Example Midterm Problem

Magnetics Design and Loss Analysis

ECE 482

Fig. 1 shows the power stage of the drivetrain boost converter to be assembled in experiment 2. For all parts of this prelab, consider operation of the converter at an operating point around which:

- $V_{bat} = 20$ V
- $V_{bus} = 50$ V
- $P_{out} = V_{bus}I_{bus} = 100$ W
- $\Delta i_l = 80\%$ of I_L
- $f_s = 200$ kHz

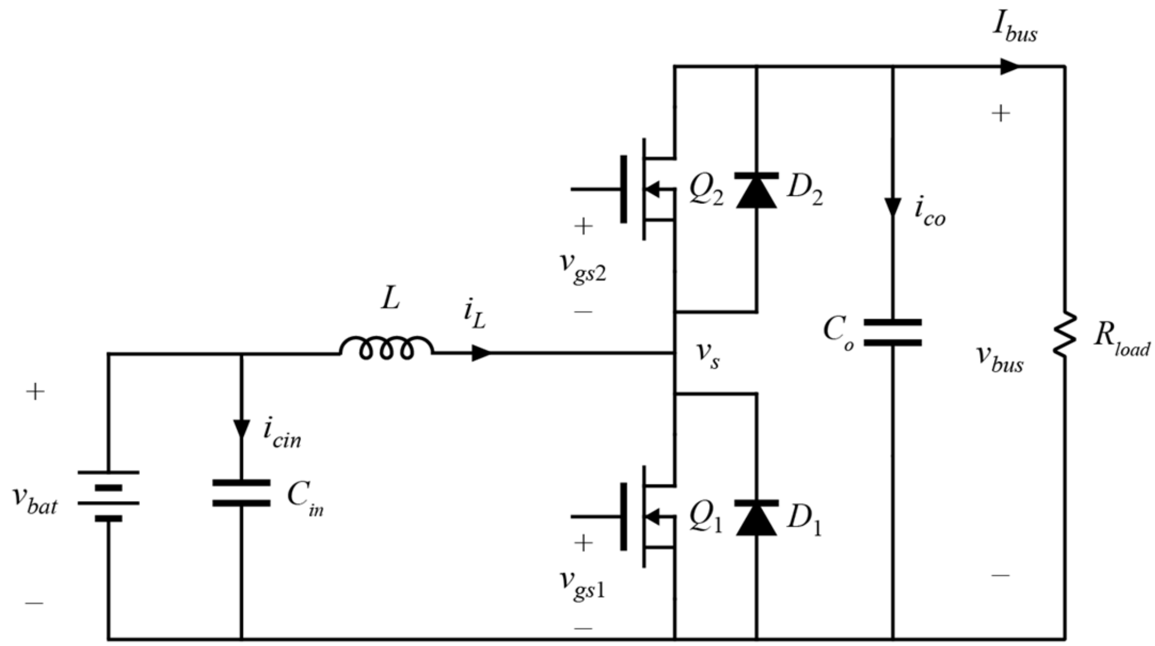


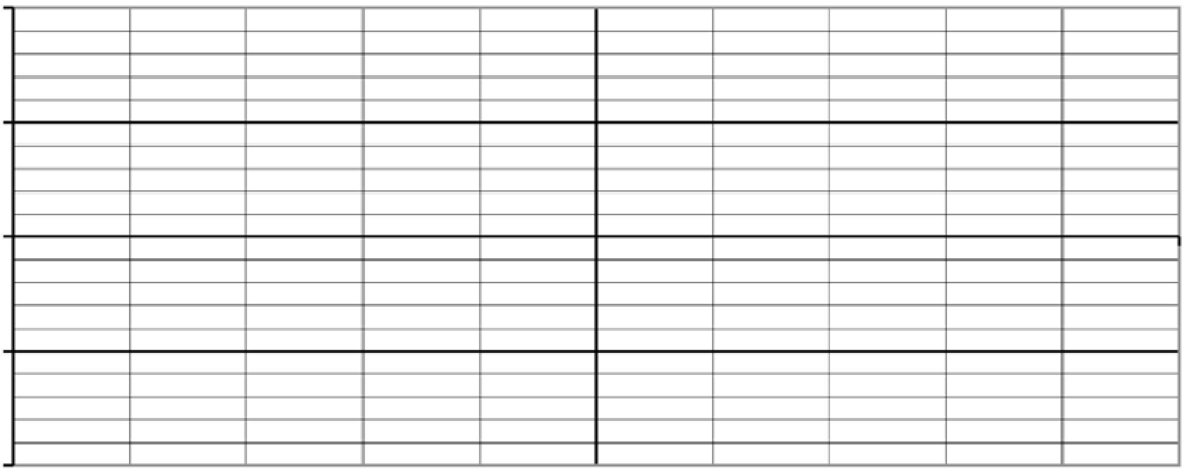
Figure 1: Open Loop Boost Converter

1. Assuming an ideal, lossless converter, find the following:
    a. Average inductor current I_L
    b. Current ripple Δi_l
    c. Maximum inductor current $I_{max} = I_L + \Delta i_l$
    d. Converter duty cycle D
    e. Inductance L

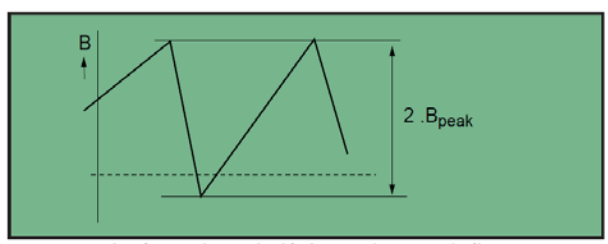
2. The inductor is designed to have a maximum flux density B_{pk} = 300 mT when the inductor current is I_{max}. The ETD29 core of 3C90 material is used (core and material information are attached). How many turns n must be wound on the inductor to achieve this B_{pk} at the specified operating point?

3. What must the inductor equivalent air gap, l_g, be in order to achieve the specified inductance with this amount of turns?

4. What is ΔB at this operating point? On the axes below, sketch the flux density in the core, B(t) over one switching period. Label all salient features.



