

Intusoft Newsletter

Personal Computer Circuit & System Design Tools



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Issue #70 May 2003
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General Feedback Theorem (GFT)

Dr. R. David Middlebrook with the California Institute of Technology developed the theorem, which describes a control system in terms of its response to signal injection inside the control loop. Application of the GFT provides simulation techniques for measuring control system characteristics when the loop is closed. Of particular interest is the loop gain and its contribution to system stability using Bode Plots. With the loop closed, the simulator automatically accounts for the DC operating point and circuit loading is properly handled at the signal injection point. The generalization of this technique removes the previous restriction of the single injection method described in

Newsletter 57.

GFT, a brief summary

Back in the days before computer simulation, network equations were commonly solved using determinants. Interestingly, determinants provide insight for understanding the effect of one network element on the overall network behavior. For example, the following equation taken from Bode in 1945 [1] shows how impedance, z , somewhere in a network affects the transfer impedance, Z_T , between the network input current at node 1 and output voltage at node 2 with an impedance z belonging to Z_{ij} in the original determinant.

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$$Z_T = \frac{\Delta^0 + z\Delta_{ij}}{\Delta_{12}^0 + z\Delta_{12ij}} \quad (1a)$$

where the superscript, Δ^0 and Δ_{ij}^0 are properties of the network when $z = 0$.

This comes about by expanding the determinants and their minor elements into the parts shown in (1a). The terms Δ_{ij} and Δ_{12ij} are also not dependent on z . Bode went on to show that for any given frequency, when z and Z are complex numbers (1a) can be recast as follows where A, B, C and D are network parameters that are independent of z :

$$Z = \frac{A + Bz}{C + Dz} \quad (1b)$$

This representation is a bilinear transform that maps variations in z at each frequency into circles in Z .

Re-arranging Bodes equation results in the following interpretation.

$$Z_T = \frac{E1}{I2} = Z_{T0} \begin{pmatrix} 1 + \frac{z}{Zn1} \\ 1 + \frac{z}{Zd1} \end{pmatrix} \quad (2)$$

Where Z_T is the impedance with z present

$$Z_{T0} = \frac{\Delta^0}{\Delta_{12}^0} \text{ is the impedance with } z \text{ shorted.} \quad (3)$$

$$Zn1 = \frac{\Delta^0}{\Delta_{ij}} \quad (4)$$

$$Zd1 = \frac{\Delta_{12}^0}{\Delta_{12ij}} \quad (5)$$

Now we can further generalize the concept to measure the transfer response of any pair of voltages or currents, using the notation u_i for input voltage or current and u_o for output voltage or current. With this interpretation, this becomes the Extra Element Theorem [2]. Middlebrook goes on to show that:

$$Zd1 = \left. \frac{v}{i} \right|_{ui=0} \quad (6)$$

$$Zn1 = \left. \frac{v}{i} \right|_{uo=0} \quad (7)$$

Where v and i are the voltage and current in z . Both $Zn1$ and $Zd1$ can be measured using a simulator by injecting a voltage in place of z and measuring the ratio of v/i . For $Zd1$, the input, u_i , is set to zero. However, to calculate $Zn1$ you must null u_o and not set it to zero. The null is achieved by connecting a high gain amplifier between u_o and u_i . The rational for this null injection technique was discussed in the last newsletter, NL69.

Moreover, we can replace Z with voltage or current sources so that we are dealing with the response of a network transfer function to signals injected at some point in the network. Next, we can expand the EET to the 2EET by considering 2 extra elements. Dr. Middlebrook details this expansion in [3] and shows how it can be used in [4]. Using dual voltage and current injection, the GFT is capable of having a loop-cut or injection point in the middle of a network where the input is neither a current source or a voltage source. Applying the EET twice, once for each source or by directly using the 2EET, exposes an extra product term as shown in (8).

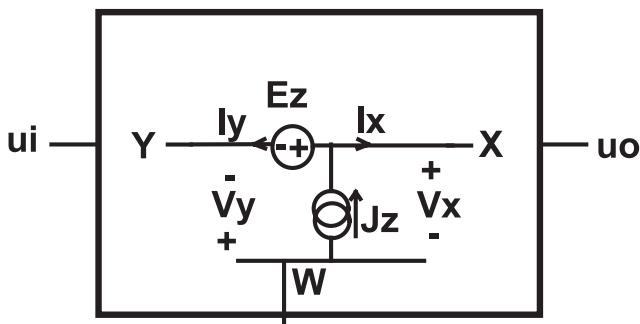


Figure 1. A GFT dual current/voltage injection point.

