Application Brief

Calculating Performance of Planar Magnetics

Planar magnetic components using a ferrite magnetic core and numerous conductor/insulation layers have been built for many years. Historically however, the only way to consider temperature rise when calculating winding and core loss was to use build-test iterations, due to the difficulty in calculating 3-D frequency and thermal-dependent effects. Accurate calculations can only be accomplished by using frequency- and thermally-dependent material properties in a two-way spatially coupled simulation. Furthermore, a frequency-dependent system model accurately representing the real device can only be constructed after a steady-state temperature condition has been reached throughout the device. Using ANSYS you can design, simulate and optimize planar magnetic components without needing build-test augmentation. This application note describes how ANSYS software tools are used to automatically set up and solve a two-way coupled magnetic-thermal model, which is frequency dependent using a customized interface complete with manufacturer libraries. This example is based on an application note published by Ferroxcube and publicly available.

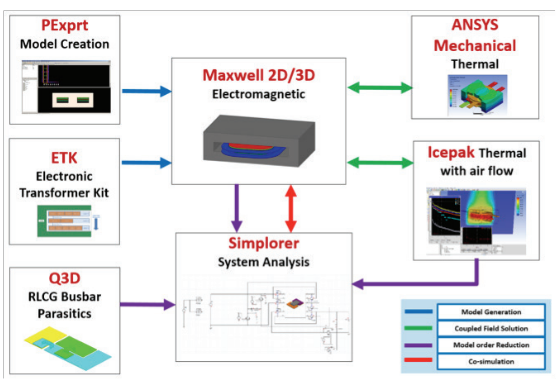


Figure 1. Flow Chart for ANSYS Planar Magnetic solution including two-way thermal coupling and system analysis

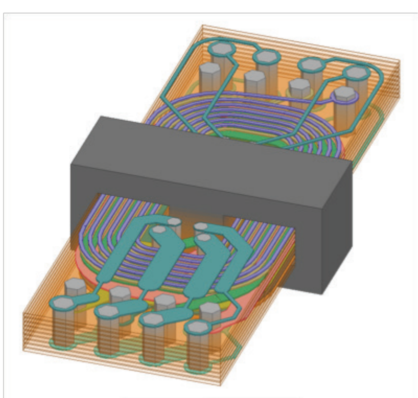


Figure 2. Physical layout of 500 kHz, 18W DC-DC forward converter

Products Used:
ANSYS® Maxwell®, ANSYS® Simplorer®, ANSYS® Mechanical Pro™, ANSYS® Icepak®

Keywords:
Planar Magnetics, Planar Transformer, Ferrite, Core Loss, Eddy Current Loss, Frequency Dependent Reduced Order Model (ROM)

Introduction: ANSYS Planar Magnetics Solution
The ANSYS planar magnetics solution provides a complete solution for planar transformers operating in the 10kHz–10MHz range including the magnetic, thermal and system performance. Depending on the engineer's preference, different products can be used such as: Maxwell, ANSYS Mechanical and ANSYS Icepak. The complete ANSYS solution flow for planar magnetics is shown in Figure 1.

Problem Description
The analysis of a ferrite core transformer is described here using a combination of ANSYS products. We used PEmag to automatically create the geometry, Maxwell 3D to perform the magnetic analysis, ANSYS Mechanical and Icepak to perform two-way thermal coupling and Simplorer to run a complete system analysis, including losses and efficiency.