5. Given the data in the attached core datasheet, give an *estimate* the core loss of the inductor at this operating point, assuming 100°C temperature. Argue whether or not this is a good design, and what could be done differently to improve it.
(*Note: on the ferroxcube datasheets,* $\hat{B}$ = *"*B_{peak}*" is defined as in the following figure:*)



B_{peak} in the formulas is half the peak to peak flux excursion in the core.

6. Is the K_g or K_{gfe} method more appropriate for this design? Just answer one or the other, no need to justify.

7. Inductor Design: Simplified Equations:

1. MMF and Field Strength

$$\mathcal{F} = l_m H$$

2. Flux and Flux Density

$$\Phi = BA_c$$

3. Faraday's Law (integral and differential form)

$$B = \frac{1}{nA_c}\int_0^t v(\tau)d\tau \qquad v(t) = nA_c\frac{dB(t)}{dt}$$

4. Ampere's Law for an *ungapped* core

$$ni(t) = H(t)l_m$$

5. Core Material Characteristics:

$$B = \mu H$$

Inductor Circuit Behavior:

6. Inductor Behavior (integral and differential form)

$$I_L = \frac{1}{L}\int_0^t v_L(\tau)d\tau \qquad v_L(t) = L\frac{dI_L(t)}{dt}$$

Magnetic Circuits:

7. Reluctances:

$$\Re_c = \frac{l_m}{\mu A_c} \qquad \Re_g = \frac{l_g}{\mu_0 A_c}$$

8. Inductance of a gapped core:

$$L = \frac{n^2}{\Re_c + \Re_g}$$

3C90 SPECIFICATIONS

A low frequency power material for use in power and general purpose transformers at frequencies up to 0.2 MHz.