Using the voltage and current definitions in Figure 1, the loop gain T is given by equation 8.

$$\frac{1}{T} = \left. \frac{ix}{iy} \right|_{vy=0} + \left. \frac{vx}{vy} \right|_{iy=0} + \left. \frac{ix}{iy} \right|_{vx=0} \left. \frac{vx}{vy} \right|_{iy=0} \quad (8)$$

Finding T, then requires 3 simulations.

The GFT is more than just a method to extract the principal loop gain. It reorganizes control system theory, providing a new set of parameters used for design-oriented analysis. Beginning with a control system block diagram shown in Figure 2,

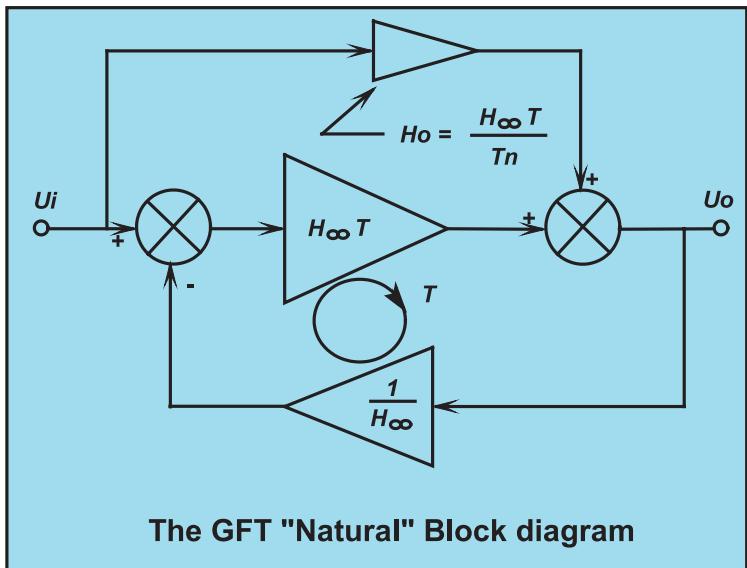


Figure 2. The GFT “Natural” Block diagram

$$H = \frac{uo}{ui} = H_\infty \frac{1 + \frac{1}{Tn}}{1 + \frac{1}{T}} = H_\infty DDn \quad (9)$$

Notice the relationship between the formulation in (9) and (2). That's how the EET gets to be part of the GFT. The term H_∞ is the transfer function if the forward loop gain is infinite. This condition is met when iy and vy are nulled for the case when vy and iy are in the forward loop.

Implementing the GFT in ICAP/4

The GFT has been implemented using ICAP/4's powerful simulation templates. The GFT models include analog multiplexers that are configured by the template scripts to change the way stimulus and nulling amplifiers are connected. After the null signal is selected, it goes through a high pass filter so that the DC bias is not altered. Finally, a high gain is applied in order to make the null target vanishingly small.

Up to 13 simulations are needed to get the complete GFT data set. Figure 3 illustrates how the GFT model selects the signals to be nulled using an analog multiplexer. The null selections are made using the ICL Alter command shown in Table 1. The Script must know the name of the subcircuit so the GFT subcircuit must be named Xgft. A new ICL function, msgbox, is used to notify the user if he forgets this requirement.

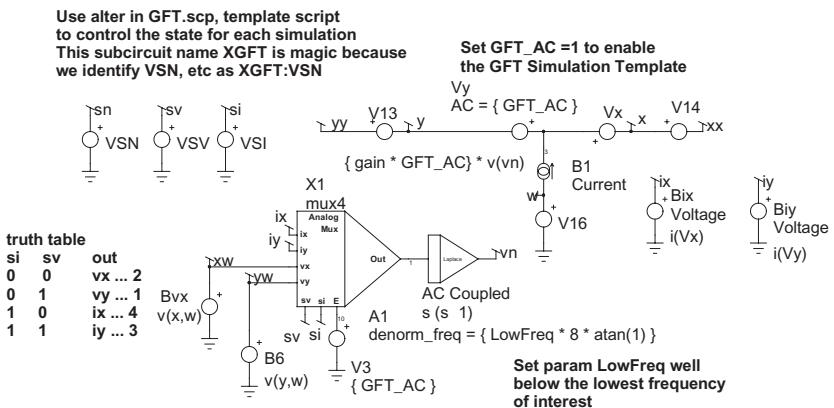


Figure 3. The various nulls are selected using a behavioral analog multiplexer, controlled using Alter commands in the template script.