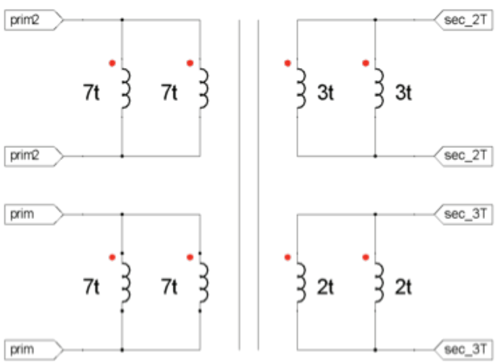


Figure 3. Schematic

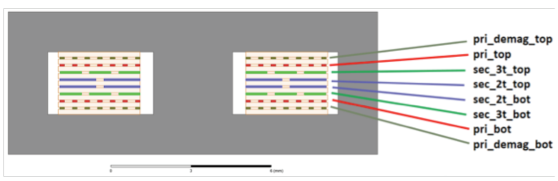


Figure 4. Physical arrangement of the primary and secondary windings

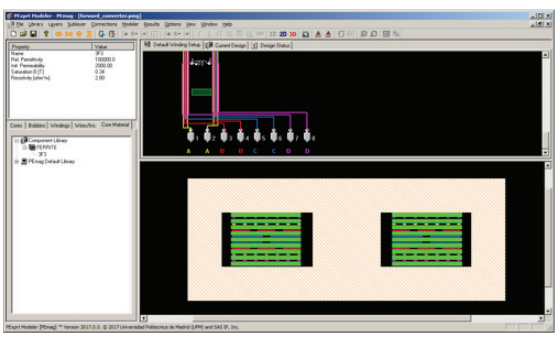


Figure 5. PEmag input panel

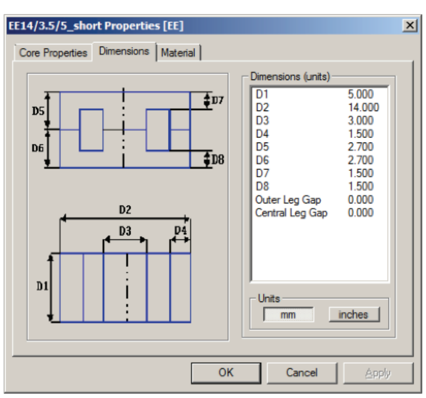


Figure 6. PEmag core dimensions and inputs

The DC-DC Forward Converter modeled had the following characteristics:

- Multiple input-output voltages: 48-5V, 48-3.3V, 24:5V, 24-3.3V
- Switching Frequency: 500kHz
- Output Power: 18W
- Duty Cycle: 0.46
- Ferroxcube E-E14 core with 3F3 ferrite
- Ambient Temperature: 40°C

The transformer consisted of four windings having eight layers and 38 turns total. A picture of the device is shown in Figure 2. We changed the voltage ratio by using different series/parallel connections. For this analysis, a 24:5V connection was used, which results in the highest current densities. The schematic and physical arrangement of the windings are shown in Figures 3 and 4.

Electromagnetic Simulation

The first step was to create the FEA model. Using the PEmag feature shipped with Maxwell, we automatically created both of the 2-D and 3-D designs based on user inputs and manufacturer libraries. These libraries included the core, conductors, insulators and material properties. The PEmag layout is shown in Figure 5, including the core and conductor dimensions shown in Figures 6 and 7. The Maxwell 2D and Maxwell 3D designs were created directly from PEmag as shown in Figure 8.

The Maxwell design was modified as needed. Specifically, the thermally dependent material properties were included for the core and conductors. The thermal properties for copper conductivity are shown in Figure 9 and for ferrite permeability in Figure 10. Also, we added the frequency-dependent properties for ferrite as shown in Figure 11. Finally, the Steimetz core loss coefficients are shown in Figure 12.

Typically, planar magnetic components use a switching circuit to operate. This can be accomplished in both Maxwell 2D/3D by using the Maxwell Circuit Editor or by coupling transient-transient to Simplorer. In this example, we used a sinusoidal voltage excitation in the 3D Eddy Current solver as shown in Figure 13. Also, a PWM voltage source was used, switching at 500KHz with a 0.48 duty cycle and using the Maxwell 2D Transient solver as shown in Figure 14. The results for the loss and output voltage from the Maxwell 2D Transient are shown in Figure 15, while the results for the magnetic flux density and core loss density from the Maxwell 3D Eddy Current solver are shown in Figure 16. We used frequency-dependent resistance and inductance to create the reduced order model (ROM) for Simplorer, which is shown in Figure 17. We then used the average core and winding losses from the 3D eddy current solver to couple to both ANSYS Thermal and Icepak for separate temperature rise calculations.

