requirements. The first section will illustrate how to generate requirements for inductors which have mostly DC current. Next, three low frequency transformer rectifier circuits will be studied in order to demonstrate how to calculate low frequency transformer and inductor requirements. Finally, several switching regulator topologies will be described in order to show how to derive high frequency switching regulator magnetic component requirements.

DC Chokes

Many filter applications require an inductor which has a very large component of DC current and a very small component of AC current. Typically, these types of inductors are required to have a specified inductance at the maximum rated DC current. For example, consider an EMI filter inductor for a 28 Vdc bus. Such an inductor will be specified to satisfy a minimum inductance requirement at a maximum DC current. For example, an EMI filter inductor might be required to have a minimum inductance of 20 µH at 10 Adc.

The tables in Appendix A provide formulas for calculating the RMS, DC, and AC-RMS components of various waveforms.

Occasionally, an inductor will only handle a small steady state current but must not saturate at a much higher current during a transient condition. In this case, the copper cross-sectional area is chosen in order to provide acceptably low losses based on the steady state current. However, the core size and gap length must be chosen in order to prevent core saturation at the maximum expected current.

Finally, the inductor may be required to support a small AC voltage. This AC voltage tends to cause core losses, and causes an AC current to flow in the inductor. The Edt associated with the AC voltage and the frequency must be specified to the program as well as the amplitude of the AC current.

Therefore, when specifying inductor design requirements, it will be necessary to determine the following requirements:

- **Worst Case Edt (volt-seconds)**
- **Operating Frequency (Hz)**
- **Maximum Peak Current (Amps)**
- **Steady State DC Current (Adc)**
- **Steady State AC Current (Arms)**
- **The required inductance at the peak current**

Consider the following buck regulator example. The figure below shows a simplified schematic diagram of a buck regulator which converts 20 Vdc to 5 Vdc.

**Buck Regulator
Inductor Application**
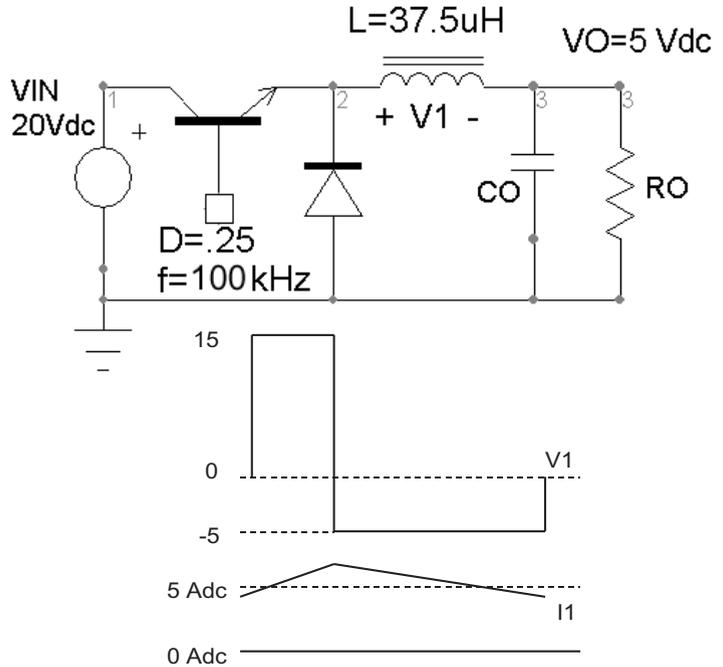
Assume that a current limit circuit prevents the inductor current from exceeding 10 Apk. The steady state output current (and therefore the steady state inductor current) is 5 Adc. The peak-to-peak ripple current is found from the equation:

$$\Delta I = \frac{V_t \Delta T}{L} = \frac{(Vin - Vo)D/F}{L}$$

$$\Delta I = \frac{.15(.25/100000)}{37.5 \times 10^{-6}} = 1 \; Amp(p-p)$$

From the waveform formulas in Appendix A, the RMS value of a ramp ($Ip\sqrt{D}$) is .577 x Ip = .289 Ip-p = .289 Arms. Edt is calculated as follows:

$$Edt = (Vin - Vo)(\frac{D}{F}) = 20 - 5(\frac{.25}{100000})$$

$$Edt \quad = \quad 37.5 \times 10^{-6}\, \text{volt} - \sec$$

The buck regulator requirements are summarized below:

Edt   **= 37.5µ volt-sec** - (Edt Winding #1)
Frequency   **= 100k Hz**
Peak Current   **= 10 A pk** - (Current Peak Specified)
AC Current   **= 0.289 A rms**
DC Current   **= 5 A**
Min. Induct.   **= 37.5µH** - (Minimum Inductance)

These requirements are entered on the Inductor design screen, using u for µ. Two additional entries are required on the Inductor screen before the initial design can be completed by Magnetics Designer. The core family and the material type must be selected. Material characteristics will be discussed in a later section, and will describe how to select appropriate materials for various applications.

Low Frequency Sine Wave Applications

Three low frequency transformer rectifier examples will illustrate how to specify transformer requirements. Specifically, they describe how to handle transformer rectifier circuits with resistive loads, capacitive loads, and inductive loads, respectively.

Full-wave Transformer Rectifier, Resistive Load

The figure below illustrates the basic waveforms of a full wave transformer rectifier with a resistive load. Assuming that the rectifier forward voltage drop is small compared to the output voltage, and that the transformer magnetizing current is small compared to the reflected load current, the primary current will be essentially in phase with the input voltage. Each side of the secondary will have currents which are half-wave rectified sine waves.

$$Ip2 = \frac{N\ Vp1}{R_o} \qquad Ip1 = N\ Ip2$$
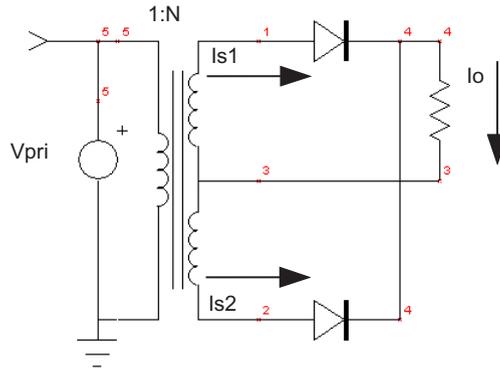
Full Wave Transformer-Rectifier: Resistive Load
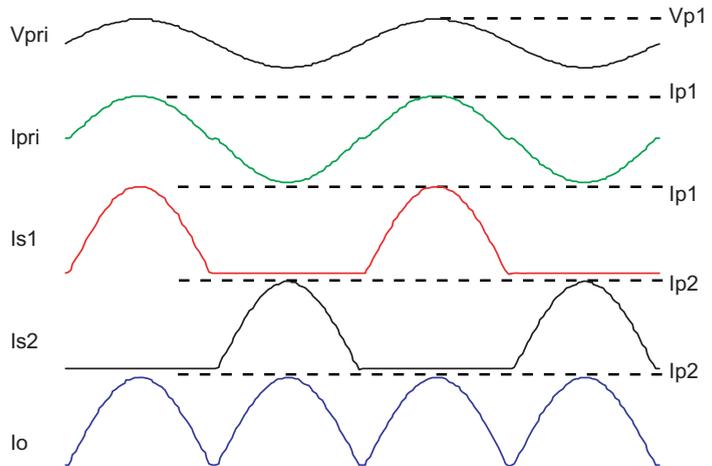
Since the transformer rectifier must satisfy the following requirements, it will be necessary to convert the requirements to the parameters which are required by the Transformer screen. That is, each of the entries on the Transformer design screen must be calculated from the basic requirements.

Input voltage	**= 95 to 135 V rms**
Average Output volt.	**= 24.3 V avg. at 135 V rms**
Frequency	**= 60 Hz**
Load Resistance	**= 8 to 80 ohms**

Referring to the Transformer screen, the first parameter to be entered is the flux swing type. Since the input voltage is driven equally in both polarities, the Flux Swing is Full Wave. The maximum output power is equal to the square of the maximum RMS output voltage, divided by the minimum load resistance:

However, the transformer is to be designed to give 24.3 Volts (avg.) at the maximum input voltage. Convert the average voltage to an RMS voltage:

$$Vrms = \frac{\pi \, Vave}{2\sqrt{2}} = 1.11 \times (24.3)$$

$$Vrms = 26.97 \, Vave$$

Therefore, the output power is

$$Po = \frac{26.97^2}{8} = 90.9 \, Watts$$

The frequency was given to be 60 Hz. The average voltage of a sine wave is related to the RMS voltage by the following equation:

$$Vave = \left(\frac{2\sqrt{2}}{\pi} \right) Vrms$$

Therefore, the average input voltage ranges from 85.5 to 121.5 Volts. As the input voltage varies from 85.53 to 121.54 Vavg, the average output voltage will range from 17.1 to 24.3 Volts.

The peak current on the secondary is equal to the peak voltage divided by 8 ohms. That is,

$$I_{s2}(pk) = \frac{\pi}{2}\frac{Vave}{R_o(\min)}$$

$$I_{s2}(pk) = \left[\frac{\pi}{2}\right]\left[\frac{243}{8}\right] = 4.77$$

The secondary current can now be separated into a DC component, and an AC component which is based on the equations in *Appendix A* for half-wave rectified sine waves. That is, the maximum DC component of current is

$$Idc \quad = \quad \frac{2DIp}{\pi} = .318 \times 4.77 = 1.52 Adc$$

The AC RMS current can be similarly calculated from the equation shown in Table 4.2-2:

$$I_{ac}(rms) \quad = \quad Ip\sqrt{\frac{D}{2} - \left(\frac{2D}{\pi}\right)^2}$$

$$I_{ac}(rms) \quad = \quad 4.77\sqrt{\frac{0.5}{2} - \left(\frac{2 \times 0.5}{\pi}\right)^2} = 1.84 Arms$$

The peak current reflects from the secondary to the primary by the turns ratio (Ns/Np = 24.3/121.54 = .2). Therefore, the peak current on the primary is 0.954 Amps (.2x4.77). Since the primary only has AC current, the AC RMS current is 0.707 x Ip = 0.674 Arms and the DC current is 0. The list of requirements which are necessary to design the transformer is given below:

Flux Swing Type = Full Wave
Output Power = 90.9 Watts
Frequency = 60 Hz
Pri. Voltage = 121.5 V avg. - (Volts Avg Specified)
Pri. AC Current = .674 A rms
Pri. DC Current = 0 A
Sec. Voltage = 24.3 V avg. - (Volts Avg Specified)
Sec. AC Current = 1.84 A rms
Sec. DC Current = 1.52 A
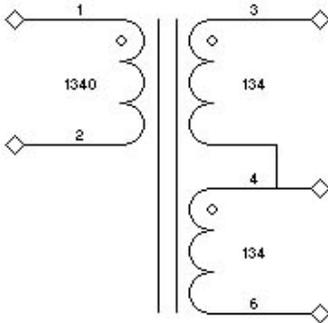
Once a core family and material have been selected, the requirements can be specified on the Transformer design screen, as shown below. The program will perform the trial design: the core will be selected, the wire sizes will be determined, and the number of turns for each winding will be calculated.

To achieve the center tap winding configuration, enter two windings for the secondary. The secondary voltage is split evenly between two windings (=12.15V) while the currents are left the same. The Finish ID number of the first secondary should be the same as the Start ID number of the bottom secondary winding. This will cause the schematic symbol to be structured properly, as shown to the left.

The "Cut C 4 mil Simple" core family and MC1515-004 geometry were used in this example.

Transformer screen with data entered. Note the Start and Finish ID numbers that create the center tap effect.

Bridge Transformer Rectifier, Capacitive Load

The figure below illustrates a transformer circuit which is loaded with a rectifier bridge and a capacitive load. Assuming that the capacitor is large, the output voltage will be a DC voltage with

Transformer Rectifier: Capacitive Load
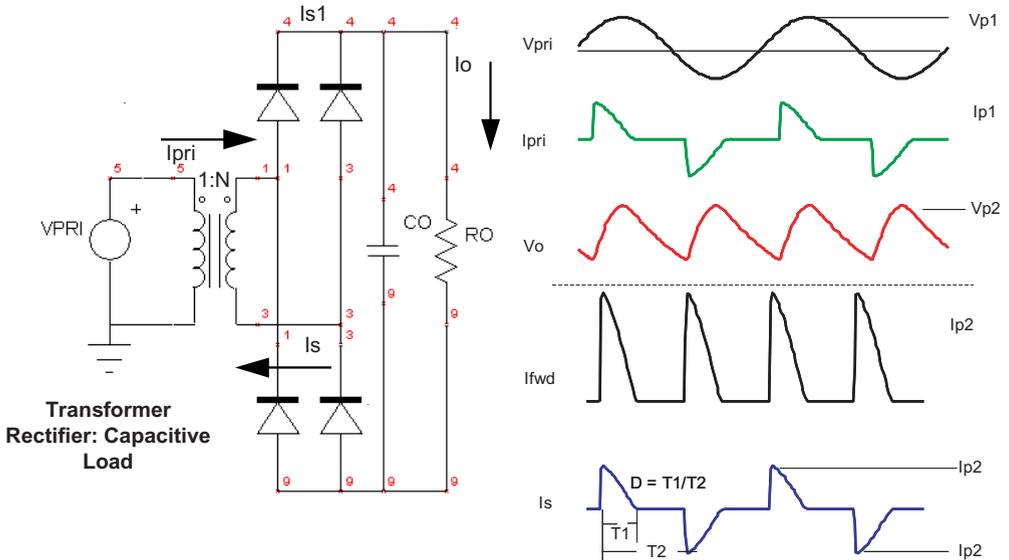
After peak charging the output capacitor to Vp2, the output voltage from the transformer begins to decrease. Since the voltage on the capacitor is larger than the output from the transformer, the rectifiers are reverse biased. Therefore, the current in the transformer is zero. On the next half cycle, the output from the transformer eventually exceeds the capacitor voltage, and current starts to flow through the rectifier.