	CONDITIONS	VALUE	UNIT
μ_i	25 °C; ≤10 kHz; 0.25 mT	2300 ±20%	
μ_a	100 °C; 25 kHz; 200 mT	5500 ±25%	
B	25 °C; 10 kHz; 1200 A/m	≈ 470	mT
	100 °C; 10 kHz; 1200 A/m	≈ 380	mT
P_V	100 °C; 25 kHz; 200 mT	≤ 80	kW/m^3
	100 °C; 100 kHz; 100 mT	≤ 80	
	100 °C; 100 kHz; 200 mT	≈ 450	
ρ	DC, 25 °C	≈ 5	Ωm
T_C		≥ 220	°C
density		≈ 4800	kg/m^3

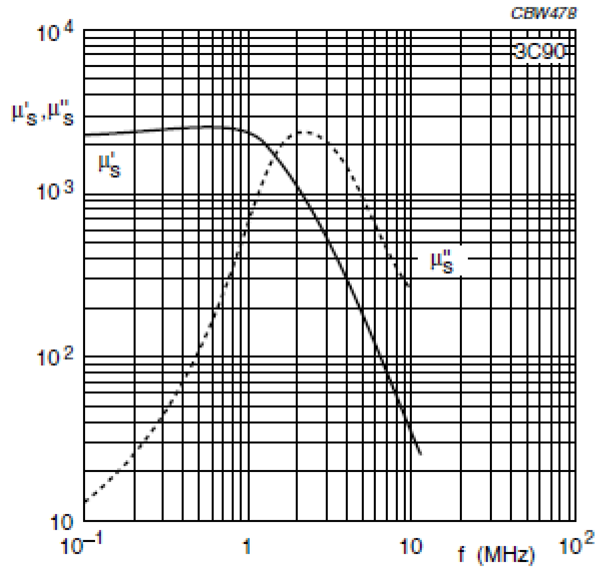


Fig.1 Complex permeability as a function of frequency.

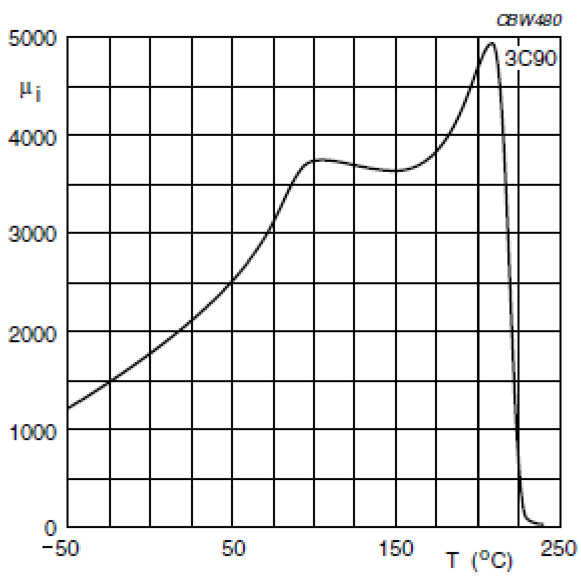


Fig.2 Initial permeability as a function of temperature.

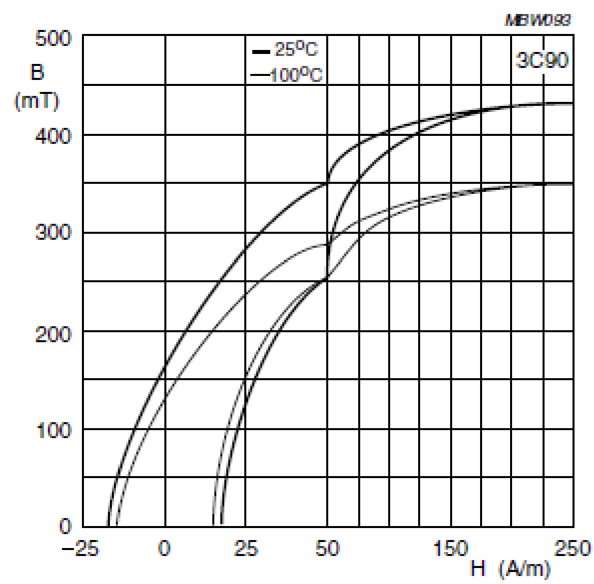


Fig.3 Typical B-H loops.

