

Homework Assignment #10 – due via Moodle at 11:59 pm on Monday, April 29, 2024***Instructions, notes, and hints:***

You may make reasonable assumptions and approximations to compensate for missing information, if any. Provide the details of all solutions, including important intermediate steps. You will not receive credit if you do not show your work.

The first set of problems will be graded and the rest will not be graded. Only the graded problems must be submitted by the deadline above. Do not submit the ungraded problems.

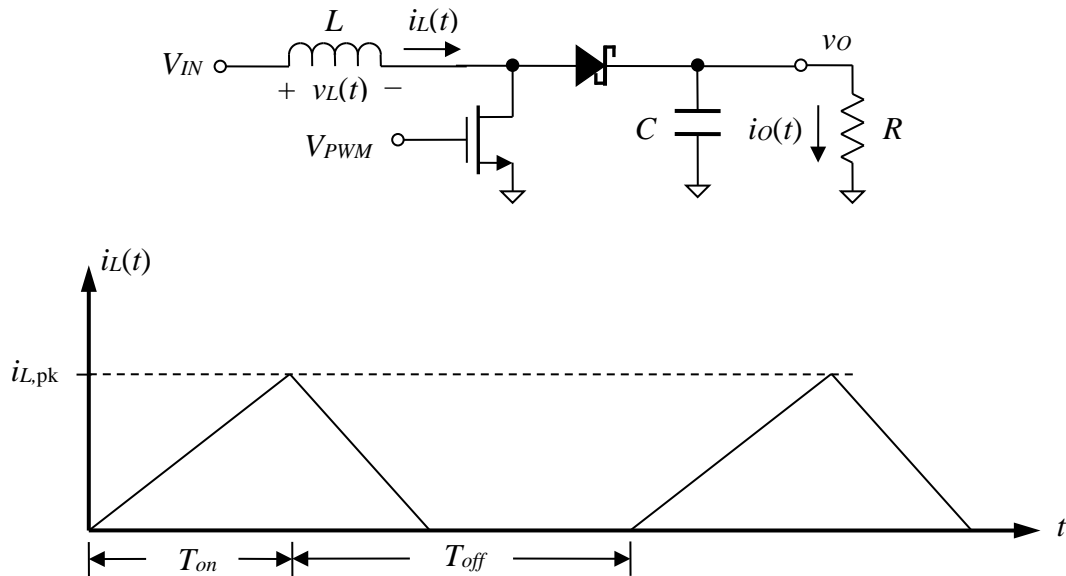
Graded Problems:

1. [adapted from Prob. 5.15 of Erickson and Maksimovic, *Fundamentals of Power Electronics*, 2nd ed.] Battery-operated equipment sometimes enters “sleep” mode in which a regulated power supply voltage is still needed to operate various monitoring functions, but the circuitry draws very little current. Thus, if a switch-mode voltage converter is used, it typically operates in discontinuous conduction mode (DCM). Since the power loss in a voltage converter circuit varies with switching frequency, the converter frequency is usually reduced in sleep mode.

The boost converter depicted in the upper diagram at the top of the next page is designed to produce a regulated output voltage of 5.0 V when powered by a pair of series-connected ZnO cells that have a total voltage of 3.0 V. The converter operates in DCM with a constant MOSFET on-time T_{on} ; that is $DT_s = T_{on}$. The off-time T_{off} is varied as necessary to keep the output voltage at a constant 5.0 V. This means that the duty cycle D and the switching frequency f_s must be simultaneously varied to maintain a constant on time since $T_{on} = D/f_s$. Assume that all components are ideal and that there are no significant voltage drops across the diode or the MOSFET. The switching voltage v_{PWM} is positive during the DT_s interval of the switching cycle.

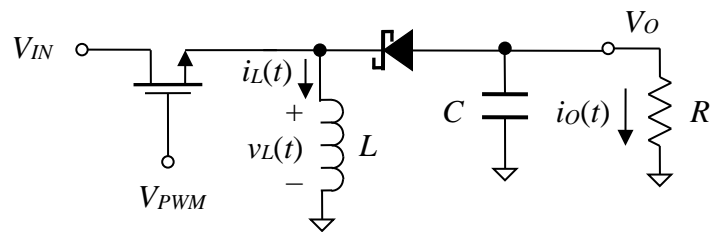
- a. Find an algebraic expression for the CCM-DCM boundary and the voltage conversion ratio V_O/V_{IN} in terms of T_{on} , T_{off} , the inductance L , and the effective load resistance R .
- b. Assuming that the MOSFET on-time is $T_{on} = 10 \mu\text{s}$ and that the time-average load current I_O varies from 100 μA to 10 mA, select values for L and C such that the output voltage peak ripple Δv_O (which is half the peak-to-peak ripple) is less than 50 mV, the converter always operates in DCM, and the peak inductor current is as small as possible.
- c. Given the specifications in part b, find the minimum and maximum values of the switching frequency f_s .

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Diagrams for Graded Prob. 1.