The conduction duty cycle (D = T1/T2) is dependent upon the size of the capacitor and the load current. For a given load current, decreasing C increases the duty cycle and decreases the transformer RMS currents. A numerical analysis of the circuit shown above was performed with IsSPICE4 in order to demonstrate the relationship between ripple voltage, duty cycle, transformer RMS current, and average load current. The basic model for the analysis is shown in the next figure.

BRIDGE TRANSFORMER RECTIFIER, CAPACITIVE LOAD

Transformer Rectifier Equivalent Circuit
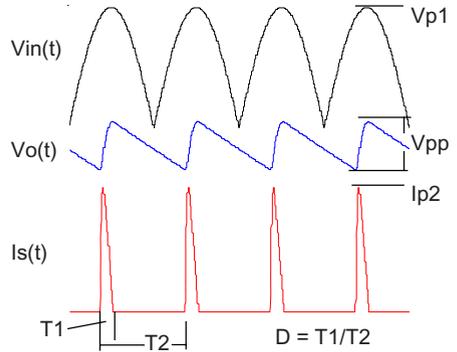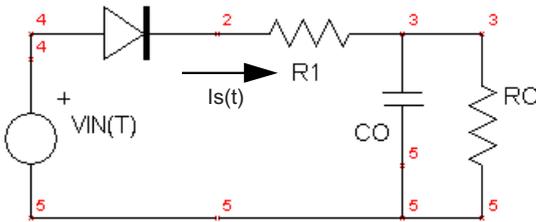
The model does not attempt to account for the transformer characteristics, except to the extent that R1 represents the transformer-rectifier output impedance. The capacitor size was varied over a large range of values, and the following parameters were calculated for each case: Vpp/Vp, D, Irms/Iavg. Vpp/Vp is the ratio of peak-to-peak output ripple divided by the peak output voltage, D is the conduction duty cycle, and Irms/Iave is the ratio of AC RMS current in the source to the average (DC) load current. The results of the analysis are summarized below.
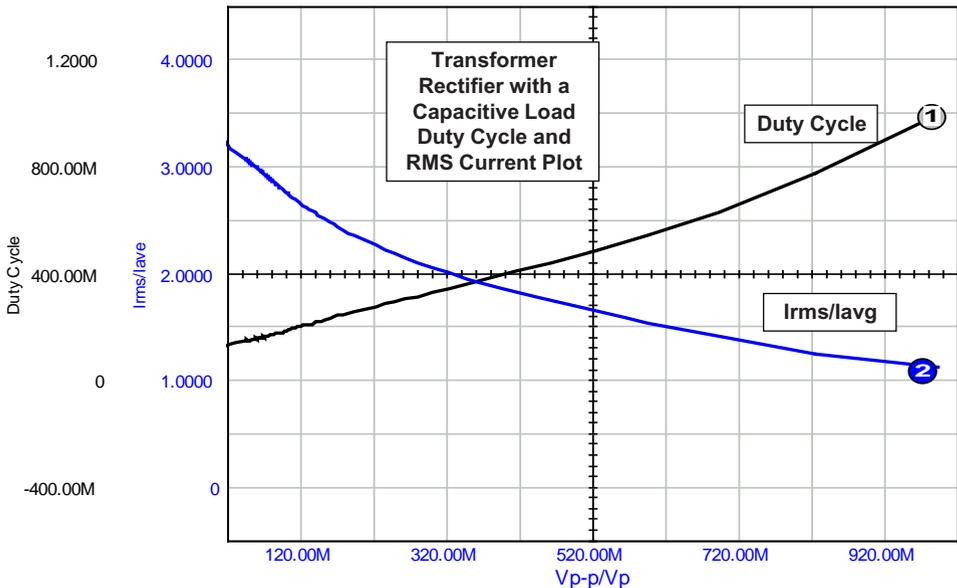
Now we need to convert the following requirements to the Transformer screen requirements:

Input Voltage = 115 V rms
Frequency = 50 Hz
Avg. Output DC voltage = 100 V
Output ripple (p-p) = 16.2 V p-p
Load Resistance = 100 ohm

Once again, referring to the half wave rectified sine wave figure, the transformer flux swing is full wave, the DC output power is 100 W, and the frequency is 50 Hz.

Since the rectified DC voltage is 100 volts (avg) and there is 16.2 Vpp of ripple, the peak voltage on the secondary must be 108.1. Therefore, the average voltage across the winding is 68.8 Vac ($2/\pi$ x 108.1). From the graph, the ratio of Irms to Idc at Vpp/Vp = .15 (16.2/108.1) is 2.52. Since the DC current is 1 Adc, the RMS current on the secondary is then 2.52 Arms. Since the circuit shown is a bridge rectifier, the DC component of current in the winding is 0. The peak voltage across the primary is 162.6 Vpk ($\sqrt{2}$ x115 Vrms). The average voltage is then 103.5 volts average ([$2/\pi$]x162.6). The turns ratio from primary to secondary is 1.5 (162.6/108.1). The RMS current on the primary is 1.68 Arms (2.52/1.5) and the DC current is zero. The Transformer screen requirements are summarized as follows:

Flux Swing Type = Full Wave
Output Power = 100 W
Frequency = 50 Hz
Pri. Voltage = **103.5 V avg.** - (Volts Avg Specified)
Pri. AC Current = **1.68 A rms**
Pri. DC Current = **0 A**
Sec. Voltage = **68.8 V avg.** - (Volts Avg Specified)
Sec. AC Current = **2.52 A rms**
Sec. DC Current = **0 A**

The capacitive loading of the transformer-rectifier considerably increases the VA rating of the transformer with respect to the DC load power. That is, the VA (Vrms x Irms) rating of the

secondary of the transformer is nearly twice (193.2 VA) the output power. Any attempt to reduce the output ripple by adding additional capacitance will result in an increased transformer rating. Therefore, rectifier circuits are sometimes followed by an L-C filter to achieve lower output ripple without increasing the VA rating of the transformer.

Bridge Transformer Rectifier, Inductive Load

The figure below illustrates a transformer circuit which is loaded with a rectifier bridge, an inductor, and a capacitor. If the inductor is very large so that the ripple current is significantly smaller than the DC load current, the current in the transformer is essentially a square wave with a peak current which is equal to the load current. The output voltage is the average of the rectified sine wave. For this example, the requirements are summarized below:

Input voltage = 220 V rms
Frequency = 400 Hz
Output Voltage = 50 V dc
Load Resistance = 15 ohm

The output power on the secondary side is 167 Watts (50²/15). Moreover, if the output voltage is 50 Vdc, the secondary voltage must be 50 Volts average. The RMS secondary current, which is approximately equal to the load current (assuming very little

ripple in the inductor,) is 3.33 Arms. The secondary does not have a DC component of current.

The average voltage on the primary is 198 VAC. Therefore, the current on the primary is .84 Arms. In summary, the transformer requirements are listed below:

Flux Swing Type = **Full Wave**
Output Power = **167 W**
Frequency = **400 Hz**
Pri. Voltage = **198 V avg.** - (Volts Avg Specified)
Pri. AC Current = **0.84 A rms**
Pri. DC Current = **0 A**
Sec. Voltage = **50 V avg.** - (Volts Avg Specified)
Sec. AC Current = **3.33 A rms**
Sec. DC Current = **0 A**

In this case, the VA rating of the transformer is much closer to the actual output, i.e. 185 VA as opposed to 167 watts.

High Frequency Switching Regulator Components

A Buck switching regulator was previously described in the DC chokes section in order to illustrate how to specify inductor requirements. This section will continue by describing two other common switching regulator topologies: the forward converter, and the flyback converter.

Forward Converter

As shown in the next figure, the forward converter is quite similar to the Buck regulator, but the secondary is isolated from the primary by a transformer. Therefore, we will need to design both a transformer and an inductor. We will start by describing the basic behavior of the converter through equations and waveforms.

FORWARD CONVERTER

Forward Converter

T1
Kt
D1
Vo=5Vdc

D2
Np
Ns
D3
Co
Ro
L

Vin =
300Vdc

Nm

Forward Converter Waveforms

Vpri
+300
-300

Ipri
0.3
0

Vsec
+15
0
-15

Isec
6
4
0

Ton   Toff
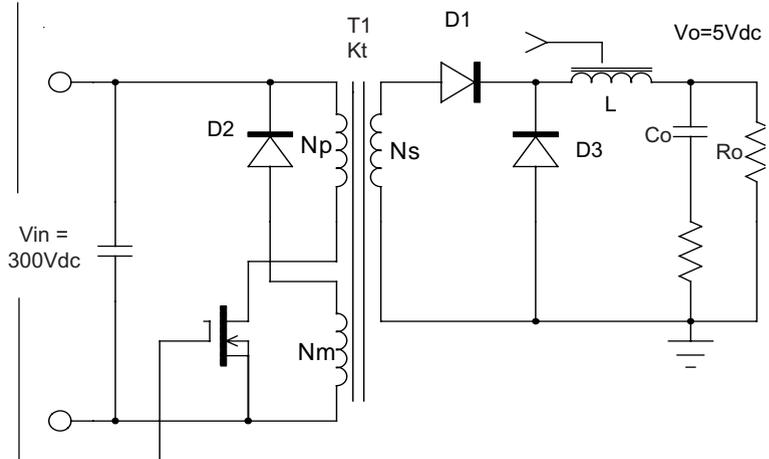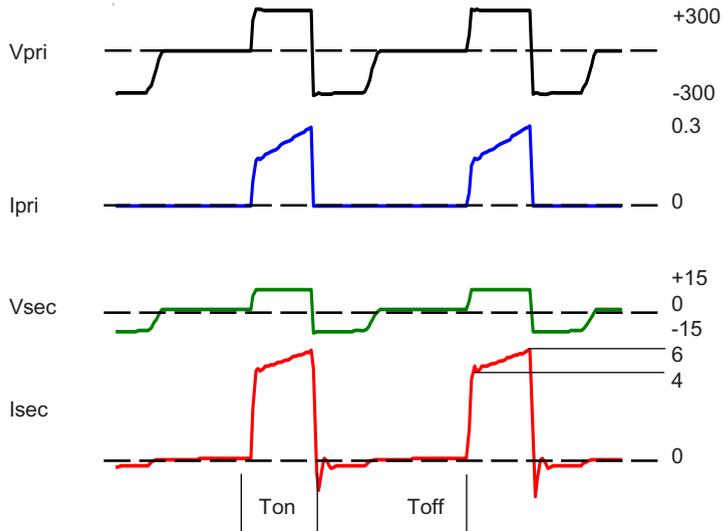
When the transistor turns on, the voltages on the starts (dotted ends) of the transformer are driven positive, and forward bias D1. While the voltage is positive, the inductor current increases towards its maximum value while magnetizing current builds up in the transformer. When the transistor turns off, transformer magnetizing current must continue to flow. Therefore, the only path for magnetizing current to flow through is D2, thus reversing the polarity across the transformer and providing a voltage to

reset the flux. However, when the current in the transformer winding reaches zero, the voltage across the winding reduces to zero, indicating that the transformer flux has returned to the residual flux of the core material.

Throughout the off-time of the transistor, inductor current decays. However, if the inductance is large enough, the inductor current will not return to zero and the converter will operate in the continuous conduction mode. If the inductance is small, the inductor current returns to zero during the off time. The second case is the discontinuous mode. In this example, we will assume that the converter is operating in the continuous mode. The forward converter waveforms are shown below the circuit diagram. The following equations describe the converter behavior:

Output voltage: $Vo = Dk_t\eta\, Vin$

where Vo is the output voltage, D is the duty cycle of the switch, η is the efficiency of the converter, Vin is the input voltage, and Kt is the turns ratio transformer.

P-P Inductor Current: $\Delta I_l = \dfrac{(1-D)T_{sw}}{L}(Vo + Vfwd)$

where I_L is the peak-to-peak inductor current, Vfwd is the rectifier forward voltage, Tsw is the switching time, and L is the inductance.

Avg. Inductor Current: $I_{l(ave)} = I_o = \dfrac{V_o}{R_o}$

where Io is the output current, and Ro is the load resistance.

Max. Edt (Transformer primary): $Edt_{pri} = \dfrac{DV_{in}}{F_{sw}}$

where, Fsw is the switching frequency.

Max. Edt (Inductor): $Edt_l = \left(V_o + V_{fwd}\right)(1-D)T_{sw}$

Generally, a converter must operate over a wide dynamic range of input voltage and load current. However, Magnetics Designer only needs to consider the case which results in the maximum transformer ratings. For the forward converter, this is low line where the RMS current in the windings is maximum. Since the average output voltage from the regulator is maintained at a constant, the core losses, on a first order basis, are unaffected by line and load changes. Based on circuit considerations, the following requirements have been generated:

Minimum Input Voltage   **= 300 V dc**
Frequency   **= 100 kHz**
Inductance   **= 17.7uH**
Vfwd   **= .7 V dc**
Duty Cycle   **= .38**
Turns ratio (Kt)   **= 1/20**
Maximum Load Current **= 5 A dc**

First, let's consider the output inductor. The peak-to-peak inductor current is:

$$I_{pp} = \frac{(1-D)}{f_{sw}L}\left(V_o + Vfwd\right) = \frac{(1-.38)(5.7)}{(100K)(17.7\mu\,H)}$$

$$I_{pp} = 2\text{Ap-p}$$

The peak inductor current is then 6 Apk. The DC current is 5 Adc. The AC current is .577 Arms ($I_{pp}/2\sqrt{3}$).