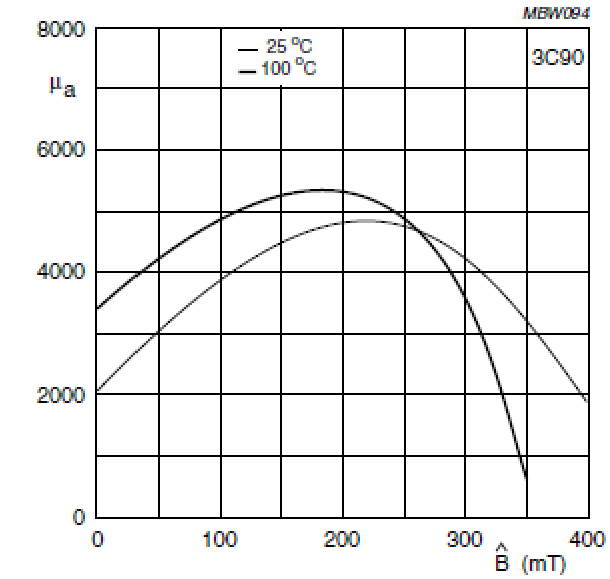


Fig.4 Amplitude permeability as a function of peak flux density.

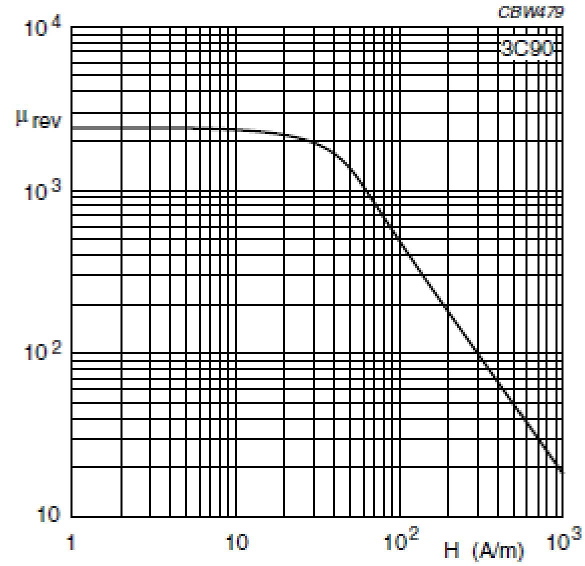


Fig.5 Reversible permeability as a function of magnetic field strength.

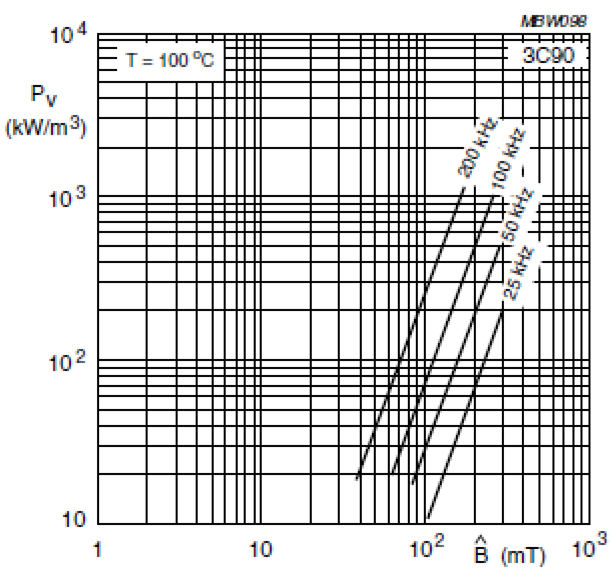


Fig.6 Specific power loss as a function of peak flux density with frequency as a parameter.