Table 1. A portion of the Simulation Template Script, GFTs

```

if isdef(v(yw:xgft))
...
alter @vsv:xgft[dc] = 1
alter @vsi:xgft[dc] = 0
alter @vsn:xgft[dc] = 0
* null vy
#simulation
#mprint
result.Ti_vy = v(iy:xgft) / v(ix:xgft)
...
setplot result
t_iv = ti_vx * tv_iy
t = 1/(ti_vy + 1/tv_iy + 1/t_iv)
else
msgbox "You need to name the GFTs subcircuit Xgft"
end

```

More information is available when the input and output are included. Figure 4 illustrates the technique used for the GFTg model and a portion of the template script. Several built-in scope scripts can be invoked to plot some common functions. For example, running “gft/T” will make a Bode Plot of the principal loop gain, T as seen in Figure 5. While the math behind the GFT can be daunting, its use is simple.

The transistor amplifier shown in Figure 4 illustrates the use of the GFT in exploring this design. This is a portion of Sample.dwg, a drawing delivered with ICAP/4 that is used for training. Q1 and Q2 have been upgraded to use wider bandwidth transistors, which requires the addition of R6 to eliminate ringing. Breaking the loop at Q2's base lets us look at the Bode plot, shown in figure 5. The 3 components of the loop gain T are shown in Figure 6.

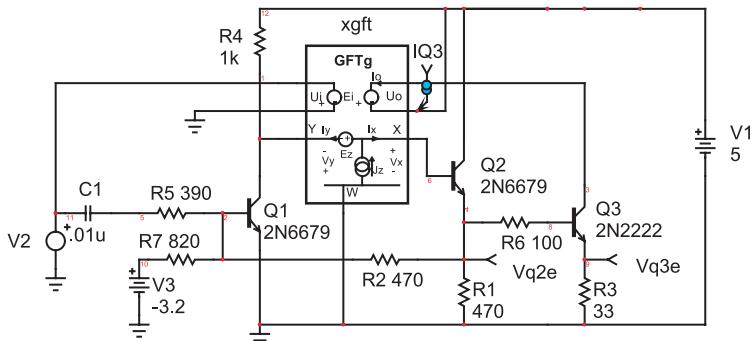


Figure 4. Transistor Amplifier with feedback

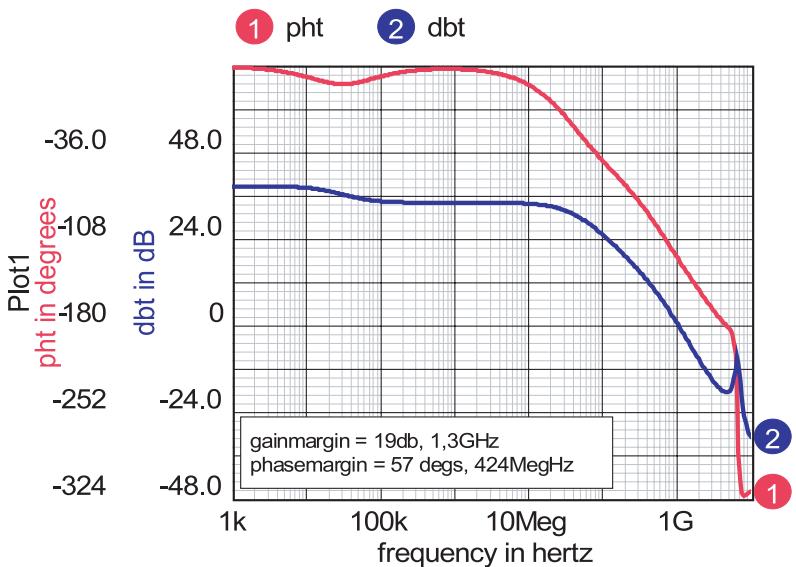


Figure 5. The GFT principal loop gain.