The remainder of the requirements were determined by the same basic approach which was used to determine the requirements for the Buck regulator inductor in the DC chokes section. They may be entered onto the Inductor screen.

Edt Winding #1   **= 35.3 x 10^{-6} Vsec**
Frequency   **= 100k Hz**
Current Pk Specified, Ipk   **= 6 A pk**
AC Current, Iac   **= .577 Arms**
DC Current, Idc   **= 5 A**
Minimum Inductance   **= 17.7 uH**

The transformer waveforms are shown at the beginning of this section. In this case, since the transformer is allowed to reset itself, the flux type is half-wave. The output power is 28.5 watts (5.7 Vdc x 5 Adc). The average voltage across the secondary can be calculated from equation 4-3B.

$$V_{ave} = 2\,fEdt = 2\,f_{SW}\left(V_{in}\,\frac{N_{sec}}{N_{pri}}\right)\left(\frac{D}{f_{SW}}\right)$$

$$V_{ave} = 2DV_{in}\,\frac{N_{sec}}{N_{pri}}$$

$$V_{ave} = 2(.38)(300)\left(\frac{1}{20}\right) = 11.4\,\text{Volts(ave)}$$

Using the formula from appendix A for a unipolar trapezoidal waveform, the DC current is:

$$I_{dc} = \frac{D(Ip + Im)}{2}$$

$$I_{dc} = \frac{.38(6+4)}{2} = 1.9A$$

Likewise, the RMS current in the winding is:

$$Irms = \sqrt{D\left(I_p \times I_m + \frac{1}{3}(I_p - I_m)^2\right)}$$

$$= \sqrt{38\left(6 \times 4 + \frac{1}{3}(6-4)^2\right)} = 3.103A$$

Knowing the DC and RMS currents, the AC current is

$$I_{ac} = \sqrt{I^2{}_{rms} - I^2{}_{dc}}$$

$$I_{ac} = \sqrt{3.103^2 - 1.9^2} = 2.45A$$

The average voltage on the primary is 228 Vavg. (20x11.4 Vavg.). The DC component of the primary current is then 0.095 Adc (1.9/20) and the AC component of the primary current is 0.123 Arms (2.45/20). The transformer requirements are summarized below, and may be entered onto the Transformer screen:

Flux Swing   **= Half Wave**
Frequency   **= 100 kHz**
Pri. Voltage   **= 228 Volts avg.** - (Volts Avg Specified)
Pri. AC current   **= .123 A rms**
Pri. DC current   **= .095 A**
Sec. Voltage   **= 11.4 Volts avg.** - (Volts Avg Specified)
Sec. DC current   **= 1.9 A**
Sec. AC current   **= 2.45 A rms**

Flyback Regulator

Although it's called a transformer, the principal magnetic component in a flyback regulator is actually an inductor. It is best described as an inductor because energy is intentionally stored in the core or core gap. Therefore, one should use the Inductor screen to design a flyback transformer.

A flyback regulator is designed to operate in the discontinuous mode. That is, the flux in the flyback transformer (inductor) returns to 0 on every cycle, as evidenced by the fact that the current on both the primary and secondary are equal to zero during a part of the switching cycle. During the "on" time of the transistor, the current ramps up to .945 A as energy is stored in the flyback transformer. The rate of rise of current is proportional to the line voltage (400 V), and is inversely proportional to the primary inductance (Lp = 1 mH).

Flyback Regulator

Kt = 0.1
Vo=15Vdc
Ipri
Vpri
Isec
CO RO
Vin = 400Vdc
D = .157
D' = .398
Tsw = 15us
D

Vpri

400V
0
-157.4V
D Tsw
Tsw

Ipri

.942A
0
D'Tsw

Isec

9.42A
0
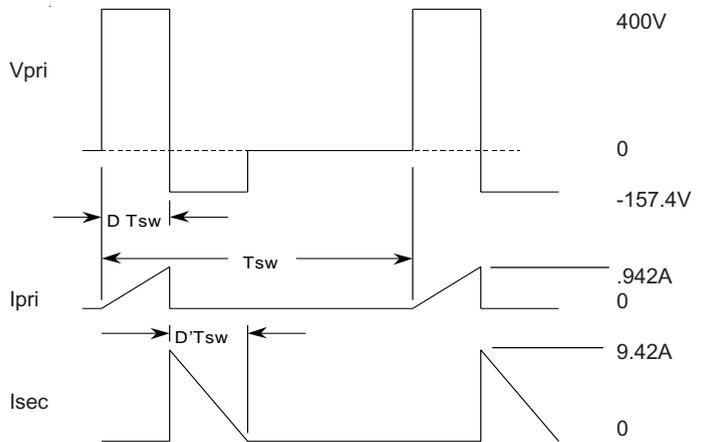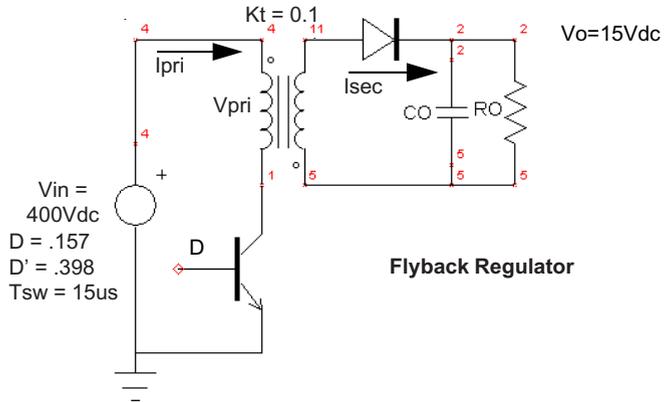
When the transistor turns "off", current must continue to flow into a dotted end of a winding. Therefore, the current immediately commutates to the secondary winding. Since the turns ratio is 10:1 and the ampere-turns must be preserved, the current is 10 times higher at the secondary than it was on the primary winding. The rate of fall of inductor current on the secondary is proportional to the output voltage plus the rectifier forward voltage, and is inversely proportional to the inductance at the secondary ($Kt^2 Lp$).

The basic waveform data is shown above and must be converted to inductor design requirements. Edt is easily calculated from the primary winding:

$$Edt = V_{in}t_{on} = V_{in}\ DT_{sw}$$

$$Edt = 400 \times 2.36x10^{-6} = 9.44 \times 10^{-4}\ volt - \sec$$

The frequency is 66.7 kHz (1/15 sec). The peak current on the primary is .944 Amp-peak. From appendix A, the Idc and Iac are calculated as:

$$I_{dc} = \frac{D}{2} Ip = \frac{.157}{2}(.944) = .074A$$

$$I_{ac} = Ip\sqrt{\frac{D}{3}(1-.75D)}$$

$$I_{ac} = .945\sqrt{\frac{.157}{3}(1-.75 \times .157)} = .203Arms$$

The winding is a primary and the required inductance is 1 mH. On the secondary side, the peak current is 9.44 Apk. The DC current is then:

$$I_{dc2} = \frac{D'}{2} Ipk = \frac{.398}{2}(9.44) = 1.88Adc$$

where D' is the secondary conduction period divided by the full switching period. The AC current is:

$$I_{ac} = Ip\sqrt{\frac{D'}{3}(1-.75D')}$$

$$I_{ac} = 9.44\sqrt{\frac{.398}{3}(1-.75 \times .398)} = 2.88Arms$$

The winding type is a secondary. The inductance is 10 uH (Kt^2 Lp). The flyback transformer design requirements are summarized below:

Edt winding #1	**= 9.42x10^{-4} volt-sec**
Frequency	**= 66.7 kHz**
Current Pk Specified	**= .944** (Primary)
Pri. AC Current	**= .203 A rms**
Pri. DC Current	**= .0743 A**
Current Pk Specified	**= 9.44** (Secondary)
Sec. AC Current	**= 2.88 A rms**
Sec. DC Current	**= 1.88 A**

Note that although the peak current reflects from the primary to the secondary by the turns ratio, the AC and DC currents do not. This is due to the fact that the conduction time on the secondary is much longer than the conduction time on the primary.

FLYBACK REGULATOR

Choosing the Right Core

Choosing the Right Core

Cores are available in many different materials and shapes. This fact can be either a blessing or a curse. It's a blessing because there are many options available to optimize any given design. It's a curse because there are sometimes too many options to investigate.

The following sections discuss the various materials and core types and offer suggestions with regard to selecting a specific material and geometry. Much of the following data is taken from lecture notes prepared by W.J. Muldoon (ref. 7).

Material Types

Materials can be classified according to their behavior in a magnetic field. That is, there are certain properties that can be measured and used to classify materials into three groups: Ferromagnetic, Paramagnetic, and Diamagnetic.

If a small piece of material is suspended on a thin thread in a powerful magnetic field, paramagnetic materials will generally be attracted towards the strongest part of the field, while diamagnetic materials will be attracted to the weakest part of the field. If the material experiences a particularly strong attraction to the strongest part of the field, the material is ferromagnetic.

Another way of describing these three phenomena is that ferromagnetic materials have a very high relative permeability, paramagnetic materials have a relative permeability near to but greater than 1. Diamagnetic materials have a relative permeability less than 1.

Ferromagnetic atoms are characterized by an excess of electron spins in one direction, which results in a magnetic polarization of the atom (a dipole). A single crystal is made up of regions or groups of atoms. In a ferromagnetic material, some of the regions have their atoms arranged in cubic groups with their magnetic axes of polarization in parallel. The regions are called magnetic domains. In these regions, atoms are arranged at corners of a cube, and either in the center of a cube face (as in nickel) or in the center of the cube (iron), depending on the material.

In an iron crystal, the atomic magnetic moments in the domain are lined up in parallel with one edge of a cubic crystal. However, in the crystal as a whole, the orientation of each domain is random along any of the six directions of the cube. When an external field is applied to a ferromagnetic material, initially magnetic dipoles flip from their natural alignment to align with the cube face which is most parallel with the field. When all of the domains have flipped to the faces which are most nearly in line with the field, the material is at the saturation knee of the B-H loop. Further increase of the field tends to rotate the domains as a whole until their axes are directly in line with the applied field. Eventually, when any further increase in field intensity has less and less effect on the flux density, the material is saturated.

When the applied field is slowly decreased to zero, the flux density does not return to zero. Instead, some of the magnetic domains remain aligned with the previous field direction. When the externally applied field is zero (H=0), the remaining flux density is called the residual flux density (Br).

To force the flux density back to zero, a magnetizing force must be applied in the opposite direction. The magnetizing force

which is required to return the flux to zero is called the coercive force (Hc). The plot of flux density (B) versus field intensity (H) is usually referred to as the B-H loop of a material.

If the intensity is rapidly cycled, the area inside of the loop increases, becoming larger as the frequency increases. These loops are called hysteresis loops. If the peak magnetizing force is decreased, the area will decrease not only because the peak flux density is reduced, but also because the loop becomes narrower.

The hysteresis loop area represents energy loss. In the case of the DC loop, this loss may be considered to be work done in rotating domains against molecular friction. At higher frequencies, additional losses (as indicated by the wider B-H loop) are due to eddy currents circulating in the core material. These currents are caused by induced voltages in the conducting loops of material surrounding the AC flux lines.

One could plot B-H loops and calculate core losses by finding the work done per cycle and multiplying by the frequency. Fortunately, vendors typically characterize material losses and provide curves to describe the losses as a function of frequency and peak flux density.

At a certain temperature, the permeability of a magnetic material decreases rapidly towards 1. This temperature is called the Curie temperature. It ranges from approximately 150 degrees C for ferrites to more than 750 degrees C for silicon steel.

There are only a few atoms such as iron, cobalt, nickel, and manganese that exhibit ferromagnetic properties. However, these metals may be combined as alloys and can be specially treated in order to align the magnetic domains and enhance their useful properties. Furthermore, oxides of these metals may be used to make materials (called ferrites) which have much higher resistivity and therefore lower losses at high frequency. The following list of materials, although by no means exhaustive, will provide an indication of the advantages and disadvantages of various materials.

Silicon Steel

Non-grain oriented steel is most commonly used for commercial 50 Hz and 60 Hz power transformers and inductors, and is sometimes used in audio transformers. Typically, the material is hot-rolled into thin sheets and cut in laminations with more or less non-directional properties. Lamination thicknesses may vary from .004 to .014 inch.

Silicon steel is typically a 3% silicon alloy with a saturated flux density of approximately 18 kilogauss. Core losses at high frequency prohibit the use of this material for high efficiency power transformers at frequencies above approximately 2000 Hz. For example, core loss at 10 kHz and 2 kGauss is approximately 100 Watts/lb for .014 inch thick material. Losses drop to approximately 25 Watts/lb for .004 inch laminations. However, in applications which have a high DC flux density (for example, DC chokes) and a small AC flux density, this material may be used at frequencies up to 10 kHz.

Grain-oriented, cold rolled steel achieves more desirable properties by successive cold-rolling operations which result in a high degree of grain orientation in the direction of the rolling. This reduces the coercive force (Hc) and the associated losses, while increasing the saturation flux level. The material is available in sheets which are suitable for making laminations or thin strips (as thin as .001 inch) which can be wound into C cores or toroids. Although the losses are significantly lower than non-oriented silicon steel, the core loss at 10k Hz and 2 kGauss is still too high for switching regulator transformer applications. However, grain-oriented steel is very attractive for DC chokes which have a very high DC bias and a small AC flux. Typical applications include EMI filter inductors, switching regulator output chokes (up to 30 kHz), and 60-400 Hz AC chokes.

Silicon steel is useful to very high temperatures since the Curie temperature for silicon steel exceeds 750 degrees C.