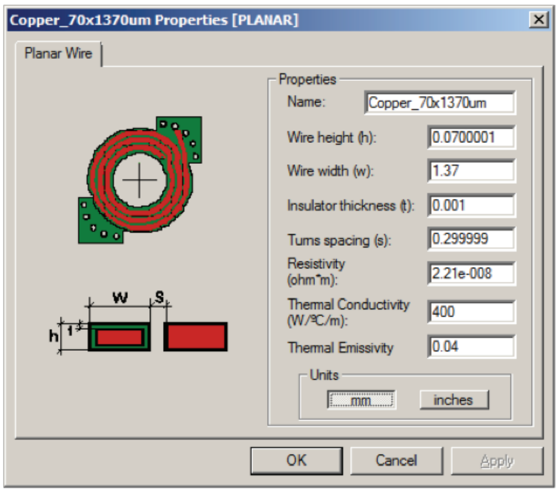


Figure 7. PEmag conductor dimensions and inputs

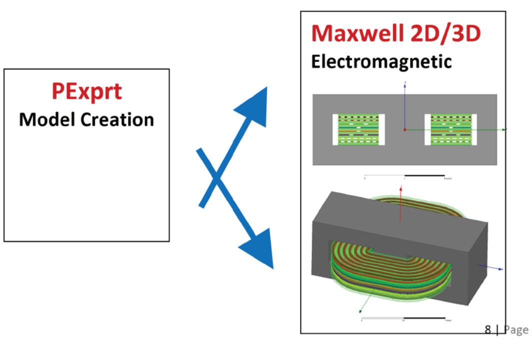
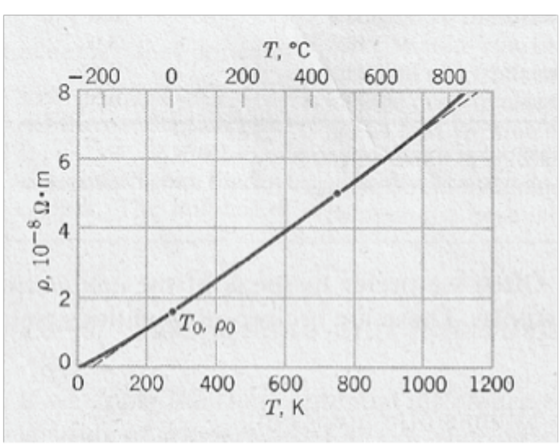


Figure 8. Maxwell 2D/3D model creation from PEmag



$$\sigma = \frac{\sigma_{at\,22C}}{(1+0.0039*(Temp-22C))}$$

Figure 9. Thermal properties for copper conductivity

Using the Time Decomposition Method (TDM) in the Maxwell 3-D transient solver provided significant speed improvements of approximately 20x, reducing the solution time from 2.6 days to 3 hours, as shown in Figure 18.

Thermal Simulation

The spatially dependent loss density from Maxwell in watts/m^3 was directly coupled to both ANSYS Mechanical and Icepak separately. We used Workbench for both couplings as shown in Figures 20 and 21. A prerequisite is that the mesh in both Maxwell and in ANSYS Mechanical be sufficiently fine to interpolate the loss mapping from Maxwell to the thermal solution. Using the feedback iterator, the Maxwell and thermal solution were automatically two-way coupled so that the solution continued back and forth until the difference in temperature used by Maxwell for the magnetic solution and from the thermal solution was below the maximum specified (for example, 5°C). The feedback iterator is shown in Figure 19. The ANSYS Mechanical simulation requires that the user supply the appropriate convection coefficients. The Icepak simulation, on the other hand, determines the appropriate cooling based only on the specified direction of gravity and is more appropriate for applications having air flow, where convection coefficients are very difficult to estimate.

The final temperature converged in fewer than 4 passes for both thermal approaches. The measured temperature rise using sinusoidal currents was 32°C + 40°C ambient = 72°C temperature. Using ANSYS Mechanical with assumed convection coefficients, the resultant temperature was 82.9°C, as shown in Figure 22. Using ANSYS Icepak and considering airflow directly, the resultant temperature was 73.5°C, as shown in Figure 23.

System Simulation

We simulated the system using Simplorer as shown in Figure 24. The first step was to import the R, L, ROM and capacitance matrix to the schematic. Next the other components we added including the voltage source, resistors, inductors, capacitors, Power Mosfet, diodes and watt meters. The variables used during the system simulation were: input voltage, switching frequency, duty cycle, load resistance and assorted MOSFET/diode parameters, which allows for quick parametric cases to be solved in a few seconds because the ROM is valid over the complete range of frequencies. Finally, the efficiency calculation was performed by comparing the input/output power of the various watt meters in a formula.

The system simulation showed efficiency results of 93.8 percent for the transformer alone, 91.5 percent for the converter excluding the Mosfet, and 87.0 percent for the entire converter with all components. Plots of instantaneous power and output voltage are given in Figures 25 and 26.