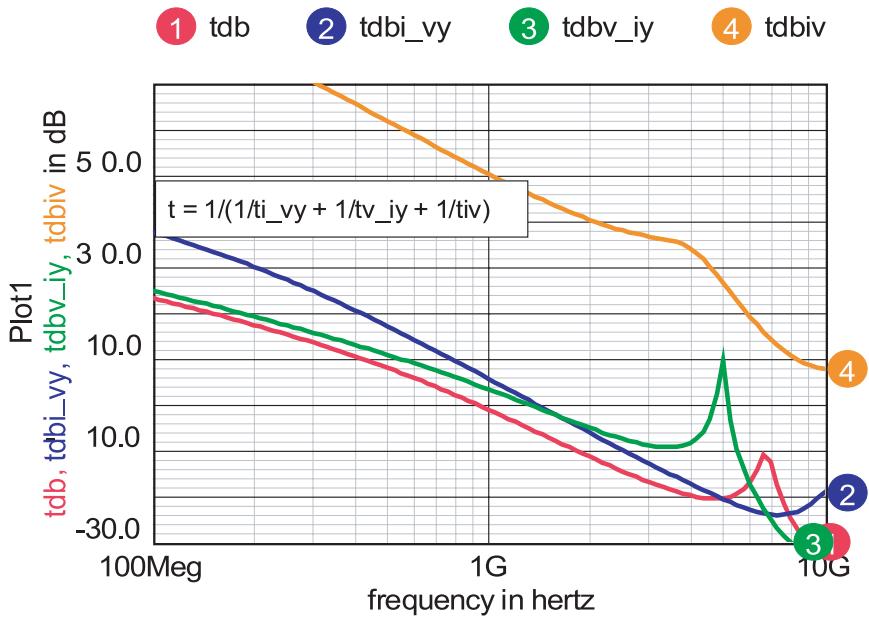


Figure 6. The principal loop gain and its components

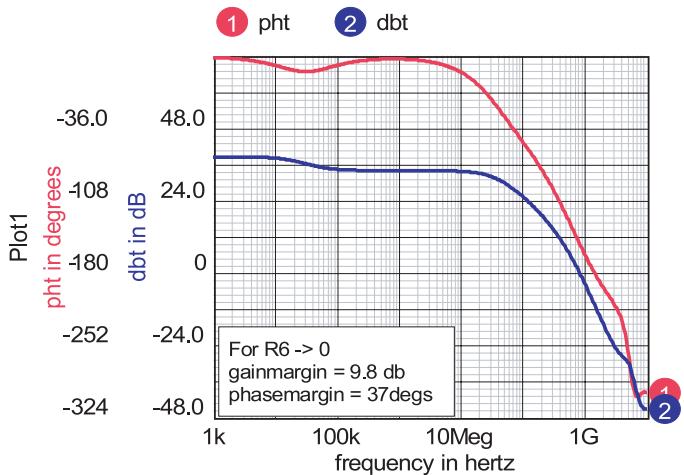


Figure 7. Bode plot with small R6.

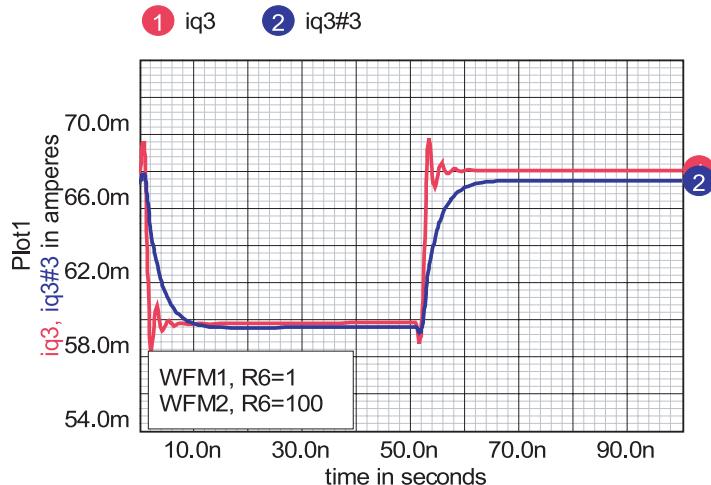


Figure 8. Increasing R6 damps the ringing as confirmed by the GFT analysis.