Iron-Cobalt (Supermendur)

Supermendur is a highly refined iron-vanadium-cobalt alloy. It is available in .002 inch and .004 inch thickness. This material is processed and annealed in a magnetic field to develop a very high saturation flux density (approximately 22 kGauss. .002 inch Supermedur is useful at up to 20 kGauss and up to 1500 Hz. .004 inch Supermendur is useful to 750 Hz at 20 kGauss.

Permalloy 80 (80/20 Nife)

Permalloy 80 is a non-oriented 80% nickel, 20% iron alloy. It is available in thicknesses of .001, .002, and .004 inch tape wound cores and .004, .006 and .014 inch thick sheets which are used for making laminations.

Permalloy 80 is processed to have high initial permeability and low losses. However, the saturated flux density at 7500 Gauss is considerably lower than that of silicon steel. At 5 kGauss, .001 inch Permalloy 80 is usable to 25 kHz. Typical applications include power transformers (up to 30 kHz), switching regulator output chokes with a large DC component of current (up to 100 kHz), pulse power transformers, magnetic amplifiers (up to 100 kHz), and current transformers. The Curie temperature of Permalloy 80 is 460°C.

Orthonol (50/50 Nife)

Although more lossy than Permalloy 80, Orthonol has a much higher saturation flux density of 15 kGauss. Orthonol is a grain-oriented 50/50 Nickel-iron alloy. It is available in .001, .002, and .004 tape wound form and .004, .006, and .014 in laminations. The losses are approximately one-half those of similar grain-oriented silicon steels. .001, .002, and .004 are usable at 10 kGauss at 2000, 4000, and 8000 kHz, respectively. In applications where there is a large DC bias, Orthonol is useful in switching regulators up to 40 kHz.

In applications where core losses are critical, Orthonol may be a better choice than silicon-steel for frequencies on the order of 400 Hz.

Ferrites

Ferrites are characterized by very low core losses at high frequencies and moderately low coercive forces. However, the saturation flux density is considerably lower than even Permalloy 80. Ferrites are formed from alloys of iron-oxide which are combined with other metals such as zinc and manganese. The material is made in a fine powder with an insulating oxide which is molded or sintered under high pressure. The presence of oxides increases the resistivity of ferrites to much higher levels than the other magnetic materials which have been previously described. Therefore, eddy current losses are very low.

Ferrites typically have a saturated flux density ranging from 3 to 5 kGauss. Core losses are usually significantly lower than even .001 inch Permalloy 80.

Since ferrites are molded and fired using ceramic techniques, they can be made in a large variety of shapes. Furthermore, they can be machined to precise tolerances after the firing operation. Available shapes include pot cores, toroids, EI, EE, and UI cores. In the Core screen, materials with an LF designation have been characterized at frequencies below 100kHz, while materials with an HF designation have been characterized at frequencies above 100kHz.

Ferrites are used in many high frequency applications, including switching regulator transformers and chokes at frequencies up to 500 kHz.

The Curie temperature ranges from 100 to 300°C, depending upon the particular material.

Powdered Irons

Powdered iron is available in pure iron and in nickel-iron alloys (Permalloys). The cores are made from a fine powder which is typically die-pressed into molds. Core losses are generally higher than those of ferrites. However, the saturated flux density is generally higher (ranging from 5 to 10 kGauss).

Powdered cores are typically designed for a specific relative permeability between 14 and 550. Furthermore, permeability tends to decrease fairly rapidly with a DC bias in higher permeability cores.

The materials are often used for high frequency, low cost chokes in such applications as EMI filters, resonant circuits, high Q filters, and switch-mode filter chokes. Usually, the cores are toroidal. However, EI and EE cores are also common.

Core Types and Configurations

Core geometries are generally dependent on the material type. Structures can generally be classified as tape wound, lamination, or pressed/formed. The figure on the following page illustrates several common core shapes.

Materials which are fabricated in sheets such as silicon steel, Permalloy 80, or Orthonol can be fabricated into cores in one of two ways: (1) thin strips of material are wound onto a form. (2) laminations are stamped from the sheet materials. Cores are then made by stacking laminations.

The typical core geometries figure illustrates two kinds of tape wound cores, a cut C core and a tape wound toroid. This figure also illustrates a core which has been made from EI laminations. Usually, the windings are pre-wound on a bobbin or coil form and then the laminations are stacked with the center leg of the lamination inside the center of the coil.

Toroid

**Typical Core
Geometries**

EE

EP

Pot

Cut-C

Ferrites are available in a wide variety of shapes. The figure illustrates some common configurations: Pot core, EE (or EI) core, Toroid, Cut-C, and EP core. Pot cores are often used when a high degree of magnetic shielding is desired. EP and EE (or EI) cores are commonly used as power transformers for switching regulators. Toroids are often used as pulse transformers or in applications which require a very low packaging profile.

Powdered iron cores are typically available as toroids and EE or EI cores. Toroids are especially popular in filter inductor applications. In high current applications, EE and EI cores are often used in DC chokes.

Core Material and Geometry Summary

The following table lists a number of common materials and gives general guidelines with respect to their applications.

Material	Relative Permeability (Curie Temp)	Perm @ 1 KG.	Typical Operating Frequency	Core Geometries	Application Information
Silicon Steel (Unoriented)	2000-20,000 (~730°C)	22	50 Hz to 1k Hz	EI, EE, UI, UU Laminations	.004 - .014 inch thick material. Primarily used in low frequency power from 60 -1000 Hz. Also useful in DC chokes, audio transformers, and power line AC inductors.
Silicon Steel (Oriented)	5000 (~730°C)	15-20	50 Hz to 1k Hz	EI, EE, UI, UU Laminations	.004 - .014 inch thick material. Used in low frequency power from 60 -1kHz. Used in DC chokes, audio transformers, power line inductors.
Silicion Steel (Oriented)	10,000 (~730°C)	13-18	50 Hz to 1 kHz *1

50 Hz to 30 kHz *2 | Cut C, Toroid, 3 Phase EE | .001-.012 inch thick material. Primarily used in low frequency power applications from 50 to 1000 Hz. .001 inch thick material sometimes is used for DC chokes at freq.up to 30 KHz. |
| Iron-Cobalt Supermendur | 30,000 (~940°C) | 23 | 50 Hz to 2 kHz *1
50 Hz to 30 kHz *2 | Cut C, 3 Phase EE, Toroid | .001-.004 in thick material. An expensive material that performs better than silicon steel (> Bsat, lower core losses). |
| Orthonol (50/50 NiFe) | 30,000 (~360-500°C) | 14-16 | 50 Hz to 10 kHz *1

50 Hz to 50 kHz *2 | Cut C, 3 Phase EE, Toroid | .0005-.004 inch thick material. A good material for low loss low frequency (50-5000 Hz) power transformers and saturable reactors, high performance audio transformers, high power pulse transformers, and DC chokes with a small AC flux (to 50 KHz). |
| Permalloy 80 | 70,000 (~450°C) | 7 | 400 Hz to 30 kHz *1

400 Hz to 100 kHz *2 | Cut C, 3 Phase EE, Toroid | .0005-.004 in thick material. An excellent material for power transformers and saturable reactors, high perf. audio and high power pulse transformers, and DC chokes with a modest AC flux (to 100kHz). |
Permalloy Powder	14-550 (~450°C)	5-10	10 kHz to 200 kHz	Toroid, EI, EE	Relative permeability varies as a function of the particular powder. Often used in EMI filters and switching regulator chokes.
Iron Powder	4-100 (~770°C)	10	100 kHz to 250 MHz	Toroid	Relative permeability varies from 4 - 100 as a function of the particular powder. Most often used in RF applications as EMI filters and high Q tuned circuits.
Ferrites	700 - 15,000 (~150-450°C)	2.5-4.5	1 kHz to 100 MHz	EE, EI, Pot, Toroid, PQ, EC, ETD, RM	Permeability varies as a function of material choice. Because of their very low core losses at high frequencies, Ferrites are the most common materials used in switching regulator power and drive transformers. Ferrite cores are often gapped and used in DC inductors and RF filters.

*1 High AC flux applications.
*2 High DC flux with a small AC flux superimposed.

Design Examples

Design Examples

A design using Magnetics Designer proceeds in four steps:

1. The desired Core family and material are selected using the Core screen.

2. The design requirements are entered using the Transformer and/or Inductor screen, depending on the type of device.

3. The Apply button is clicked, allowing Magnetics Designer to complete the design; i.e. selects the core geometry, number of turns, and wire sizes.

4. At this point, manual exploration and optimization of the design can be performed by trying different configurations, cores, materials, etc.

5. Output is generated in the form of a SPICE model or summary report.

The following design examples illustrate the basic capabilities of Magnetics Designer.

50 W Forward Converter Transformer

We will design a forward converter transformer, similar to that shown on the next page, in order to give 5 Vdc at 10 Adc. The minimum input voltage is 110 Vdc. The maximum duty cycle, which occurs at the 110 Vdc line voltage, is limited to 50%. To provide an average voltage of 5.5 Vdc (output + rectifier drop), the transformer secondary voltage must be 11 Vpk (Vo/duty) which, at 50 percent duty cycle, is 11 Vavg (i.e. the voltage is +11 V half of the time and -11 V the rest of the time). The transformer current is 10 amps when the output voltage is high and 0 amps when the output voltage is low. The DC component is therefore D x Ipeak = .5 x 10 = 5 Adc. The remaining current when the DC component is subtracted is a 10 Ap-p square wave which has a RMS value of 5 Arms. A forward converter has a flux swing which begins at Br and achieves a maximum value, Bmax. Therefore, the flux swing type is half wave. We will assume that the maximum desired temperature rise in still air is 50°C and that the maximum air temperature is 55°C. We will also assume that the converter operates at 40 kHz and that the maximum flux density is constrained to less than 3000 Gauss.

The basic transformer design specifications are summarized below:

Core Type = Pot core
Material type = F (Magnetics)
Max Temp. Rise = 50 degrees C
Amb. Temp. = 55 degrees C
Flux Type = Half Wave
Waveform = Pulse, D=50%,TR=2%
Output power = 55 Watts
Frequency = 40 kHz
Vpri = 110 V avg.
Idcpri = .5 A dc
Iacpri = .5 A rms
V(5v) = 11 V avg.
Idc(5v) = 5 A dc
Iac(5v) = 5 A rms
Bmax < 3000 Gauss

Forward Converter
(The flyback winding has been left out in order to simplify the example)

Vin = 110 Vdc

Np   Ns   5 Vdc

Nm
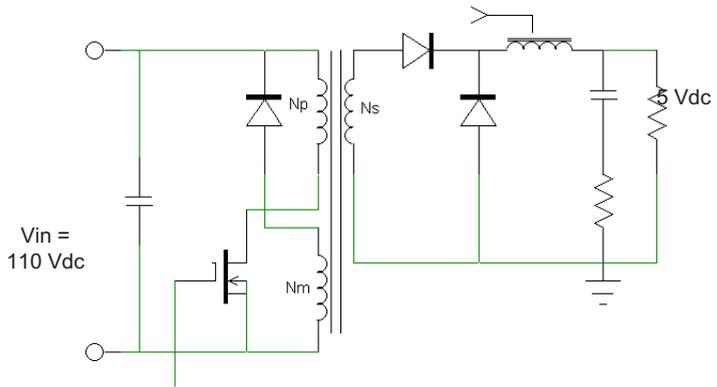
If Magnetics Designer is not already running, start Magnetics Designer by double-clicking on the program icon.

Magnetics Designer Program Icon

• Select the Pot Ferrite entry from the Core Family pop-up in the opening Core screen.

• Select Magnetics from the Vendor pop-up list.

• Select F-LF-100C (<100kHz, ≈100°C) from the material list.

Magnetics Designer (TM) - Design Info

Core | Bobbin | Transformer | Inductor | IsSpice | Options | Vendors | Wire

◉ Transformer   ○ Inductor

Family: POT   Ferrite   Material: 77_10100K_100C

Core Browser (Trise = 50 Deg. C)
Frequency: 0   Power: 0   Vendor: Fair-Rite
Auto Select   Geometry: 7mm x 4mm
☐ Lock Geometry

Core Material and Geometry Data

Vendor MAGNETICS	Br 1.850k	MPL 1.000	CoreWt 0.5000	Hw 0.1445
Material F-LF-100C	Bsat 3.450k	Ac 70.00m	Acmin 53.00m	Lw 0.2890
Mumax 2.500k	B1 1.800k	☑ Gap OK Min gap 450.0u		As 1.770

Pc = K p * B^n* f^m * vol
n 2.53   Kp 6.500f
m 1.19

Cost 0
Ap 2.923m
Vol 70.00m

ID 0.2950   MLT 1.381

Winding Shape
◉ Round
○ Square

Restore   Apply
Help   Close

- Change to the Transformer screen by clicking on the Transformer tab at the top of Design Info window.

The Transformer screen displays with several blank fields that we must fill in.

- Enter the operating frequency, 40K (40kHz), into the Frequency field in the center right of the screen.

- Select the Pulse entry in the Waveform pop-up under the Frequency field. This will force Magnetics Designer to calculate the increased AC losses due to the higher harmonic content in the square waveshape.

- Scroll down the User Data buttons in the upper right area of the Transformer screen and enter a value of 3k into the field beside the Bp(max) button.

- Click the Half Wave button in the Flux Swing area.

- Click the Add button in the far lower left corner of the Transformer screen to add a second winding.

- Place the mouse pointer over the "Volts Avg Specified" edit field (the three consecutive question marks) for winding number 1 and click the left mouse button.

- Enter the primary voltage of 110 (110 volts).