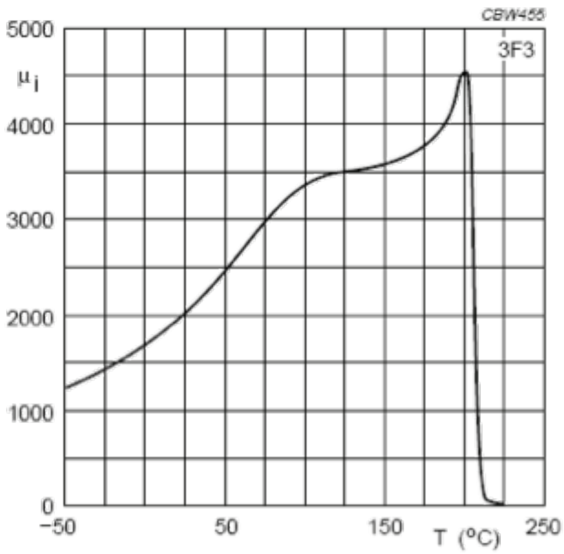


Figure 10. Thermal properties for 3F3 ferrite permeability

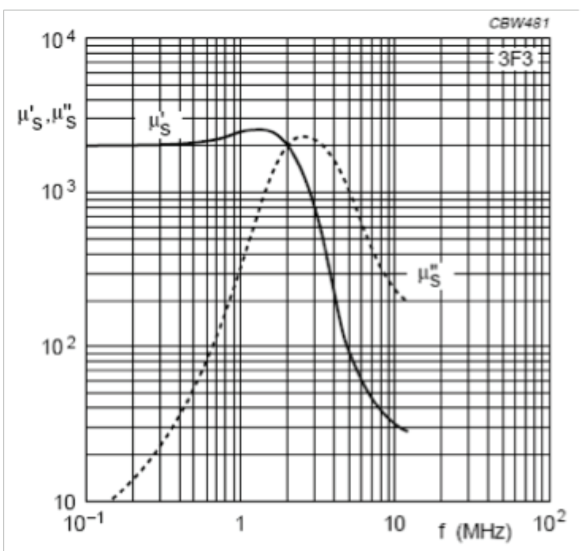


Figure 11. Frequency dependent permeability and imaginary permeability for 3F3 ferrite

grade	frequency (kHz)	C_m	x	y
3F3	20-300	0.25	1.6	2.5
	300-500	2.10^{-2}	1.8	2.5
	500-1000	36.10^{-7}	2.4	2.25