- [1] H.W.Bode, "Network Analyais and Feedback Amplifier Design"Princeton, NJ: Van'Nostrand, p. 10, 1945.
- [2] R.D.Middlebrook, "Null Double Injection and the Extra Element Theorem," IEEE Trans. on Education, vol. 32, no. 3, Aug. 1989; pp. 167-180.
- [3] R.D.Middlebrook, "The GFT: A General Yet Practical Feedback Theorem," to be published.
- [4] R.D.Middlebrook, "GFT Template User's Manual v.1.0" published at <http://www.intusoft.com/gft.htm>.

Features for Summer 2003 Update

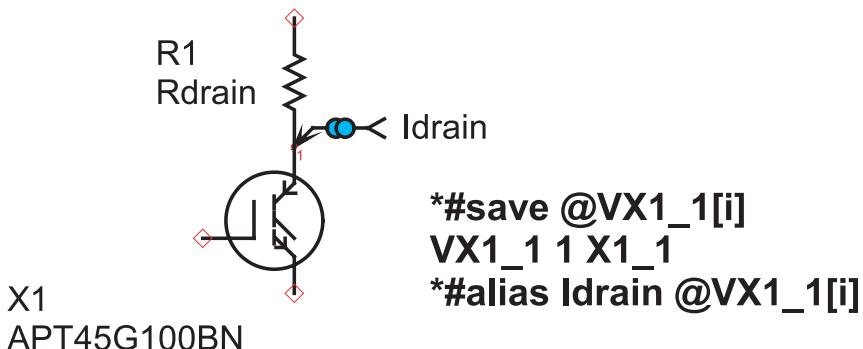
EDIF Capability Coming

SpiceNet will create a Mentor compatible EDIF description that works with their DxAnalog and PADSAnalog products. That lets you use ICAP/4 for the design phase and transfer production to the Mentor products.

Coming soon is a Layout and Auto Routing package. We'll let you know as we fill in the details.

Connect Current Test Point to Subcircuit Pins

For our next update, we will advance the file system to version 13. This step was needed in order to manage the saving of certain Edit Control dialog settings. In addition, we've added the capability to place current test points on subcircuit pins. Placing the y.6 symbol on a subcircuit pin achieves this. Try either of two methods: 1) Pull down the parts menu and select "Y Test Point/6y Current Subcircuit," or 2) press the key "6" then "y." The test point is drawn at the insertion point. It can be dragged anywhere on the drawing. When it is placed on a subcircuit pin, it attaches to the pin and creates a voltage source in series with the appropriate alias as shown below.



The subcircuit test point creates a voltage source and an extra node to measure the current. The new test point is saved into the new file version. Saving to a file version older than version 13 will delete the test points.

Test Point Support Added to B-Elements

You will now be able to assign current and power test points to B-elements.

IntuScope Now Reads in CSDF File Format

Scope5 can now read CSDF(Common Simulation Data File) file output. This is particularly useful for importing raw waveform data from IsSpice4 or other external simulation offerings like HSPICE™ and PSPice™.

Successfully Reduce Schematic Image for Publication

Certain features are now available for transferring schematics for publishing purposes. For example, when you shrink a schematic to fit in a small space (as done in our newsletter) the line widths may become too small. Other flaws can also occur. Techniques to successfully reduce schematics for publication are:

1. Increase font size to 16 point.
2. Increase line width to 50/100 millimeter.
3. Print, Copy to clipboard and paste into your target publication.
4. Shrink the schematic in the target publication by 50% to get 8-point fonts and 1-point lines.

Save Schematic Image Directly to EMF File

Copy to clipboard in SpiceNet now has extra shift key options. When you press the shift key and left click on Copy to Clipboard in the print dialog, you get the dialog shown below, Figure 9.