- Press the Tab key, then enter the AC current of .5 (.5 Arms). Press the Tab key, then enter the DC current of .5 (.5Adc).

- Similarly, repeat the previous 4 steps for the secondary winding specifications and enter values of 11 (11 Volts), 5 (5Arms AC current) and 5 (5A DC current), respectively.

- Enter the maximum allowed temperature rise, 50°C, in the Trise(max) field on the top right of the Transformer screen, if necessary.

- Click the Options tab to activate the Options screen. Enter an ambient temperature of 55 (55 °C), if necessary.

- Click on the Transformer tab.

- Click the Apply button.
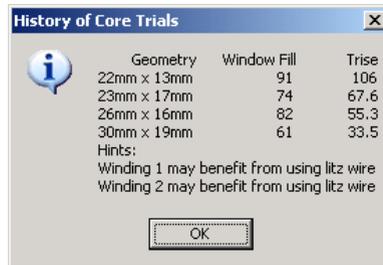
From the History of Core Trials dialog, you can see that Magnetics Designer tested 4 core geometries. The 30mm x 19mm core was able to yield a valid design with a temperature rise (Trise) of 33.5 degrees and a window fill of 61%.

- Click OK to dismiss the "History of Core Trials" dialog.

The following Transformer screen displays.

• Press "Apply using fields" to get a more accurate AC resistance calculation. Click on the Close button.
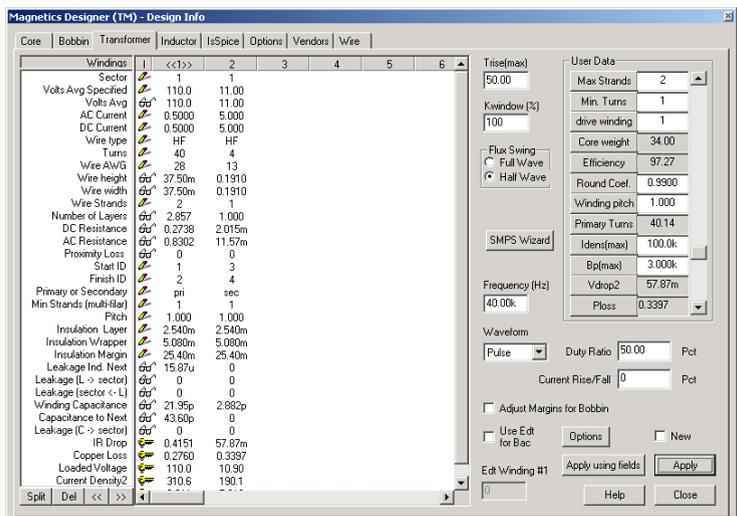
Trise is the first button in the User Data area; scroll up to see it.

The temperature rise is now 35.20 degrees, in good agreement with the first estimate. The winding spreadsheet area contains the data for the 30mm x 19mm core.

• Next select the Bobbin screen where you can view the geometry and the field distribution as shown in the next figure.
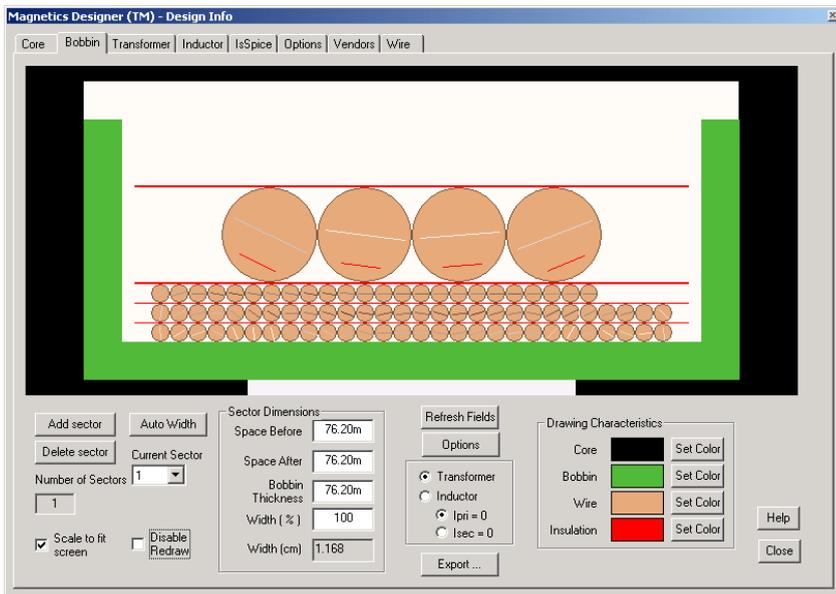
Examination of the data reveals that improvements can be made. For instance, the AC resistance is up to 3 times the DC resistance. Litz wire was suggested by Magnetics Designer in the "History of Core Trials" dialog.

• Click on the Transformer tab.

• Click in the Wire Type field ("HF") for winding 1 and select the Litz wire type.

- Similarly, select the Litz wire type for the secondary wind-ing.

- Next, switch to the core screen and check "Lock Geometry" so that the optimization will stay with this core. This allows us to easily see the affect of using Litz wire.

New and Apply are in the lower right of the Transformer screen.

- Return to the Transformer screen and check the New box.

- Click the Apply button.

Magnetics Designer will then perform its optimization using the same core.

- Click OK to dismiss the "History of Core Trials" dialog.

The following Transformer screen displays.

Magnetics Designer (TM) - Design Info								

Core | Bobbin | Transformer | Inductor | IsSpice | Options | Vendors | Wire |

Windings		1	<<2>>	3	4	5	6
Sector		1	1				
Volts Avg Specified		110.0	11.00				
Volts Avg		110.0	11.00				
AC Current		0.5000	5.000				
DC Current		0.5000	5.000				
Wire type		Litz	Litz				
Turns		60	6				
Wire AWG		29	19				
Wire height		43.80m	0.1320				
Wire width		43.80m	0.1320				
Wire Strands		2	2				
Number of Layers		5.000	2.000				
DC Resistance		0.5798	7.457m				
AC Resistance		0.5798	7.457m				
Proximity Loss		0	0				
Start ID		1	3				
Finish ID		2	4				
Primary or Secondary		pri	sec				
Min Strands (multi-filar)		1	1				
Pitch		1.000	1.000				
Insulation Layer		2.540m	2.540m				
Insulation Wrapper		5.080m	5.080m				
Insulation Margin		25.40m	25.40m				
Leakage Ind. Next		59.15u	0				
Leakage (L -> sector)		0	0				
Leakage (sector <- L)		0	0				
Winding Capacitance		13.25p	17.60p				
Capacitance to Next		33.80p	0				
Leakage (C -> sector)		0	0				
IR Drop		0.2899	37.28m				
Copper Loss		0.2899	0.3728				
Loaded Voltage		110.0	10.93				
Current Density2		386.4	382.8				

Split | Del | << | >> |

Trise(max)
50.00

Kwindow (%)
100

Flux Swing
○ Full Wave
● Half Wave

SMPS Wizard

Frequency (Hz)
40.00k

Waveform
Pulse ▾   Duty Ratio 50.00   Pct

Current Rise/Fall 0   Pct

☐ Adjust Margins for Bobbin

☐ Use Edt for Bac   Options   ☐ New

Edt Winding #1   Apply using fields   Apply
0   Help   Close

User Data

Trise	21.84
Winding fill %	96.62
Tlevel	0
Total Weight	95.29m
Copper Loss	0.6627
Core Loss	0.3171
Bac(max)	100.0k
Bac	842.5
Output Power	55.00
Calculator	4.000
Gap	3.783
Lmag	-2.012u

The temperature rise was reduced, but only by about 34%. Generally speaking, this is too little gain for using Litz wire;

however, in this case if the core had been free to be chosen, the next smaller core would have been selected. Perhaps this would have convinced you to specify Litz wire in your design. Or, you could have reduced the rise time and bobbin thickness and used the smaller core with HF wire. You could also have tried foil for the low voltage winding, again dropping the core size but increasing cost. It turns out that there are many design variations that are very close to the optimization selected by Magnetics Designer, especially when multiple strands are used. The tendency to use less wire than will fill the bobbin is counter-intuitive to experience at low frequencies. Bobbins will be under-filled when wire size reduction actually reduces the AC resistance. Using multiple strands tends to offset this, but again, the complexity and cost increases.

To view a summary report of the design:

•   Select the "Design Info" menu item in the View menu.

This will turn off the Design info screen so that you can see the main Magnetics Designer report window.

•   Select the Transformer Summary function from the Reports menu. You may have to stretch the window or scroll down to see the entire contents of the report.
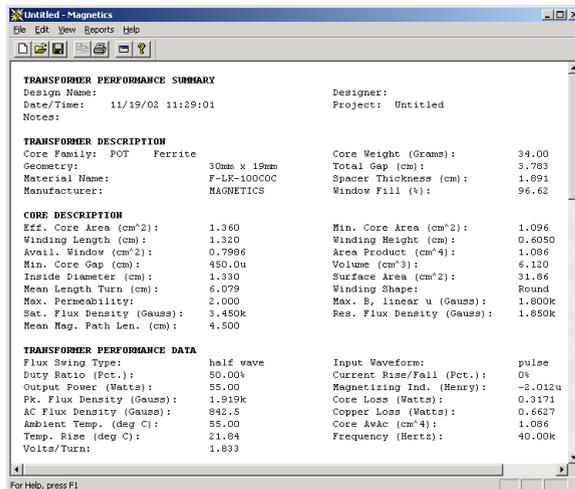
You can print the report or save it to disk by selecting the "Print Report..." or "Save Report..." function, respectively, from the File menu.

•	Select the "Design Info" menu item in the View menu.

Next, let's revise the design, placing the primary and secondary winding on adjacent sectors. This will give excellent isolation between the high voltage primary and low voltage secondary. Moreover, the EMI injection from the switching on the primary will be reduced by more than an order of magnitude. To wind on multiple sectors, you must first switch to the Bobbin tab and define the sectors.

•	Click on the Bobbin tab.

•	Click "Add sector" to get a new sector.

•	Click "Auto Width" to divide the bobbin into 2 equal parts.

The remaining settings were adjusted after a preliminary design was made to distribute the copper between the windings.

•	To speed things up, enter the width for the new sector as 45% and switch the current sector to 1 using the "Current Sector" pop-up list box.

•	Then make the sector 1 width 55% and enter 10m in the "Space After" data field.

The transformer will draw itself into the first sector. If this redraw is annoying or takes too long, it can be disabled by checking the "Disable Redraw" check box. The units option for these entries was set to inches in the Options screen.
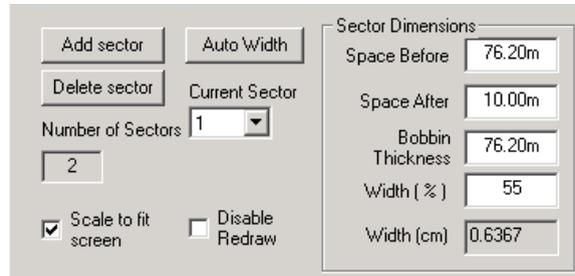
		Sector Dimensions	
Add sector	Auto Width	Space Before	76.20m
Delete sector	Current Sector	Space After	10.00m
Number of Sectors 1 ▼		Bobbin Thickness	76.20m
2		Width (%)	55
☑ Scale to fit screen	☐ Disable Redraw	Width (cm)	0.6367

- Now switch back to the Transformer screen and enter 2 for the sector in the second winding.

- Check New and click the Apply button.

- Click OK to dismiss the "History of Core Trials" dialog.

- Switch back to the Bobbin screen.

You can see that the secondary overfilled the bobbin. This happened because of the large wire.

- Return to the Transformer screen and enter 3 in the "Min strands (multi-filar) row for the second winding.

- Check New and click the Apply button.

- Click OK to dismiss the "History of Core Trials" dialog.

- Select the Bobbin tab.

The windings will then fit nicely. Notice that the leakage inductance between sectors is high enough so that a catch winding will be needed in order to limit the voltage across the switching transistor while that leakage inductance charges. The coupling between the catch winding and the primary can be maximized by sandwiching the catch primary inside the primary. To accomplish this, we need to split the primary. Here's how it works:

- Select the Transformer tab.

- Check New and click the Add button at the far lower left.

- Enter 110 for "Volts Avg Specified" and 0 for the AC current.

If you want, you can run a simulation at a later time and insert actual AC and DC currents into the design.

- Then uncheck the New check box and select the first winding by clicking on the first row data field for winding 1.

- Press "Ctrl+Split".

The Split button in the far lower left corner of the Transformer screen changes to "Add" when the New check box is checked.

This will split the first winding into 2 series parts. Next, we'll rearrange the windings.

- Select winding 2 by clicking on the first column data field entry for winding 2.

- Click the ">>" button (to the right of the Split button) twice in order to move winding 2 to the last (4th) position.

- Enter 15m Insulation Wrapper values for windings 1 and 2 so that the catch winding will be able to withstand the voltage stress.

- Enter 5m Insulation Wrapper values for windings 3 and 4.

- Set all Insulation Margin values to 10m (as necessary) and set all of the Insulation Layer values to 5m (as necessary).

- Check the "Adjust Margins for Bobbin" box.

- Check New and click the Apply button.

- Click OK to dismiss the "History of Core Trials" dialog.

