ECE194J Power Electronics
Lab 2: Inductor design, efficiency improvement

Lab times: Monday April 29, 12:30-2:30, 4:00-6:00
Write-up due: Friday May 3, 5:00pm

Equipment
Linear Technology Demo circuit 392A-B, High Efficiency Dual Regulator, built with the LTC3728EUH controller. Schematic, bill of materials, and description of the test circuit and data sheet for the controller are available at the course web site, or at www.linear.com.

One C055071A2 MPP toroid from Magnetics Inc.
18AWG magnet wire
DC power supply, 7V to 24V up to 5A
Oscilloscope and probe
Decade resistor box, 200W rating.
Precision meters for measuring input and output DC voltage and current.

Useful data
C055071A2 data sheet,
Magnet wire data:
http://my.ece.ucsb.edu/York/Bobsclass/194/References/Magnetics/slup201.pdf
MPP Material Curves:
http://my.ece.ucsb.edu/York/Bobsclass/194/References/Magnetics/Core%20Selection/Manufacturers/MPPMaterialPropertyCurves-1.pdf

Problem Statement
Your boss walks into your office and says, “Good job with the converter Weatherby [he never gets your name right], but the customer is changing the spec. The European Union just announced a new energy efficiency standard, and the proposed product won’t comply unless we can increase the efficiency. The customer is willing to relax the overall size requirement to get the efficiency. The bad news is that we already placed volume orders for all the parts except the inductor. So the only thing you can change to improve the efficiency is the inductor. We don’t actually have money in the budget for inductors, but we do have a warehouse full of Magnetics Inc. C055071A2 toroids left over from the Nintendo-phone fiasco; you’ll have to find a way to work with those.”

The specific data points that have to be met to comply with the new standard are for the 5V output:
At 12V in, 50% load (Iout=2A), improve the efficiency by 1% over the existing LT3728/392A-B design.
At 24V in, 50% load (Iout=2A), improve the efficiency by 2% over the existing LT3728/392A-B design.
(use your data from Lab 1 as the baseline)

Preparation
The 2.2uH inductor used in the original design of the buck regulator was probably chosen as a compromise between size and efficiency. While it is very small, it does not result in maximum efficiency for the converter. The given toroidal is a molypermalloy powder core (MPP), and the magnet wire available is 18 gauge. This is a rather large toroid compared to the existing inductor. We won’t worry about mounting it securely to the PCB for the lab – the two ends of the magnet wire will be soldered to
Ultimately, the problem is just to come up with a number of turns (N) for your inductor. You may use analysis, simulation, or intuition to come up with a value for L, and hence N, that will improve efficiency (refer to the Post Lab section for inductor analysis steps). Use the SPICE circuit from the last lab to evaluate the improvements in efficiency at the specified combinations of input voltage and output current. If you think core loss will be an important factor, try to model it. If you think the dominant inductor-related loss is due to ripple current and/or dc copper loss, then just using the correct values of inductance and winding resistance in the model will suffice.

Notes:
1. The switching frequency of the controller is a design variable: pick whichever switching frequency (250kHz or 550kHz) you think will give the best efficiency when coupled with an appropriate inductor. Remember: switching loss is proportional to f; \( \Delta I_f \) is inversely proportional to \( fL \).
2. The controller should work in the continuous current mode. If the inductance becomes large the controller will switch to a burst mode. The spice model of the LT3728 will correctly indicate the mode of operation. Be sure to look at the switching node waveform over a long time period to verify that the switching is continuous. If it isn’t, then your chosen inductance is probably too large. (for instance, 100\( \mu \)H is probably too much)
3. A soldering iron and a spool of magent wire will be available in the lab if you need or want to try a different number of turns.

Lab Procedure
Once you have a design you like, wind the toroid. Leave a reasonable length of wire at the beginning and end of the winding. With a pair of pliers, strip the insulation off the ends of the wire. Measure the inductance and resistance of your inductor.