2. [adapted from Prob. 3.1 of Erickson and Maksimovic]: In the voltage inverter circuit (called a “buck-boost converter” in Erickson and Maksimovic) shown below, the inductor has winding resistance R_w . All other losses can be ignored.
 - a. Applying the same approximations used in Chap. 3 of Erickson and Maksimovic, derive an expression for the voltage conversion ratio V_O/V_{IN} that includes the nonzero inductor winding resistance. Ignore the diode voltage drop and the equivalent “on” resistances of the diode and FET. The FET is on (conducting) during the DT_s switching interval.
 - b. Derive an expression for the efficiency of the converter circuit. Manipulate your expression into a form similar to Eqn. (3.35) in *Fundamentals of Power Electronics*, 2nd ed.



3. A PIC32 microcontroller operates from a unipolar 3.3 V power supply and draws an absolute maximum current of 300 mA. In the quad-flat no-leads (QFN) package, the rated thermal resistance is 28 °C/W, and its maximum safe junction temperature is 125 °C. Find the absolute maximum ambient temperature in the vicinity of the PIC32 for which the microcontroller does not need a heat sink.

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Ungraded Problems:

The following problems will not be graded. However, you should attempt to solve them on your own and then check the solutions. Do not give up too quickly if you struggle to solve any of them. Move on to a different problem and then come back to the difficult one after a few hours.

1. The expressions for the output voltage V_O of a boost converter operating in continuous current mode (CCM) and discontinuous current mode (DCM) are given below. Show that the two expressions give the same result at the boundary between CCM and DCM; that is, show that the output voltage is a continuous function of the equivalent load resistance as the converter makes the transition. Assume that the switching frequency f_s and the duty cycle $D = D_1$ of the switching waveform do not change.

$$\text{CCM: } V_O = \frac{V_{IN}}{1-D} \quad \text{DCM: } V_O = V_{IN} \frac{1 + \sqrt{1 + \frac{4D_1^2}{K}}}{2}, \text{ where } K = \frac{2Lf_s}{R}$$

2. Suppose that a 2N2222A BJT is to be used as an electronic switch in an underwater sensor that will be operating near hydrothermal vents on the ocean floor. The ambient temperature could therefore approach 100 °C. As shown in the datasheet available on the Laboratory page of the course web site, the 2N2222A is fabricated in a TO-18 package. The BJT is used in a circuit that operates from a unipolar power supply with $V_{CC} = 5.0$ V, and its maximum collector current in the “on” state is 10 mA. The power dissipated in the base-emitter path is negligible. Determine whether the 2N2222A should have a heat sink in this application. Apply a $\times 2$ safety factor for the maximum safe power dissipation. Note that because the BJT is used as a switch, it alternates between the cut-off region and the saturation region.
3. Depicted on the next page is a simple linear voltage regulator that produces a fairly stable output voltage of 12.3 V at a load current I_L of up to 5.0 A. The zener diode provides the voltage regulation, and the BJT passes the load current, which is much too large for the diode to handle. The input of the regulator (the V_{IN} port) is connected to the output of a filtered full-wave bridge rectifier circuit with an average output voltage of 18 V and a ripple of ± 2 V. A type 2N3055 *npn* BJT serves as the pass transistor. It is packaged in a TO-3 type case, which is well suited for mounting on a heat sink. You may assume that $V_{BE} \approx 0.7$ V for the 2N3055, and you may ignore the Early effect. The voltage across the zener diode stays very close to 13 V as long as it operates in reverse breakdown mode; it can be modeled as an ideal 13 V source in which current flows against the direction of the arrow in the circuit symbol.
 - a. Find a rough estimate of the average power dissipated by the pass transistor. Note that it normally operates in the active region.
 - b. Find the power efficiency of the regulator circuit when full rated current is delivered to the load. You may ignore the comparatively negligible power dissipated by resistor R_{bias} and the zener diode.
 - c. Repeat part b for the case when half of the rated current is delivered to the load.

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UG Prob. 3 (continued)

- d. Using the 2N3055 datasheet (available on the Laboratory page at the ECEG 351 course web site), show that the transistor should be mounted on a heat sink if it is to be operated at ambient temperatures up to 50 °C. Note that the thermal time constant of the transistor is much longer than the period of a 60 Hz AC waveform. This implies that the operating temperature of the transistor is determined by its time-average power dissipation. Assume that $\theta_{JA} \approx 30 \text{ }^\circ\text{C/W}$ for the 2N3055.
- e. Find the maximum thermal resistance θ_{SA} (in $^\circ\text{C/W}$) of the required heat sink without applying a safety factor (i.e., extra capacity to handle unexpected operating conditions). Assume that the thermal resistance θ_{CS} of the insulating pad between the transistor's case and the heat sink is 0.5 $^\circ\text{C/W}$.

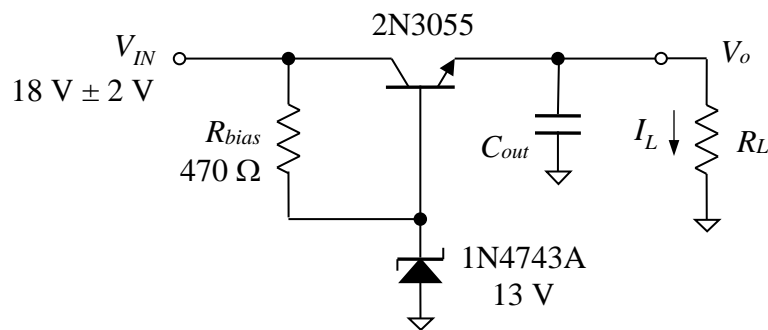


Diagram for Ungraded Prob. 3.