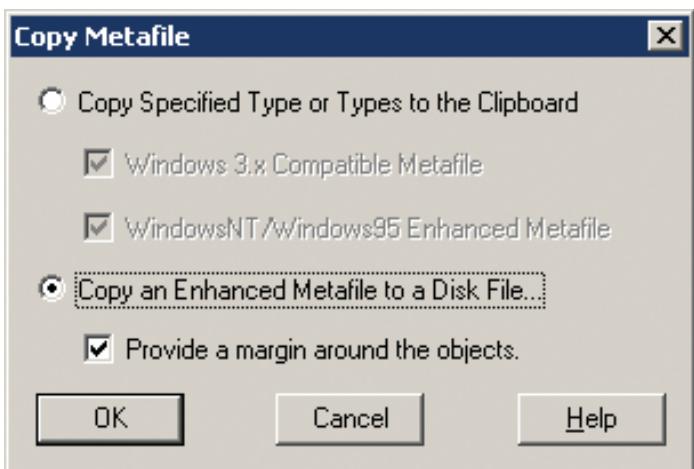


Figure 9. Save directly to EMF file instead of to the clipboard.

You can also save Enhanced Metafiles to disk. The EMF format is the preferred Windows clipboard format. It saves drawings and graphs as vectors so that you can render to the precision of your output device.

“Save as” added to SpiceNet File Menu



Figure 10. New Save as... command

“Save as...” has been added to the SpiceNet file menu, adding to the existing “Save Copy as...” The difference between the two is that “Save as...” abandons the current drawing and saves changes in the new “Save as...” file. It then switches the project to this new file. “Save Copy as...” works as before to produce a back up copy, but retains the current drawing as active. This adds to recent capability that enables projects to automatically switch to the drawing that the user desires as active, ultimately to invoke simulation control and running simulation.

XML Database for PCB Footprints

An xml database has been added for selecting part numbers and mechanical footprints, i.e., as required for PCB layout. When you right click on a part and select the Footprint... option, a dialog as shown in Figure 11 will appear.

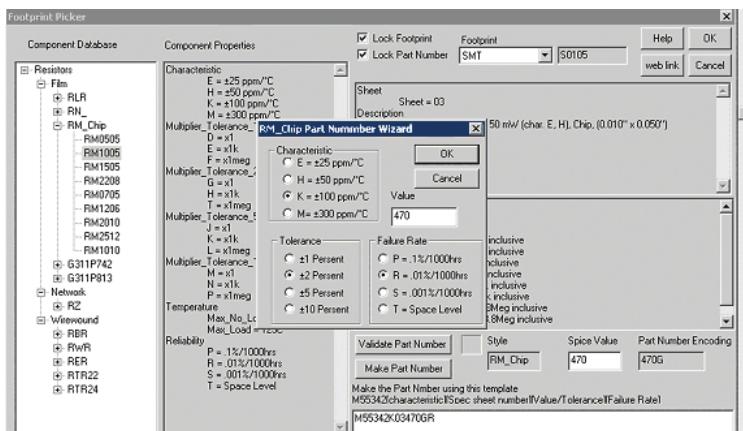


Figure 11. New Footprint Picker builds part numbers and selects package footprints

The xml files are named ???.type, where ? is the spice key for the part. For a resistor, the database is RR.type. We have initiated databases for resistors, capacitors and inductors using the NASA Parts Selection List, NPSL:

http://nepg.nasa.gov/npsl/npsl_toc.htm.

The list is comprehensive, and generally parts are also available to commercial specification. We've added built in parsers to help build the part number as shown in Figure 11. User DLL's can be added to augment or replace the built-in parsers.

The benefit of this feature is that it makes it even easier to be able to export PCB netlist with the correct syntax. Intusoft currently supports PCB netlist export to any package that can read in the following formats.

Tango PWB - Netlist for Accel

Pads 2000 - Netlist for Pads

Pads ASCII 1 - Netlist for Pads

Pads ASCII 2 - Netlist for Pads

Pads PCB- Netlist for Pads

Mentor V6 - Netlist for Mentor Graphics

OrCAD/PCB II - Netlist for OrCAD Capture PCB

Protel PWB - Netlist for Advanced PCB

Winboard - Netlist for Ivex

New XP Style UI

If you like the new XP-style dialog user interface, it will be available on XP machines simply by selecting Display Properties/Appearance/Windows and Buttons/Windows XP style.