De-solder the 2.2uH inductor and solder the toroid in its place.

Set the jumpers on the demo board as follows:

JP6/RUN2=0
JP5/FCB=0
JP4/STBY=1
JP3/FSET= 0 or 1 depending on your choice of frequency (0=250kHz, 1=550kHz)
JP2/FLTCPL N/A
JP1/RUN1=1
If the DC power supply has an adjustable current compliance, set it to 0.5A as a precaution. Set the supply to 12V and connect the supply and meters to the Vin terminals as shown in figure 1 of the quick start guide (reproduced below). With the oscilloscope verify the switching frequency and duty cycle of the switching node for the 5.0V converter.

![Figure 1. Proper Measurement Equipment Setup](image)

If operation seems correct, increase the power-supply current compliance to 3.5A. Connect the decade resistor to the 5.0V output.

Standard efficiency: Measure efficiency for the stated conditions (Vin=12V and Vin=24V, Iout=2A). Compare these results to what you achieved in Lab 1. Let your boss (or the TA) confirm the result.

Efficiency sweeps: With JP3 still in the appropriate position for your chosen frequency, measure efficiency for the same set of input voltages and output currents that you used in lab 1 (Vin=7, 12, and 24; load=20, 40, 60, 80, and 100%). Be sure to measure the output voltage and current; don’t use $V^2/R$ for $P_{out}$ since the temperature of the load resistor will be changing.

With the input at 24V and the load at 20% of full, move JP3 to the opposite position and measure efficiency. Verify the switching frequency for this case.

**Post Lab**

Analyze your inductor design. Provide theoretical values for

1. Reluctance of the core at zero DC current (100% of the initial permeability) and at $I_{dc}=2A$. Use the *Permeability versus DC Bias Curves* for MPP 60µ to get permeability at 2A (found in the MPP Material Properties Curves pdf document at the course web site). Remember that $H \cdot L_e = NI$
2. Inductance at $I=0$Adc and $I=2A$ calculated using the above reluctances. Is the difference appreciable?
3. Inductance calculated using the value of $A_L$ given in the data sheet.
4. pk-pk current ripple, $\Delta I_L$, using the value of $L$ at $I=2A$. Calculate for $V_{in}=12V$ and $V_{in}=24V$.

5. pk-pk flux ripple, $\Delta B$, at $V_{in}=12V$ and $V_{in}=24V$. Use Faraday's law $V_L = N \frac{\Delta \Phi}{\Delta t} = N \frac{\Delta B \cdot A_e}{\Delta t}$.

6. core loss. Use the formula given in the Core Loss Density Curve for MPP 60$\mu$. $B$ in the formula is $\Delta B/2$, and $f$ is frequency in kHz (e.g. use 250 not 250,000). $P_L$ is given as a density (mW/cm$^3$). Multiply by volume = $A_e L_e$.

7. winding resistance. Use the winding turn length from the C055071A2 data sheet (0% winding factor) and your value of $N$ to get total wire length. The value of $\Omega/cm$ for 18 gauge wire is available from the magnet wire data file at the course web site.

8. peak flux density ($B_{max}$). Use the Normal magnetization curve for MPP 60$\mu$, with a value of $H$ corresponding to $I_{max} = 4A + \frac{\Delta I}{2}$. If we take 0.7T as $B_{sat}$, is $B_{max} < B_{sat}$?

Tabulate the measurement data and graph efficiency vs load current for each value of $V_{in}$. Compare the measured efficiency vs load curves from the original design as measured in lab 1. Comment on differences; did you achieve the desired improvement? Where do you think the gains were made?

Tabulate the efficiency measurements made at 24V and 20% load for the two values of switching frequency. Calculate power loss and graph loss vs switching frequency for these two points. The slope of this curve is the low-load switching loss (in W/Hz = Joules). Compare the measured loss vs frequency curve to that from lab 1. Did the inductor change affect switching loss?