- Press the "Apply using fields" button. Then click on the Close button.
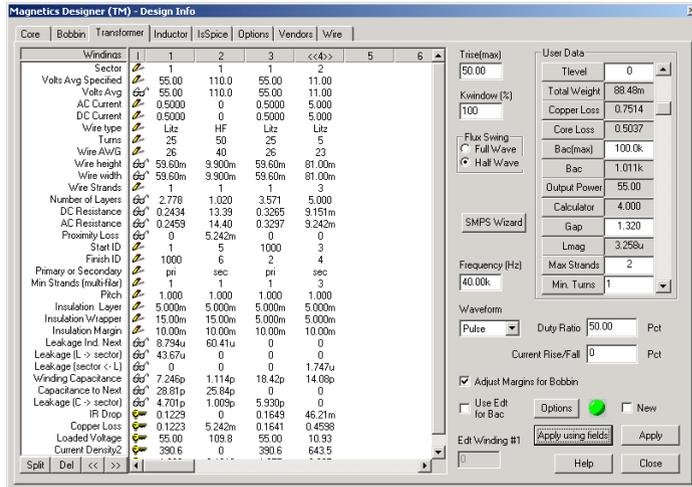
• Select the Bobbin tab.

The Bobbin screen shows the field distribution. These distributions are difficult to predict without performing the field simulation so the temperature rise prediction is less accurate than what we achieved using the barrel wound version of this design. Notice that the dissipation is higher in the high field regions near the center of the stack.
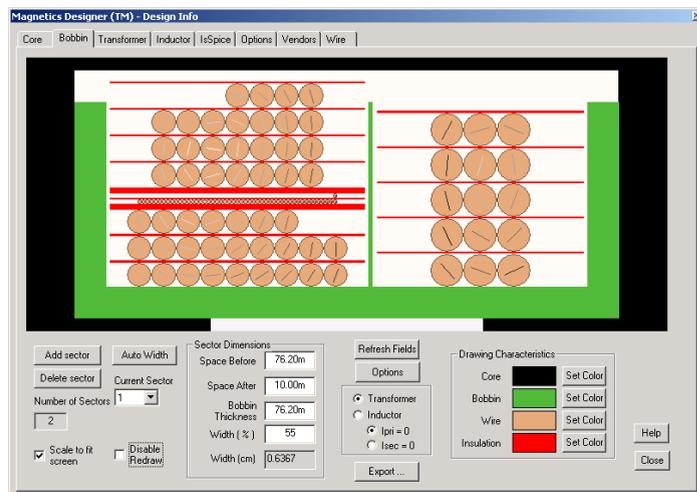
50uH Filter Inductor

In this example, we will design a filter inductor to be used with the forward converter example. It will have the following characteristics:

Core Type	**= Pot**
Material type	**= 77_10100K-100C**
Max Temp. Rise	**= 50 °C**
Max. Amb. Temp.	**= 25 °C**
Frequency	**=40 kHz**
Minimum Inductance	**= 50uH**
Peak Current (non-saturation)	**= 8A**
RMS AC Current	**= 2A**
Steady State DC Current	**= 5A**
Avg AC voltage @ 40Khz	**= 24V**

From the above specifications, the volt-seconds (Edt) can be calculated as follows:

$$Edt = \frac{V_{ave}}{2f} = \frac{24}{2*40k} = 300u$$

Now that all of the required data is known, we can begin the example by launching Magnetics Designer (if it isn't already running). If Magnetics Designer is already running, select the New function from Magnetics Designer's File menu. Then select the Core screen by clicking on the Core tab.

• Select Pot Ferrite in the Family list box on the Core screen.

The default Pot Ferrite core is: 77_10100K_100C Fair-Rite 7mm x 4mm

When you launch Magnetics Designer, the material vendor and material will be set to the correct values by default.

• Click the Inductor tab to activate the Inductor screen.

• Enter the design frequency, 40K (40kHz), in the Frequency field located at the center right of the Inductor screen.

• Select the Pulse option in the Waveform drop-down list below the Frequency field.

- Enter a value of 300u for the maximum Edt (as calculated above) into the "Edt Winding #1" field which is located below the Frequency field, near the bottom of the Inductor screen.

- Select the data field (3 question marks) beside the "Current Pk Specified" field for winding 1 and enter a peak current value of 8 (8 Apk).

- Press the Tab key and enter 2 for the AC Current. Press the Tab key and enter the DC Current of 5A. Press the Tab key and enter the minimum desired inductance of 50u.

- Enter the desired maximum temperature rise of 50 (if necessary) into the "Trise (max)" field located in the upper right of the Inductor screen.

- Click on the Options tab to activate the Options screen.

- Change the Ambient temperature to 25 (25 degrees C).

- Click on the Inductor tab to reactivate the Inductor screen.

We are now ready to make the first design pass for our choke.

- Click the Apply button.

Magnetics Designer will display the "History of Core Trials" dialog, shown below, with the results of the optimizations.
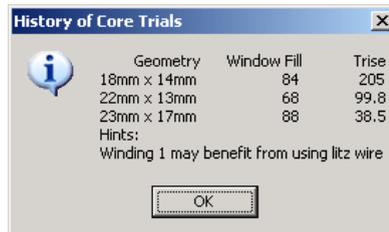
From this dialog, we can see that the MC1169 geometry will fulfill our requirements. However, Magnetics Designer has determined that the use of Litz wire may provide better characteristics.

- Click OK to dismiss the "History of Core Trials" dialog.

The inductor data for the 50uH choke we are designing is shown below.

- Press "Apply using fields" to confirm the temperature rise, and then click on the Close button.
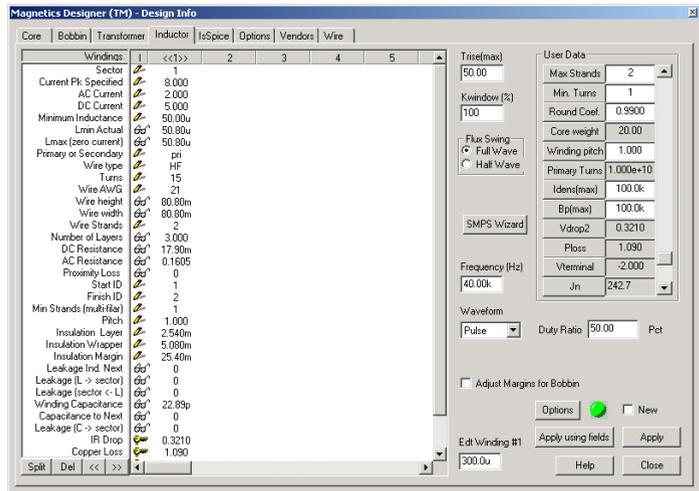
- Click on the Bobbin tab.
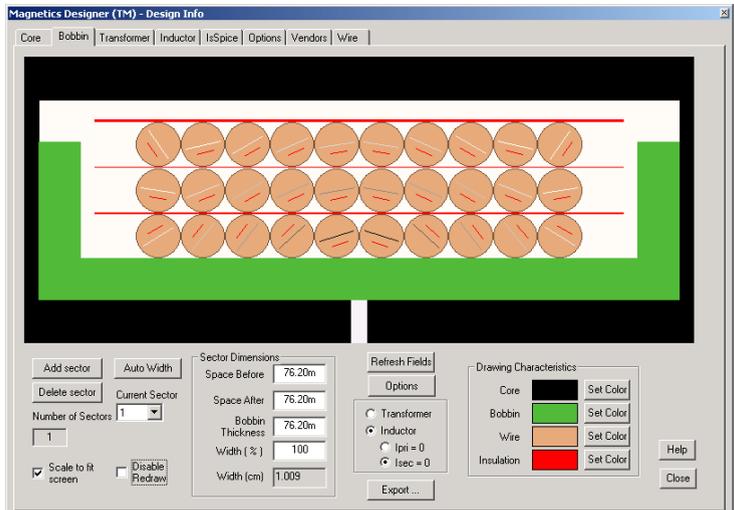
Note that for this case, the bobbin thickness was set to 76.2mils. You can experiment with different bobbin thicknesses and also set the gap coefficient to 1.0 in the Options dialog.

- Select the Inductor tab and then click on the Options button.
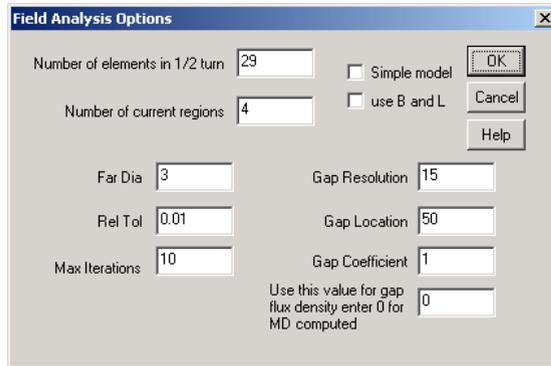
- Set the Gap Coefficient to 1.0 and click OK.

- Press "Apply using fields" in order to have the correct gap loss calculated.

- Click the Close button. View the Bobbin tab and the Inductor tab.

Notice that for a single center-leg gap and a reduced bobbin thickness, the temperature rise increases substantially and the high field strength is near the gap.

As we can see, the computed design met all of our requirements. The inductance is correct, the temperature rise is acceptable, and the window fill is acceptable. However, we may want to determine if the peak flux density will be less than the material saturated flux density (3.8 kilogauss).

We can do this by using the User Data fields to examine the internal Bpk variable which was calculated for this design.

- Scroll down the User Data buttons until the Calculator button is visible.
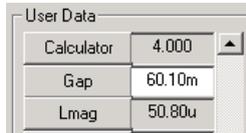
- Click on the Calculator button to activate the User Button dialog.

- Delete the "2+2" equation in the "Equation" field.

- Using the Variable list box at the top of the dialog, select the "Bpk peak flux density" variable.
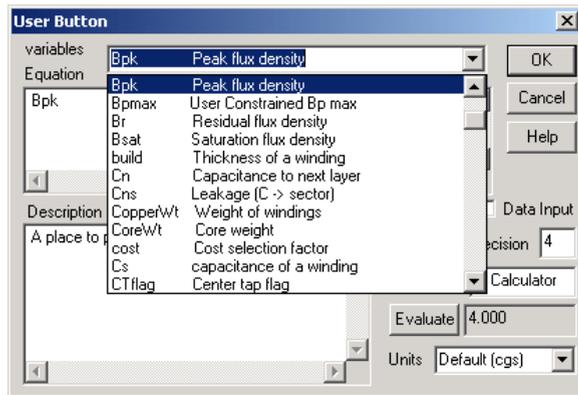
The variable will automatically be entered into the "Equation" field.
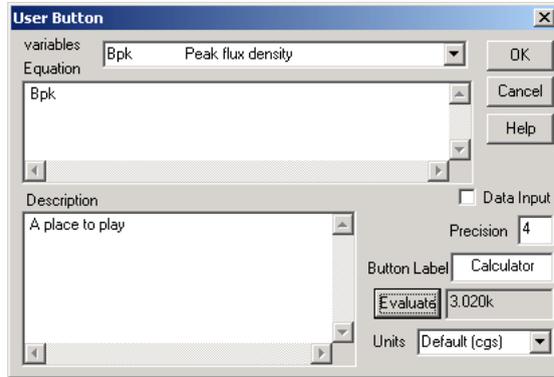
• Click the Evaluate button and click on OK.

The peak flux density of this inductor is calculated as 3.020KGauss (as shown in the Inductor Screen's User Data Calculator field to the right). This is below the 3.8KGauss saturation of the material, and is therefore acceptable.

228
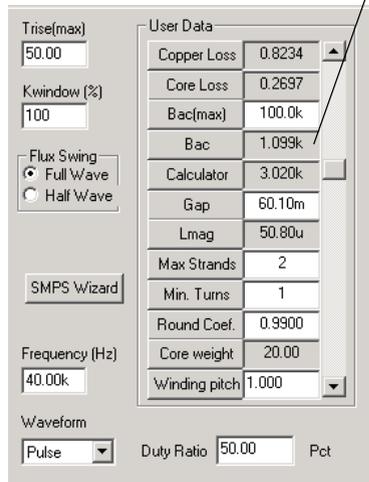
Appendices

Appendices

Appendix A - Waveform Formulas contains equations that will help you calculate the RMS current, DC current, and AC RMS current for the waveforms that you are using in your design. The formulas are quite useful and will help you generate the values required by Magnetics Designer.

Appendix B - Parameter Definitions and User Data Variables contains the terms and definitions used throughout this book.

Appendix C - Key Equations provides a summary reference of all the key equations used in this book.

Appendix D - References provides a list of the referenced papers, as well as a list of additional publications that discuss related topics.