Figure 12. Steinmetz core loss coefficients for 3F3 ferrite

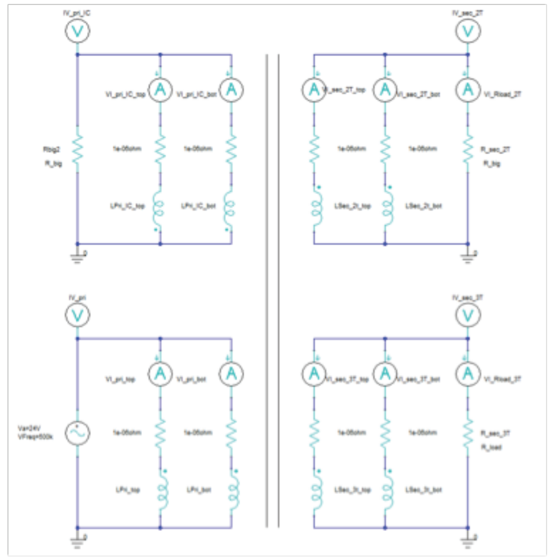


Figure 13. Eddy Current solver switching circuit in Maxwell Circuit Editor

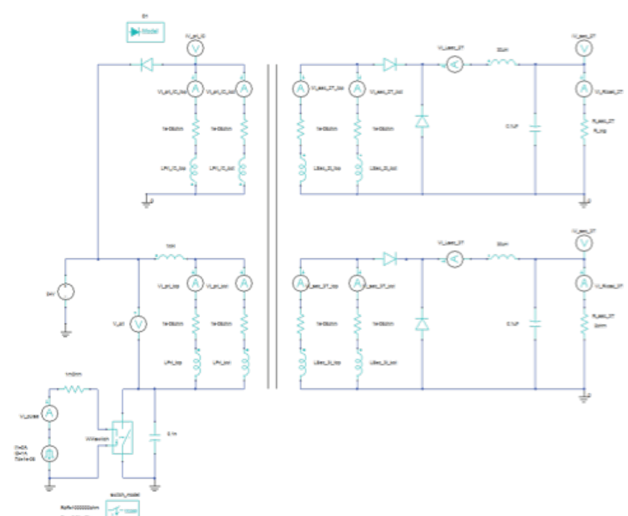


Figure 14. Transient solver switching circuit in Maxwell Circuit Editor

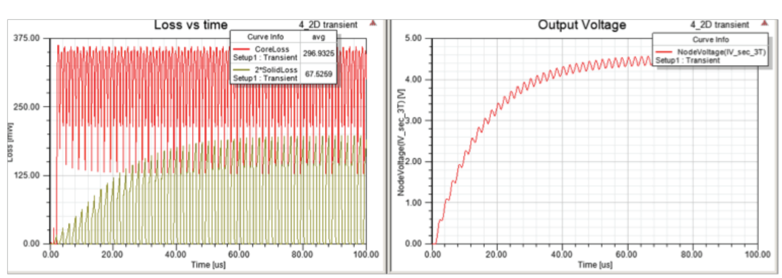


Figure 15. Maxwell 2D Transient solver loss and output voltage vs time

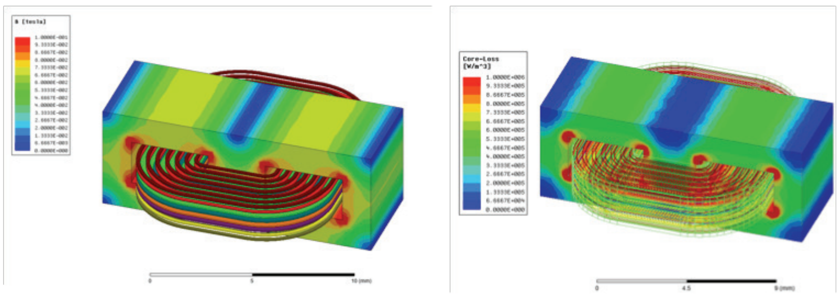


Figure 16. Maxwell 3D Eddy Current flux density and core loss density

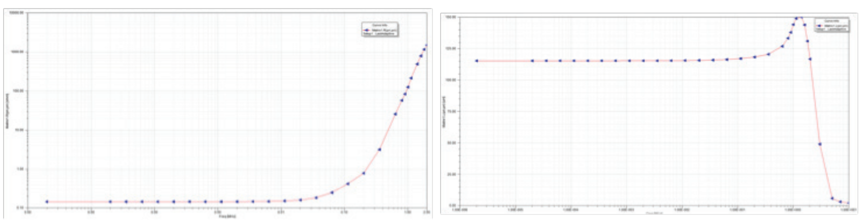


Figure 17. Resistance and inductance vs frequency

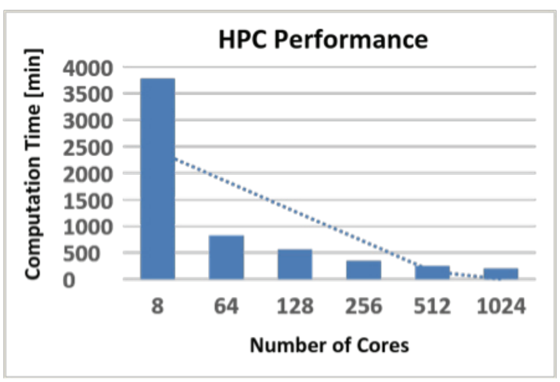


Figure 18. Speed improvement using TDM

Iterations	
Iterations Completed	3
Max Iterations	4
Callback	
Temperature Convergence	
Target Delta Temperature %	1
Latest Delta Temperature %	0.9762

