**Homework Assignment #3: Chapter 3**
*Introduction to Power Electronics*
*University of Colorado, Boulder*
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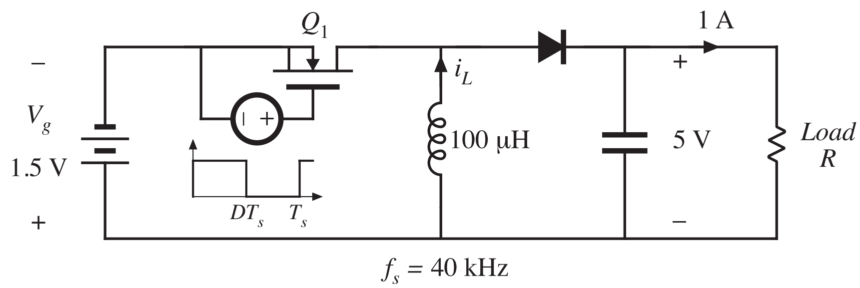
**Loss modeling and design for efficiency**

A USB (universal serial bus) connector can power its devices at 5 volts and 1 amp. In a certain portable product, it is desired to provide this power from a 1.5 V battery. It is decided to employ a buck-boost converter to increase the 1.5 V battery voltage to the required 5 V. The power converter schematic is illustrated below.




A suitable transistor is found having an on-resistance of 8 milliohms, and a Schottky diode is found that has a forward voltage drop of 0.4 V. The on-resistance of the Schottky diode may be ignored.

For this problem, you must employ the methods discussed in the Chapter 3 lectures, to analyze this converter and find analytical expressions for the output voltage, inductor current, etc., as well as to derive an equivalent circuit that can be solved for the converter efficiency. You are asked to enter expressions for intermediate steps in your analysis; these expressions must be entered as computer-readable equations using the exact variable names as defined below:

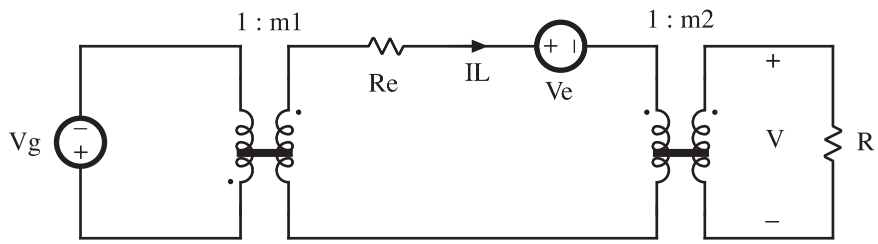
- Input voltage Vg
- Output voltage V
- Duty cycle D
- Load resistance R
- Inductor current IL
- MOSFET on-resistance Ron
- Diode forward voltage drop Vd
- Inductor winding resistance RL

When entering equations, these variable names are case-sensitive and must be entered exactly as defined above; for example, D*(Vg-V)/R. The complement of the duty cycle should be entered as (1-D). When numeric values are requested, a single numeric value must be entered that is accurate to within plus or minus 0.1% of the value computed using the methods described in lecture

It is highly recommended that you first sketch the converter circuit and work the questions with pencil and paper. Then enter your answers into the fields below.

**Question 1**. Derive an equivalent circuit that models the dc properties of this converter. Include the inductor copper loss, as well as the transistor and diode conduction losses, but ignore all other sources of loss. Your model should correctly describe the converter dc input port.

If necessary, manipulate your model into the form shown below. The quantity IL is the dc component of the inductor current.




For questions 1 to 4, you are asked to enter mathematical expressions for the elements in this model. The effective turns ratios are functions of only the duty cycle D, while the effective loss elements Re and Ve are functions of the duty cycle D and the loss elements, but no other quantities.

Enter your expression for the effective turns ratio m1 in the field below.

**Question 2**. The effective resistance Re depends on the resistive loss elements of the converter. Use your model to find an expression for Re, and enter your expression below.

**Question 3**. The effective source Ve also models losses in the converter. Enter an expression for Ve in the field below.