Appendix A - Waveform Formulas
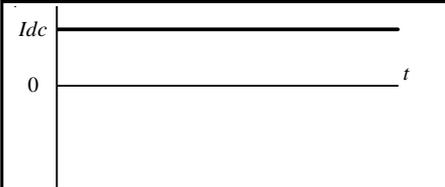
Waveform	Irms	Idc	Iac(rms)
	Idc	Idc	0
	Ip	0	Ip
	$Ip\sqrt{D}$	DIp	$Ip\sqrt{D(1-D)}$
	$Ip\sqrt{D}$	0	$Ip\sqrt{D}$
	$Ip\sqrt{\dfrac{1}{3}}$	0	$Ip\sqrt{\dfrac{1}{3}}$
	$Ip\sqrt{\dfrac{1}{3}}$	0	$Ip\sqrt{\dfrac{1}{3}}$
	$Ip\sqrt{\dfrac{D}{3}}$	$\dfrac{D}{2}Ip$	$Ip\sqrt{\dfrac{D}{3}\left(1-\dfrac{3}{4}D\right)}$
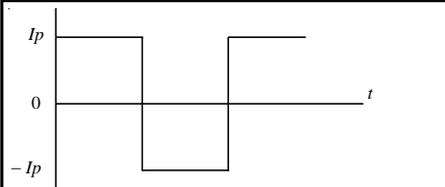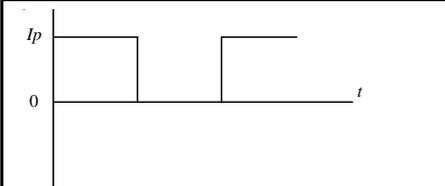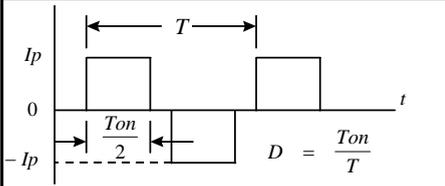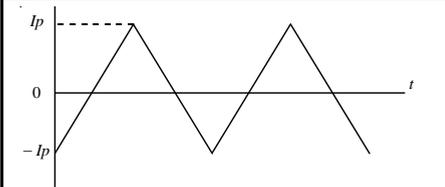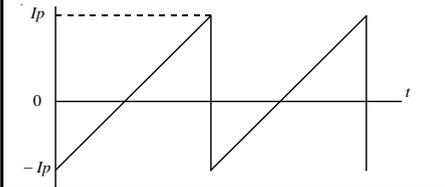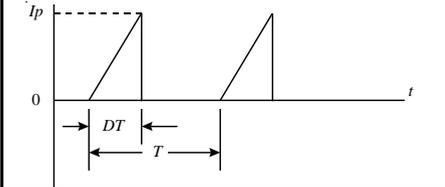
Appendix A - Waveform Formulas
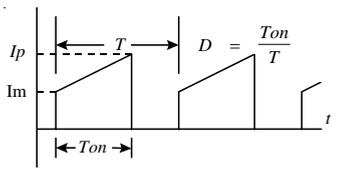
Waveform	Irms	Idc	Iac(rms)
	$\sqrt{D\left(Ip \times Im + \frac{1}{3}(Ip - Im)^2\right)}$	$\dfrac{D(Ip + Im)}{2}$	$\sqrt{Irms^2 - Idc^2}$
	$\sqrt{D\left(Ip \times Im + \frac{1}{3}(Ip - Im)^2\right)}$	0	$\sqrt{D\left(Ip \times Im + \frac{1}{3}(Ip - Im)^2\right)}$
	$\dfrac{Ip}{\sqrt{2}}$	0	$\dfrac{Ip}{\sqrt{2}}$
	$\sqrt{Idc^2 + \frac{1}{2}Ip^2}$	Idc	$\dfrac{Ip}{\sqrt{2}}$
	$\dfrac{Ip}{\sqrt{2}}$	$\dfrac{2}{\pi}Ip$	$Ip\sqrt{\dfrac{1}{2} - \dfrac{4}{\pi^2}}$
	$Ip\sqrt{\dfrac{D}{2}}$	$\dfrac{2\,D\,Ip}{\pi}$	$Ip\sqrt{\dfrac{D}{2} - \left(\dfrac{2D}{\pi}\right)^2}$
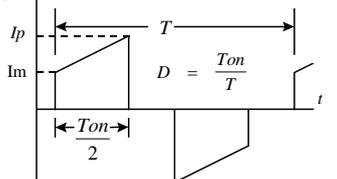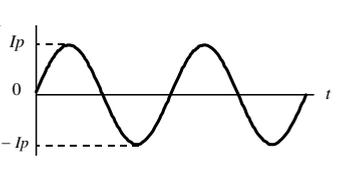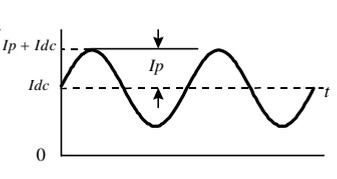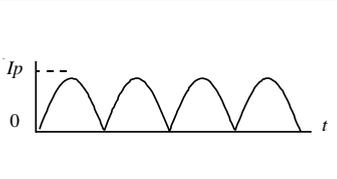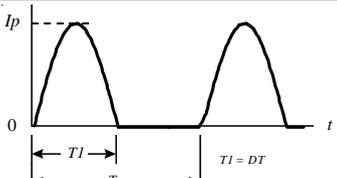
Appendix B - Parameter Definitions and User Data Variables

The following parameters are used throughout this manual. In some cases, there are two names for the same parameter.

Parameter Name   Description   cgs units

Abob   Bobbin area   cm²
The total available winding space.

Ac   Mean core cross-sectional area   cm2
The effective area of a core. This parameter is used to calculate the flux density magnitude used in the core loss equation.

Aj   Window area   cm²
The window area used by the jth winding.

Ak   Cross-sectional area   cm²
The cross-sectional area of the kth element in a magnetic path.

Amin/Acmin   Minimum core area   cm²
The smallest cross-sectional area of the core, typically the center leg. The program uses this area to determine the maximum acceptable operating flux density to avoid saturation.

Ar   Rectangular window area   cm²
The rectangular window area consumed by one turn of a given wire type.

Asurf/As   Surface area   cm²
The surface area of a magnetic component which is available for convection cooling. The finished inductor surface area in square centimeters.

Aw   Bobbin window   cm²
The usable part of the bobbin window.

AwAc/Ap   **Effective core area**   cm^4

The area product of effective core area and usable window area. The quantity used to rate the relative power handling capability of an inductor.

AwAc1   **Area product**   cm^4

The area product. core loss limited case.

AwAc2   **Area product**   cm^4

The area product. Bsat limited case.

AWG   **Wire gauge**

A system used for rating wire size. AWG stands for American Wire Gauge. A larger number indicates smaller cross-sectional area. Also used as a relative measure of wire size for none AWG wire types.

B   **Flux density**   Gauss

The flux density value.

B1/Bmax   **Max B where µ is linear**   Gauss

The maximum flux density where the permeability remains linear. Above this level, the permeability begins to decrease significantly.

Bac   **Peak flux density**   Gauss

The peak value of the AC component of flux as a function of the effective core area.

Bacmax   **Maximum Bac**   Gauss

The user constrained peak value of the AC component of flux as a function of the effective core area.

Bpk   **Peak flux density**   Gauss

The maximum value of flux density including any DC offset caused by DC currents in the windings. This parameter is the larger of the peak flux excursion due to the AC flux density or the peak flux which results from the sum of the peak ampere-turns of all of the windings.

Bpmax   **Maximum Bpk**   **Gauss**
The user constrained maximum value of flux density including any DC offset caused by DC currents in the windings. This parameter is the larger of the peak flux excursion due to the AC flux density or the peak flux which results from the sum of the peak ampere-turns of all of the windings.

Br   **Residual flux density**   **Gauss**
The residual flux density. After being driven into saturation, the flux returns to Br when the magnetizing force (H) is zero.

Bsat   **Saturated flux density**   **Gauss**
The value of flux density where the permeability, and thus the inductance, drops off rapidly.

Build
The height of the bobbin used by one or more windings.

build   **Winding Height**   **cm**
The height of the winding.

Center Tap
A connection point where two identical windings can be connected together such that the voltage at ends of the windings are equal but have opposite polarity.

Cn   **Capacitance to next layer**   **Farads**
The capacitance to the next layer.

Cns   **Capacitance to sector**   **Farads**
The capacitance to the next sector.

Copper Loss   **Total copper power loss**   **cgs**
The total copper power loss for all windings.

CopperWt   **Copper weight**   **grams**
The weight of the copper used in the design.

CoreWt   **Core weight**   **grams**
The weight of the core used in the design.

Cost
A selection factor used to eliminate a core from the automatic selection algorithm. A value of 1 removes the core's eligibility. The default is 0.

Cs   **Layer capacitance**   **Farads**
The capacitance between two layers.

CTflag   **Center tap flag**
Obsolete

dB   **Flux density rate**   **Gauss**
A change in the flux density.

Dp   **Penetration depth**   **cm**
The penetration depth.

drivenWinding   **Driven winding**   **integer**
The winding for which the specified voltage equals the calculated voltage.

Dsq   **Double square wire**
Double-square magnet wire is equivalent to two square wires laying side by side. Therefore, one 16 AWG DS wire has the same cross-sectional area as two 16 AWG SQ wires.

e   **Instantaneous voltage**   **Volts**
The instantaneous voltage across an inductor or transformer winding.

Edt   **Volt-seconds**
The volt-seconds applied to a winding in one polarity over a full cycle. For example, if 30 volts were applied to a winding for 10 microseconds, then Edt is 300×10^{-6} volt-seconds.

f   **Operating Frequency**   **Hz**
The operating (fundamental) frequency.

Fl   **Winding breadth**
The fraction of the winding breadth occupied by conductor material.

Foil   **Foil**
A thin copper strip approximately equal to the width of the Bobbin window. The thickness varies as a function of the desired resistance and available window area. The foil is wound simultaneously with a layer of insulation so that consecutive turns do not short together.

FlagFlux   **Flux swing flag**
A flag which is used to determine if the flux swing is set to half or full wave. The default is 0 (half wave). A value of 1 is used for full wave.

Fr   **Rac/Rdc**
The ratio of high frequency AC resistance to DC resistance.

gap   **Core gap**   **cm**
The round trip gap length associated with either a ground center post or spacers. If the center post has been machined to create an air gap, the core gap is equal to the length of the air gap. If spacers are used, the gap length is equal to 2 times the thickness of the spacer.

GapOK   **Gap flag**
A flag which indicates whether or not the core gap can be adjusted. A value of 1 indicates that the gap can be adjusted.

GetGauge   **Function**
This function returns the wire gauge. Its arguments are area and winding number. The winding number is used to determine the wire type.

gmin   **Minimum gap**   **cm**
This is the minimum value that the gap can have.

gName   **Function**
This function returns the name of the geometry that is currently selected.

h   **Effective thickness**   **cm**
The effective thickness of a layer. For foil or rectangular wire, it is the thickness of the conductor. For round wire, h = $\pi/4$.

H   **Magnetic field intensity**   **Oersteds**
The magnetizing force.

HF   **Heavy Formvar wire**
This is copper magnet wire doubly insulated with a synthetic film.

Hw   **Bobbin height**   **cm**
The height of the window from the inside of the first layer to outside of the last layer.

Iac   **RMS current**   **Amps**
The RMS AC component of current in a winding after the DC component has been subtracted. For a square wave current, the AC RMS current is the peak to peak current divided by 2. For sine wave current, Irms is equal to .707 times the peak current.

Iavg   **Average current**   **Amps**
The average AC component of current in a winding.

ID   **Bobbin inside diameter**   **cm**
For round center post type bobbins, this parameter is the diameter of the coil form. That is, it is the diameter of the tube upon which the first layer of wire is wound. For rectangular center post cores, such as E cores, the inside diameter is the length of one turn on the first layer divided by 4.

Idc   **DC current**   **Amps**
The DC component of current in a given winding. i.e. the average value of the waveform over a complete cycle.

Interleaved Windings
These are windings in which the primary is split into two sections (either series or parallel connected). One section is wound first and then the secondaries are wound. The other section of primary is wound last. Interleaving reduces AC resistance and leakage inductance.

Ipk   **Peak current**   **Amps**
The highest possible peak value of current. Ipk is usually larger than Idc + Iac. Use Ipk to specify the maximum current for which the inductor must not saturate. Failure to correctly specify Ipk may result in a design which will saturate at an unacceptably low current.

IR Drop   **Total voltage drop**   **Volts**
The total voltage drop for all windings.

IRMS   **RMS current**   **Amps**
The effective heating value of current. i.e. RMS current.

isPrimary   **Function**
This function returns a 1 if the winding is on the primary. The usage is isPrimary(winding).

isSecondary   **Function**
This function returns a 1 if the winding is on the secondary. The usage is isSecondary(winding).

J   **Current density**   **Amps/cm²**
The current flowing in a conductor divided by the cross-sectional area of the conductor.

Jmax   **Maximum current density** **Amps/cm²**
The user constrained maximum current density.

Jn   **Current density**   **Amps/cm²**
The current density for each winding.

Jopt   **Optimum current density**   **Amps/cm²**
The optimum current density for a given design.

K   **Boltzmann's constant**   **Joules/Deg K**

 Boltzmann's constant.

Kac_dc   **Ratio of Rac/Rdc**   **real**
The ratio of AC resistance to DC resistance.

Kcond   **Conduction constant   Watt cm-degC**
The conduction constant. Default is 1.108x 103.

Kconv   **Convection constant   cm²/watt degC**
The convection constant. Default is 710.

Kd   Relative dielectric constant of insulation
The relative dielectric constant of insulation.

Kf   Maximum winding percent factor
The user constrained winding percent factor.

Kfill   **Winding Fill**
This value indicates the window fill percentage. The algorithm calculates the build of all the windings and their respective insulation. Since a fractional layer is counted as a full layer in the build algorithm, it is desirable to replace large wires with 2 or 3 smaller wires when a winding uses only a small fraction of one layer.

Kgap   **Function**
This function returns the gap fringing factor. The usage is Kgap(gap) where gap is the size of the gap.

Kins   **Insulation constant   watt/cm-degC**
The insulation thermal coefficient.

Kp   **Multiplier   Watt-sec^m/cm²Gauss^n**
The core loss constant derived from the magnetic material data sheet. Used in the core loss equation.

Kr   **Resistivity   Ohm-cm²/cm**
The resistivity of a conductive material.

Kround   **Rounding coefficient**
This parameter is equivalent to the round coefficient value.

Kw   **Window utilization factor**
The window fill factor with respect to wire packing. It is equal to the available winding area divided by the usable area. Typically .8 to .95 as a function of wire type.

Kwire   **Wire utilization factor**

The ratio of bare copper diameter to wire diameter for a given wire type. Also computed as the bare copper area divided by the window area consumed by 1 turn. Typically .5 to .9.

l   **Magnetic path length**   **cm**

The magnetic path length.

lc   **Effective magnetic path length**   **cm**

The effective magnetic path length of the core.

lg   **Length of a gap**   **cm**

The length of the gap.