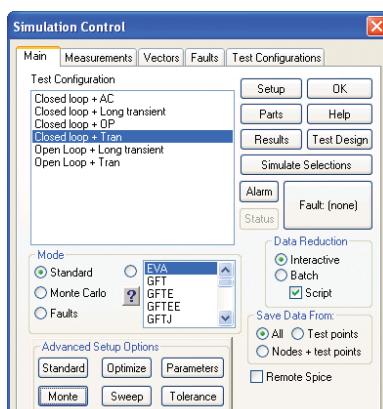
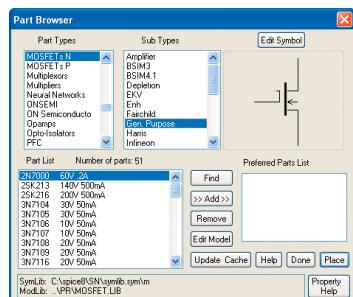


Figure 12. SpiceNet and IntuScope now support the Windows XP look and feel



Designing an Autotransformer

An auto transformer, shown in Figure 13, is a 2-winding transformer connected so that its windings are in series. Magentics Designer needs as its input the voltage and current for each of these windings. If the design requirement calls for a prescribed output current, with a transformer ratio v_o/v_i , then,

Winding	1	2
Average Voltage	$K(v_i - v_o)$	$K(v_o)$
RMS Current	$i_o(v_o/v_i)$	$i_o(1 - v_o/v_i)$

K is a waveform shape factor, so for sine waves,
 $K = 2\sqrt{2}/\pi = 0.900317$

where v and v_i are RMS quantities. The only unusual aspect to the design is the need for winding 1 to have sufficient insulation to handle the voltage at the input.

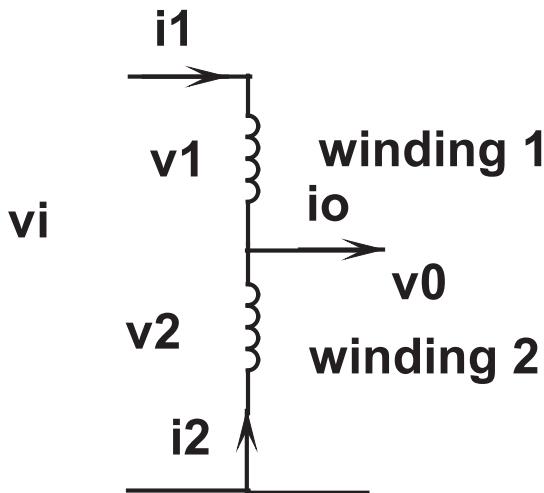


Figure 13. As v_1 approaches 0, the power handled by the transformer action approaches 0.

Autotransformers sacrifice isolation for extremely high efficiency when the turns ratio is near unity. Figure 14 shows the results of a Magnetic Designer design of an isolation transformer going from 120 VRMS to 110VRMS at 1KW. Figure 15 meets the same requirements but uses the autotransformer configuration.