Figure 19. ANSYS Workbench feedback iterator settings and results

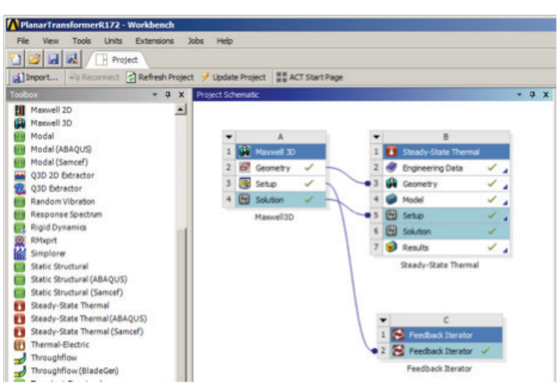


Figure 20. Maxwell 3D – ANSYS Thermal two-way thermal coupling

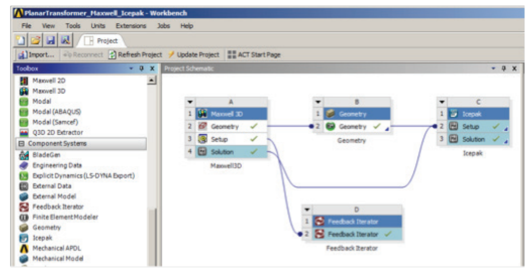


Figure 21. Maxwell 3D – Icepak two-way thermal coupling

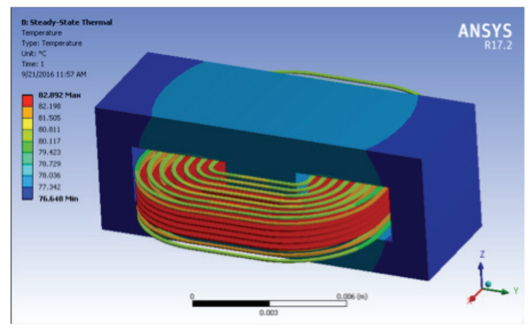


Figure 22. Final temperature rise results for ANSYS thermal

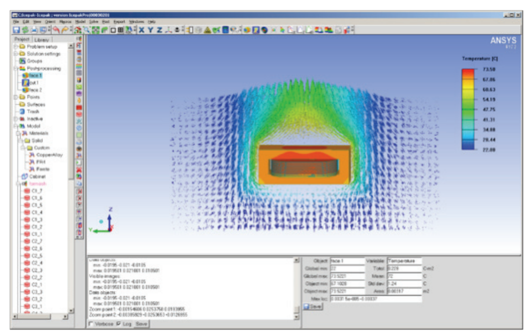


Figure 23. Final temperature rise results for Icepak

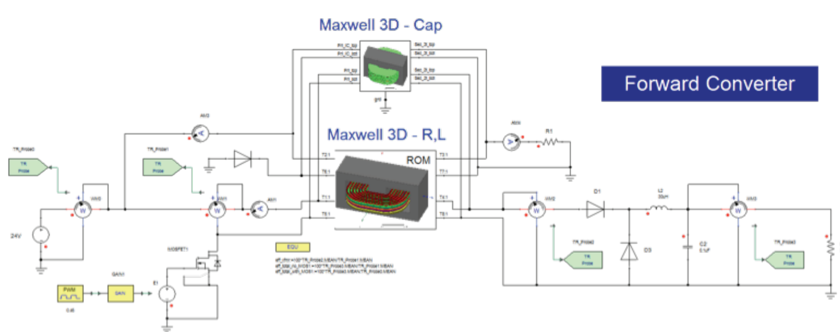


Figure 24. Transient solver switching circuit in Maxwell Circuit Editor

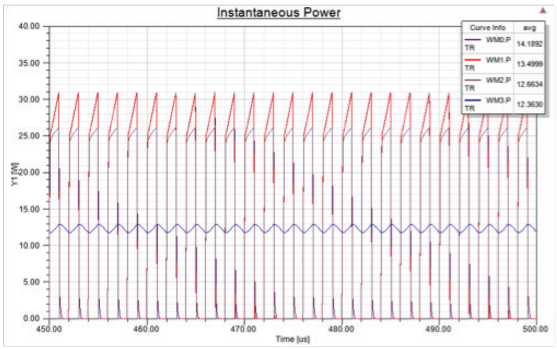


Figure 25. Instantaneous power vs time

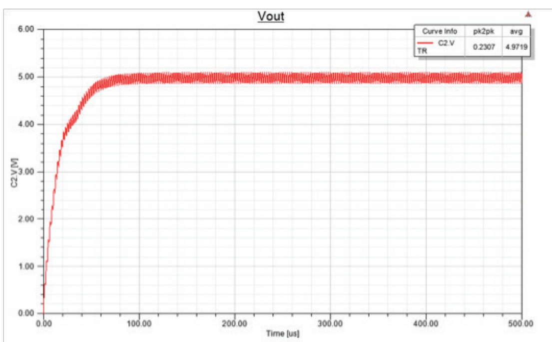


Figure 26. Output voltage vs time

Closing Summary:

The ANSYS Planar Magnetics Solution provides a complete solution for planar transformers operating in the 10kHz – 10MHz range, including the magnetic, thermal and system performance. In this application brief, we used PEmag to create the geometry, Maxwell 3D to perform the magnetic analysis, ANSYS Mechanical to perform two-way thermal coupling using convection coefficients, ANSYS Icepak to perform two-way thermal coupling using airflow directly and Simplorer to run a complete system analysis including losses and efficiency. The final efficiency of the converter, 87 percent, was reasonable, and simulated temperatures considering airflow were within 3 percent of the published results.

Reference:

Design of Planar Transformers, Application Note, Ferroxcube, May 1997.

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