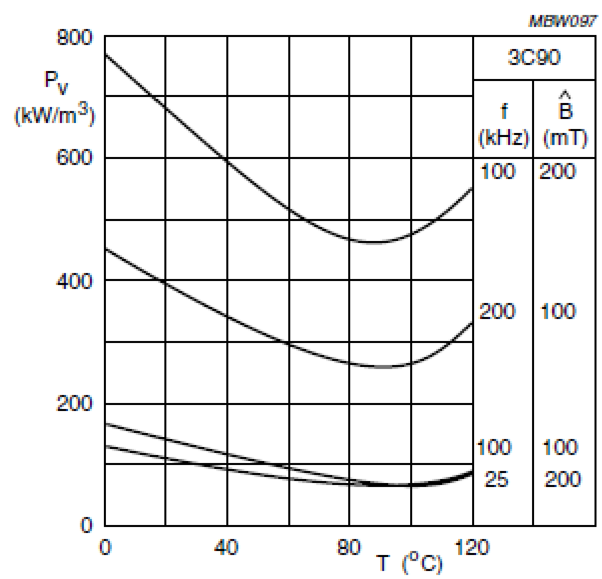
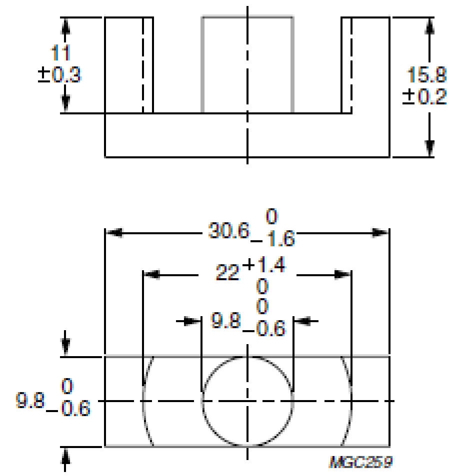


Fig.7 Specific power loss for several frequency/flux density combinations as a function of temperature.

CORE SETS

Effective core parameters

SYMBOL	PARAMETER	VALUE	UNIT
Σ(I/A)	core factor (C1)	0.947	mm^{-1}
V_e	effective volume	5470	mm^3
l_e	effective length	72.0	mm
A_e	effective area	76.0	mm^2
A_{min}	minimum area	71.0	mm^2
m	mass of core half	≈ 14	g



Dimensions in mm.

Fig.1 ETD29/16/10 core half.

Core halves

Clamping force for A_L measurements, 40 ±20 N. Gapped cores are available on request.

GRADE	A_L (nH)	μ_e	AIR GAP (µm)	TYPE NUMBER
3C90	2350 ±25%	≈ 1770	≈ 0	ETD29/16/10-3C90
3C94	2350 ±25%	≈ 1770	≈ 0	ETD29/16/10-3C94
3C95 des	2860 ±25%	≈ 2160	≈ 0	ETD29/16/10-3C95
3C96 des	2200 ±25%	≈ 1660	≈ 0	ETD29/16/10-3C96
3F3	2200 ±25%	≈ 1660	≈ 0	ETD29/16/10-3F3
3F35 des	1600 ±25%	≈ 1210	≈ 0	ETD29/16/10-3F35

Properties of core sets under power conditions

GRADE	B (mT) at	CORE LOSS (W) at				
	H = 250 A/m; f = 25 kHz; T = 100 °C	f = 25 kHz; $\hat{B}$ = 200 mT; T = 100 °C	f = 100 kHz; $\hat{B}$ = 100 mT; T = 100 °C	f = 100 kHz; $\hat{B}$ = 200 mT; T = 25 °C	f = 100 kHz; $\hat{B}$ = 200 mT; T = 100 °C	f = 400 kHz; $\hat{B}$ = 50 mT; T = 100 °C
3C90	≥330	≤ 0.66	≤ 0.69	–	–	–
3C94	≥330	–	≤ 0.5	–	≤ 3.0	–
3C95	≥330	–	–	≤ 3.23	≤ 3.06	–
3C96	≥340	–	≤ 0.37	–	≤ 2.4	–
3F3	≥320	–	≤ 0.65	–	–	≤ 1.1
3F35	≥300	–	–	–	–	–

Properties of core sets under power conditions (continued)

GRADE	B (mT) at	CORE LOSS (W) at			
	H = 250 A/m; f = 25 kHz; T = 100 °C	f = 500 kHz; $\hat{B}$ = 50 mT; T = 100 °C	f = 500 kHz; $\hat{B}$ = 100 mT; T = 100 °C	f = 1 MHz; $\hat{B}$ = 30 mT; T = 100 °C	f = 3 MHz; $\hat{B}$ = 10 mT; T = 100 °C
3C90	≥330	–	–	–	–
3C94	≥330	–	–	–	–
3C95	≥330	–	–	–	–
3C96	≥340	≤ 2.0	–	–	–
3F3	≥320	–	–	–	–
3F35	≥300	≤ 0.74	≤ 5.7	–	–