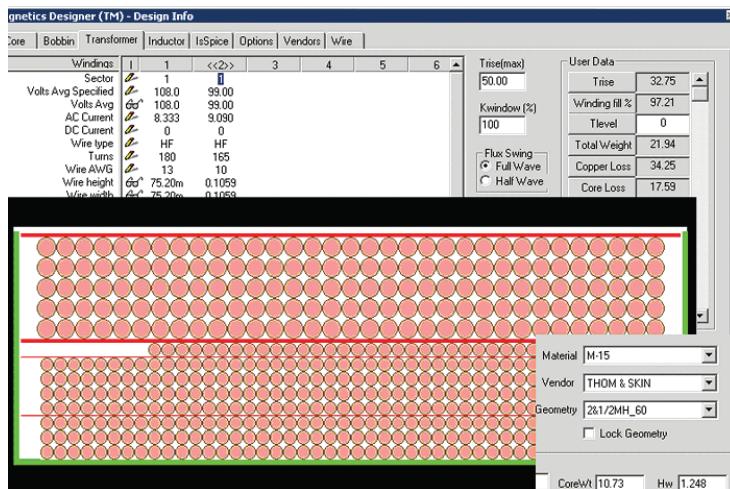


Figure 14: A 1KW isolation transformer

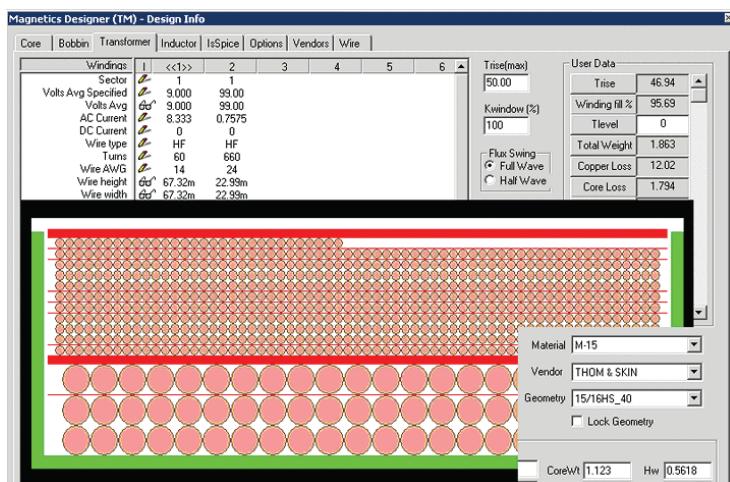


Figure 15: A 1KW autotransformer

Table 2. Summary of 1KW 120 to 110 Vrms Designs

	Efficiency	Weight
Isolation Transformer	95.07%	21.9 lbs
Autotransformer	98.6%	1.86 lbs

Magnetics Designer picked the “best” geometry from a set of rectangular laminations with variable stack size. The stack height to width ratio was .789 for the autotransformer and .444 for the isolation transformer. The automatic design algorithm searches cores from the smallest power handling capability to

the largest, beginning with the theoretically smallest core. Trial designs are made and discarded if the temperature rise is above the specification. Several “larger” power capacity designs are tested to see if they produce a lower weight. The lowest weight design is then presented to the user. The user is free to lock in any core, thereby disabling the automatic core selection. For each core, Magnetics Designer makes trial windings to pick the wire size under the constraint of minimum temperature rise. For low frequency designs like this example, the winding area will be nearly 100% full. On the other hand, high frequency designs will have significant losses because of the skin effect, proximity loss, and in some cases gap induced eddy currents. Magnetics Designer builds on the work of Bennet and Larson [5] to predict these losses. Figure 16 shows what happens to the isolation transformer if the frequency is increased to 1KHz using 4mil laminations.

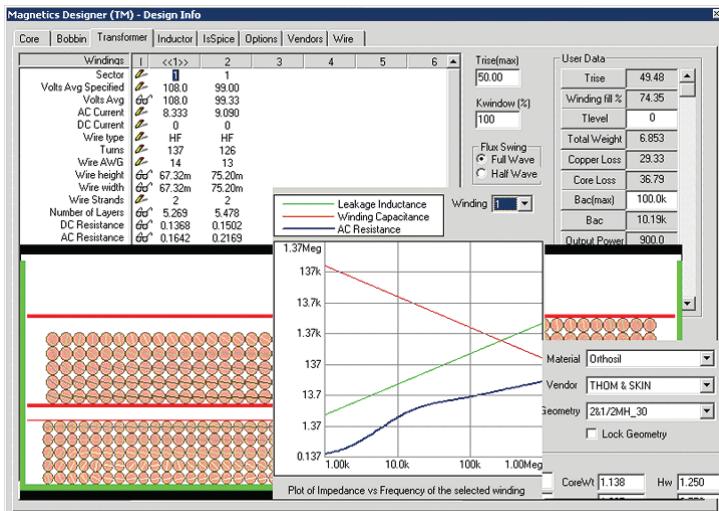


Figure 16. High frequency losses increase sharply for windings in the center of the stack where the field is highest.

There is a sharp increase in Rac in the 1KHz to 10Khz region due to the skin effect. The result is to cause the “best” design to under-fill the window. Interestingly, the onset of these high frequency effects occurs at lower frequencies as the power level increases.

[5] Bennett and Larson, Effective Resistance to Alternating Currents of Multilayer Windings, AIEE Transactions 1940, vol. 59, pages 1010-1017.

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