MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Electrical Engineering and Computer Science

6.622 Power Electronics
Design Project

In this project you are to design a buck converter with the following specifications:

Input voltage range:	24-36 V
Input voltage transient limit[1]:	44 V for up to 1 ms
Output Power Range (resistive load):	50 - 125 W
Output Voltage (static requirement):	14 V ± 3%
Output Voltage (transient limits)[2]:	14 V ± 20%
Allowed output voltage ripple (p-p, any R load):	100 mV
Allowed input current ripple (p-p, ideal source):	50 mA
Minimum efficiency (across voltage, load):	90%
Ambient temperature range	-20ºC – +50ºC

As part of this project, you need to:

1. Design and specify numerical component values for the power stage, input filter, and output filter.
2. Specify the power devices and heatsink(s).
3. Specify/design the passive components (e.g. capacitors and inductors) for the power stage and input and output filters.
4. Design a feedback controller that results in a stable closed-loop system across line (input voltage) and load variations and also meets the static and transient control requirements. (A mathematical description of the controller coupled with supporting simulations is sufficient.)

You should provide sufficient analysis and simulation to validate that the proposed design will meet the specifications. Datasheets for a set of components (such as power devices, inductor cores, etc.) are provided for your use. Reasonable departures from this component set are permitted but datasheets with sufficient design data must be provided for any such departures. (Note that pre-designed components, such as EMI filters, wound inductors, and converters are *not* permissible.) Provided below are some guidelines to help you with the design:

Power Devices and Heat Sinks

When specifying each power device you must ensure that the device junction temperature remains sufficiently (e.g., at least 25 °C) below the allowable maximum junction temperature (typ. 175 °C) under all operating conditions. A first step is to make approximate calculations of device losses, including conduction and switching losses. For switching losses of the power MOSFET you may assume linear rise and fall of the current waveforms, and use the nominal

[1] The converter must be able to survive this input voltage transient, but does not have to run during the transient.
[2] The voltage should not vary outside this range during steps between minimum and maximum load.

delay, rise, and fall times provided in the datasheet. You may neglect the switching losses associated with the diode. Note that the on-state resistance of a power MOSFET varies with junction temperature; this variation is specified in the data sheet.

Once device losses are calculated, you should select heat sink(s) with sufficiently low thermal resistance to limit the junction temperature of the devices to acceptable levels. (Junction-to-Case thermal resistances are provided in the device datasheets.) You may choose to transfer heat through the printed circuit board of your design to a heat sink mounted to the other side of the board. (TI Application Note AN-2020 may be useful for finding the thermal resistances for transferring heat in this case.) You should assume a maximum 40 °C ambient temperature when sizing the heat sink(s).

Passive Components

Ripple current capability is an important consideration when specifying capacitors. (For example, the filter capacitor at the input of a buck converter must sustain substantial ripple.) Another important consideration for filtering capability is the equivalent series resistance (ESR) of the capacitor. (For example, the output ripple voltage may be larger than expected for the selected capacitance value due to the drop across the ESR.) At higher frequencies, the capacitor equivalent series inductance (ESL) also becomes important. When specifying a capacitor, you must validate that the ripple capability of the capacitor is not exceeded, and must account for ESR (and possibly ESL) when calculating ripple voltage on the capacitor.

A set of "rectangular modular" or RM ferrite cores is provided for the design of the converter and input filter inductors. Various values of A_L (nH for one turn) are available in each core (recall that inductance is proportional to the number of turns squared.) For 3F3 core material you may assume a maximum allowable flux density of 3000 gauss (0.3 T). (You may also use other core materials, such as Epcos N49.) You should also assume a maximum allowable current density in the windings no higher than 500 A/cm^2; you may want to consider KPVS Example 18.5 when selecting your design. Of course, the specified windings must fit within the winding area of the core bobbin. For simplicity, you may neglect inductor core and winding losses and inductor temperature rise, though ambitious students may choose to estimate these.