Litz   **Litz wire**

Multi-stranded twisted magnet wire which is used in high frequency applications in order to reduce the AC resistance.

Lj   **Inductance**   **Henry**

The inductance of the jth winding.

lk   **Magnetic path length**   **cm**

The length of the kth element in a magnetic path.

Lmag   **Magnetizing inductance**   **Henry**

The open circuit parallel inductance measured across the primary winding.

Lmax   **Maximum inductance**   **Henry**

The inductance value at zero current.

Lmin   **Minimum inductance**   **Henry**

The inductance value at saturation.

Ln   **Layer leakage inductance**   **Henry**

The leakage inductance to the next layer.

Lnom   **Nominal inductance**   **Henry**

The inductance value at saturation (peak current).

Lns   Next sector leakage inductance   Henry
The leakage inductance to the next sector.

Loaded Voltage   Loaded voltage   Volts
Voltage drops from both primary and secondary are reflected to the secondary, assuming winding 0 is a primary.

Lp   Primary inductance   Henry
The inductance of the primary winding.

Lps   Previous sector leakage inductance   Henry
The leakage inductance to the previous sector.

Lw   Bobbin length   cm
The length from one end of a bobbin or coil form to the other end.

m   Core loss exponent   real
The material specific exponent of f in the core loss equation.

min gap   Minimum core gap   cm
When two machined surfaces are pressed together, a finite air gap remains between them due to surface roughness. Typically, the effective gap length for ferrite cores is .0005 cm.

Min. strands   Minimum strands
The smallest number of strands that Magnetics Designer will allow for the winding.

Min. Turns   Minimum turns
The smallest number of turns that Magnetics Designer will allow for the winding.

MLT   Mean length per turn for a conductor   cm
The mean length per turn of a bobbin which is completely filled with wire.

MLTj   Mean length per turn, winding j   cm
The mean length per turn for the jth winding.

MPL   **Magnetic path length**   **cm**
The average round trip distance around a closed path through the core.

mueff   **Effective permeability**   **real**
The effective permeability of the transformer/inductor, including the gap.

muMax   **Maximum permeability**   **real**
The maximum permeability of the material.

musat   **Saturation permeability**   **real**
The permeability value at saturation.

n   **AC resistance parameter**   **real**
The material specific exponent of Bac in the core loss equation.

N   **Number of turns**
The number of turns of wire for the given magnetic device.

NextAwg   **Function**   **integer**
This function returns the AWG value; its arguments (awg,winding) It uses the windng number to determine the wire type.

NL   **Function**
This function returns the number of layers in a particular winding. The usage is NL(winding).

Nmax   **Maximum number of windings**   **integer**
The maximum number of windings in the design.

Np   **Number of turns on the primary**
The number of turns of wire for the primary winding.

Ns   **Function**
This function returns the number of strands in a particular winding. The usage is Ns(winding).

Nsmax   **Maximum number of strands**
This parameter returns the value listed in the Max Strand User Data field.

p   **Number of layers**

The effective number of layers in a winding or winding portion.

Pcore   **Core power loss**   **Watts**

The power dissipated in the core due to hysteresis and eddy current losses in the magnetic material when an AC flux is applied.

Pcore(ΔT)   **Core power loss**   **Watts**

The optimum core loss for a specific temperature rise.

Pcu   **Copper power loss**   **Watts**

The power dissipated in the wire due to current flowing through the wire.

Pcu(ΔT)   **Copper power loss**   **Watts**

The optimum copper loss for a specific temperature rise.

Pi   **Value of Pi**

The value of Pi.

Pin   **Input Power**   **VA**

The input power.

pitch   **Winding Angle**   **Wire Widths**

The angle at which wire is wound, in wire widths. This subtracts the width of a wire times the pitch value from the space available for a winding if there is more than one turn. Defaults to 0. Pitch may be any real number.

Pitch   **Winding Pitch**   **Real**

The pitch is the wire height per turn that the winding advances along the length of the bobbin. Single windings are defined to have 0 pitch.

prevAwg   **Function**

This function returns the Awg value of the previous winding.

proxLoss   **Proximity loss**   **Watts**
The proximity loss value.

Ptot   **Total power loss**   **Watts**
The sum total of copper and core losses.

Pwndg   **Winding power loss**   **Watts**
The power dissipation in a single winding.

Q   **AC to DC resistance**
A calculated parameter which is used to calculate Fr.

r   **Core loss/copper loss**
The optimum ratio of core loss to copper loss which results in the minimum total loss.

R   **Reluctance**   **Amp-turns/Maxwell**
The reluctance of the magnetic path.

Rac   **AC resistance of a winding**   **Ohms**
The resistance of a winding at the operating frequency. Rac includes both skin and proximity effects.

Rdc   **DC resistance of a winding**   **Ohms**
The DC resistance of a given winding.

rho   **Resistivity**   **Ohm-cm**
The resistivity of the material.

rhoTC **Temperature coefficient of resistivity**   **Ohm-cm/Deg C**
The temperature coefficient of resistivity of the material.

s   **Interleave flag**
If windings are interleaved and a fractional layer is calculated, s=0.5; otherwise, s = 0.

sd   **skin depth**   **cm**
The depth of current penetration in a conductor at a given frequency.

sectors　　　　　　**Sector number**
The sector number, starting with 0.

SF　　　　　　**Small Formvar wire**
Copper magnet wire singly insulated with a synthetic film.

Shield, Electrostatic
A one turn foil winding having a single connection lead which is used to electrostatically decouple a secondary winding from the primary. To provide better isolation of ground return currents, two shields are often used with one being referenced to the primary return and the other referenced to the secondary return.

Sq　　　　　　**Square wire**
Square magnet wire which is doubly insulated with a heavy synthetic film. Since one side of a square wire is the same as the diameter of a corresponding round wire, the square wire has slightly more cross-sectional area.

Tamb　　　　　　**Ambient temperature**　　　**Degrees C**
The temperature of the air surrounding the inductor.

Tleadflag　　　　　　**Thermal flag**
The flag for copper hot spot calculation.

Tlevel　　　　　　**Thermal flag**
The flag which is used to determine the thermal model that Magnetics Designer will use to calculate the temperature rise. (See the *Thermal Models* section).

th　　　　　　**Winding height**　　　　　　**cm**
The height of the winding.

thtot　　　　　　**Total winding height**　　　**cm**
The sum of the height of all windings.

ti　　　　　　**Insulation between layers**　**cm**
The thickness of the insulation between layers.

tm   **Insulation at ends**   **cm**
This corresponds to the insulation margin value.

Tj   **Turns ratio**
The turns ratio from the jth secondary winding to the primary winding (Nj/Np).

Tlevel   **Thermal model selection**
integer
A flag that selects the thermal model level (0,1,2).

Trise   **Temperature rise**   **Degrees C**
The difference between the temperature at the surface of the core and the temperature of the surrounding air.

TriseMax   **Max. temperature rise**   **Degrees C**
The maximum allowed temperature rise specified by the user.

tw   **Insulation between windings**   **cm**
The insulation wrapper thickness value.

useEdt   **Flag**
When this flag is set, Edt is used in the calculation of Bac for transformers. This is used for Mag-amps to specify the standoff or blocking volt-seconds using the Edt field in the transformer screen.

Vavg   **Average voltage**   **Volts**
The average voltage across a winding. As used in this manual, the average voltage of a complex waveform is the voltage which if applied for a half cycle of the specified frequency results in the same change in flux as the more complex waveform. In equation form, where fsw is the switching frequency and is the integral of the voltage with respect to time over one cycle in one polarity.

Vol   **Core volume**   **cm^3**
The effective volume of the core if the loss equation is expressed in watts per cm^3 or the core weight in grams if the core loss equation is expressed in watts per gram.

Vspec **Volts specified** **Volts**
The specified Volts value shown in the Transformer/Inductor spreadsheet.

wireArea **Function** **cm**
This function returns the wire area of the named winding. The usage is wireArea(winding).

wireHeight **Function**
This function returns the wire height of the named winding. The usage is wireHeight(winding).

wireHeightx **Effective wire height** **cm**
The effective wire height of the winding.

wireWidth **Function** **cm**
This function returns the wire width of the named winding. The usage is wireWidth(winding).

wShape **Winding Shape**
The winding shape parameter. A value of 0 is used for a square shape, 1 is used for a round shape.

ΔT **Surface temperature rise** **Degrees C**
The temperature rise of the material in still air.

μ **Relative permeability**
The ratio of the permeability of a magnetic material to the permeability of free space.

μc **Relative permeability**
The relative permeability of the core material.

μk **Relative permeability**
The relative permeability of the kth element in a magnetic path.

μo **Permeability of free space** **H/cm**
The permeability of free space ($4\pi \times 10^{-9}$).

µr   **Relative permeability**
The relative permeability of a magnetic material (for copper, it has a value of 1).

µsat   **Relative permeability @Bsat**
The slope of the B-H loop at the defined saturation flux density.

Φ   **Flux lines**   **Maxwells**
The flux lines.

ρ   **Resistivity**   **Ohm-cm^2/cm**
The resistivity of the conductor (1.72×10^{-6} for copper).

Appendix C - Key Equations

Ampere's Law

$$Hl = .4\pi \ NI$$

Faraday's Law

$$e = N\frac{d\Phi}{dt} = NAc\frac{dB}{dt}x10^{-8}$$

Peak AC Flux Density

$$Bac = \frac{Vave\ 10^{-8}}{4N\ Ac\ f}\ where\ Vave = 2\ f\ E\Delta t$$

Peak Flux Density (Transformer in Half Wave operation)

$$Bp = \left[\frac{Br}{1+\dfrac{1g\ uc}{lc}}\right] + 2Bac$$

Peak Flux Density (Inductor)

$$Bpk = \frac{A\pi\sum\limits_{j=1}^{n} Nj\ IpKj}{Ac\ R} = \frac{A\pi\ Np\sum\limits_{j=1}^{n} Tj\ Ipkj}{Ac\ R}$$

where

$$R = \sum_{k=1}^{m}\frac{lk\ dHk}{d\Phi} = \sum_{k=1}^{m}\frac{lk\ dHk}{Ak\ dBk} = \sum_{k=1}^{m}\frac{lk}{Ak\ \mu k}$$

Inductance of a Winding

$$L = \frac{A\pi N^2 \times 10^{-8}}{R}$$

where

$$R = \sum_{k=1}^{m} \frac{lk \; dHk}{d\Phi} = \sum_{k=1}^{m} \frac{lk \; dHk}{Ak \; dBk} = \sum_{k=1}^{m} \frac{lk}{Ak \; \mu k}$$

Surface Temperature Rise

$$\Delta T = \frac{710 \, Ptot}{Asurf}$$

Optimization Algorithm Copper Loss Equation

$$Pcu = \frac{\pi}{4} \rho(t) J^2 \; MLT \; K^2 \; wire \; Kw \; Aw$$

Calculated Winding Loss

$$Pwndg = Idc^2 \; Rdc + Iac^2 \; Rac$$

Core Loss

$$Pcore = Kp \; Bac^n \; f^m \; Vol$$

Optimum Current Density

$$Jopt = \sqrt{\frac{4Pcu(\Delta T)}{\rho(t) \; MLT \; K^2 \; wire \; Kw \; Aw}}$$

Optimum Flux Density (Core Loss Limited Design)

$$Bopt = \left[\frac{Pcore(\Delta T)}{Kp \; f^m} \right]^{\frac{1}{n}}$$

Area Product (AwAc1 - Transformer):

$$AwAc = \frac{\left(\sum_{j=1}^{last} V_j I_j\right) \times 10^8}{\pi \ K_w \ K^2 \ wire \ f \ Jopt \ Bopt}$$

Area Product (AwAc1 - Inductor): Bsat Limited

$$AwAc1 = \frac{edt\left(\sum_{j=1}^{n} T_j \ Irms_j\right) \times 10^8}{2 \ K_w \ Kwire \ J \ Bac}$$

Area Product (AwAc1 - Inductor): Bsat Limited

$$AwAc2 = \frac{Lp\left(\sum_{j=1}^{n} T_j \ Irms_j \sum_{j=1}^{n} T_j \ Ipk_j\right) \times 10^8}{K_w \ Kwire \ J \ Bpk}$$

Optimum Ratio of Core to Copper Loss (Core Loss Limited Design)

$$r = \frac{Pcore}{Pcu} = \frac{2}{n}$$

DC Resistance of Winding j

$$Rdc_j = \frac{\rho(T) \ MLT_j \ N_j}{Awire_j}$$

where

$$\rho(T) = rho + rhoTC \times T$$

Ratio of AC to DC Resistance

$$Fr = x\left[F1 + 2\frac{(H_1 H_2)}{Hi^2}F3\right]$$

H1 and H2 are the field strengths on either side of the wire. Hi is the field produce by the wire itself. The "wire" is converted into a rectangular sheet to simplify evaluation of the boundry conditions.

$$x = \frac{h\sqrt{Fl}}{Dp}$$

$$Dp = \sqrt{\frac{\rho}{\pi\mu_0\mu_r f}}$$

The term F3 can be approximated by:
   F3 = (sinh(x)-sin(x))/(cosh(x)+cos(x))
While
   F1 = (sinh(2*x) + sin(2*x))/(cosh(2*x) - cos(2*x)))

Proximity Loss
If we let H1 = H2 = Nisum/(Lw) and let I approach zero, the power loss is then I*I*Fr*Rdc so that the proximity loss defined when I = 0 is

$$P(I = 0) = 2Rdc \; x\left[\frac{Nisum \; w \; pitch}{N \; Lw}\right]^2 F3$$

Appendix D - References

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Index

Index