For those who are ambitious, the inductor losses and temperature rises may be calculated and a design selected such that the inductor does not overheat. (A centerpost temperature rise of 50 °C over the 50 °C ambient is reasonable.) To estimate temperature rise, you should compute the (approximate) losses in the inductor (as the sum of winding and core losses) and multiply by the thermal resistance of the core to find the inductor centerpost temperature rise. Winding power loss may be (crudely) approximated as the dc winding resistance times the rms inductor current squared. (In more sophisticated calculations, skin effect may be considered in the windings.) Core power loss in a 3F3 material core can be computed by approximating the ac flux in the core as sinusoidal, and calculating the core loss as:

$$P_{core} = C_M \cdot f^{\alpha} \cdot (B_{ac,pk})^{\beta} \cdot V_{core}$$

where P_{core} is the core loss in mW, C_M is the loss density coefficient, f is the switching frequency in Hz, $B_{ac,pk}$ is the peak *ac* flux swing in T, and V_{core} is the volume of the core in cm^3. Empirical values for C_M, α, and β are shown for 3F3 material over various switching frequency ranges in Table 1. Note that these values are only approximate curve fits to measured loss for sinusoidal drive over limited ranges; computed values should thus be used conservatively.

Frequency range	C_M	α	β
100 – 300 kHz	$2.5\text{x}10^{-4}$	1.63	2.45
300 – 500 kHz	$2\ \text{x}10^{-5}$	1.8	2.5
500 – 1000 kHz	$3.6\text{x}10^{-9}$	2.4	2.25

Table 1 Core loss curve fit data for 3F3 Ferrite material at 100ºC core temperature. Data extracted from Ferroxcube Application Note "Design of Planar Power Transformers."

For the cores provided, the thermal resistance values are as follows: RM6 is 60 °C/W, RM8 is 38 °C/W, RM10 is 30 °C/W, RM12 is 23 °C/W, and RM14 is 19 °C/W. Further data about the RM family of cores may be found in KPVS Table 20.1.

Feedback Control Design

The controller can be designed using linearized, averaged models of the converter. The closed loop system should be stable and well damped for *all* allowed values of input voltage and output resistance, so you should design for the worst case. (Note that the buck converter is particularly simple in terms of control design.) Because the static voltage variation is small, an integral control component is useful for eliminating steady state error. Voltage-mode control (i.e. duty-ratio control) using a PI controller is one design option. You should specify the control law mathematically (e.g. as a transfer function from error voltage to duty ratio). Ambitious students may provide a circuit implementation of such a controller (with a duty ratio signal of specified scaling at the output). We will not consider the PWM modulator, gate drive, or several other circuit design issues in this paper design. You should provide clear validation (analysis and simulation) that the control design is acceptable. As part of this, you should demonstrate that the output voltage will remain within the allowed transient limits during step changes in load (between minimum and maximum values). If, for any reason, you are unable to provide a closed-loop controller, please demonstrate the open-loop dynamics and transient response.

YOUR REPORT SHOULD INCLUDE A COVER PAGE THAT CLEARLY AND CONCISELY STATES THE SELECTION / DESIGN OF EACH ELEMENT OF YOUR SYSTEM (E.G., INCLUDING THE DESIGN OF THE INDUCTORS, SELECTED DEVICES AND HEAT SINKS, ETC.) AND STATES THE KEY OPERATING PARAMETERS (E.G., INCLUDING SWITCHING FREQUENCY, COMPENSATOR TRANSFER FUNCTION). THE SELECTED DESIGN VALUES MUST BE JUSTIFIED IN THE BODY OF THE REPORT. THE COVER PAGE SHOULD ALSO INCLUDE A TABLE THAT STATES HOW THE PREDICTED PERFORMANCE COMPARES TO OF THE CONVERTER SPECIFICATION REQUIREMENTS ON PAGE 1.