**Question 4**. Enter your expression for the turns ratio m2 in the field below.

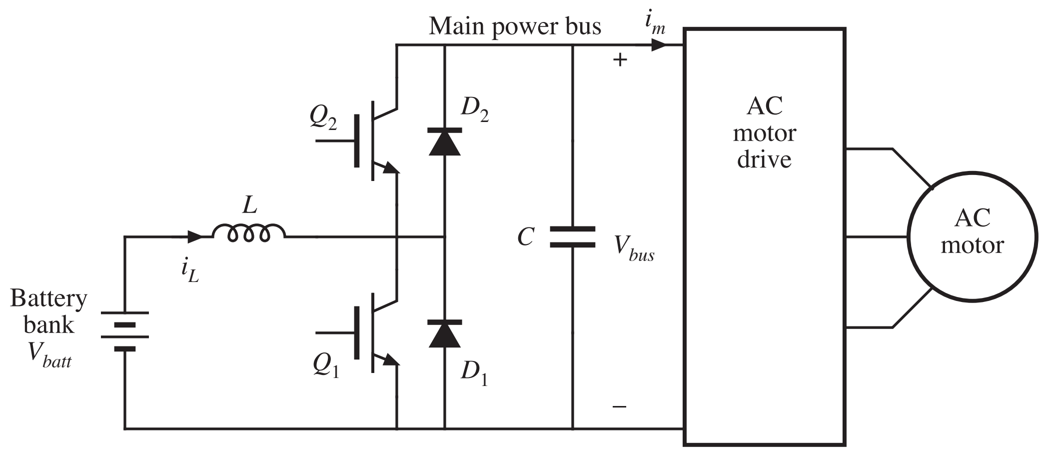
**Question 5**. Derive an expression for the conversion ratio V/Vg. Express your result in terms of Vg, D, RL, Ron, Vd, and R, and enter the result below.

**Question 6**. Derive an expression for the converter efficiency. Express your result in terms of Vg, D, RL, Ron, Vd, and R, and enter the result below.

**Question 7**. It is desired that the converter efficiency be at least 85% under nominal conditions, i.e., when the input voltage is 1.5 V and the output is 5 V at 1 A. How large (in ohms) can the inductor resistance be? Again, enter this and other numerical values with an accuracy of at least plus or minus 0.1%.

**Question 8**. For the design of Question 7, what is the duty cycle? Enter your value below.

**Question 9**. The remaining questions pertain to a bidirectional converter that interfaces a battery bank to a main power bus in an electric vehicle. A schematic of the converter and how it fits in the system is shown below. The converter switches are realized using *current bidirectional switches*, which will be discussed in Chapter 4; these allow both discharging and charging of the battery.

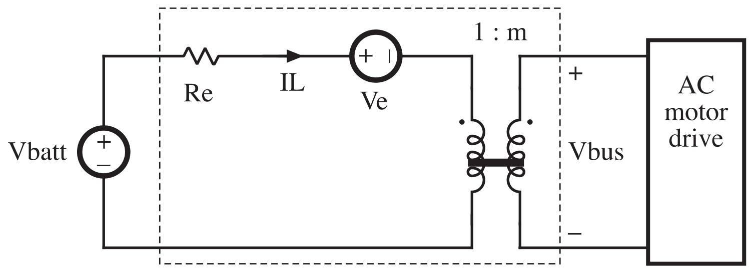



When the vehicle is accelerating, power is drawn out of the battery bank, and the converter boosts the battery voltage $V_{batt}$ to the dc bus voltage $V_{bus}$. The inductor current $i_L$ is positive under these conditions, and transistor $Q_1$ conducts during the first interval for $0 < t < DT_s$. Diode $D_2$ conducts during the second interval for $DT_s < t < T_s$. Transistor $Q_2$ and diode $D_1$ do not conduct for this case.

When the vehicle is decelerating, the AC motor can act as a generator to supply power extracted from the kinetic energy of the moving vehicle. This causes a reversal of the currents of the system, and the converter extracts power out of the dc bus to charge the battery. The inductor current $i_L$ is negative under these conditions. Transistor $Q_2$ or diode $D_1$ conduct, while transistor $Q_1$ and diode $D_2$ do not conduct for this case.

The IGBT transistors can be modeled as a constant voltage source VT in series with a resistance RT. The diodes can be modeled as a constant voltage source Vd. The inductor has dc winding resistance RL.

Derive a dc equivalent circuit model for this converter under the conditions that the vehicle is accelerating and the inductor current is positive. Manipulate your model into the form illustrated below:




Bidirectional DC-DC converter model

Express Re as a function of RT, RL, and the duty cycle D. Enter your expression below.

**Question 10**. Express Ve as a function of VT, Vd, and D, and enter your expression below.

**Question 11**. Express m as a function of D. Enter your expression below.

**Question 12**. The vehicle operates with the following conditions and parameter values:

- Vbatt = 240 V
- Vbus = 500 V
- VT = 1 V
- RT = 1.6 milli ohms
- RL = 4 milli ohms
- Vd = 1.2 V
- Power input to AC motor drive from dc bus = 150 kW

Calculate the duty cycle and enter its numeric value below.

**Question 13.** For the conditions of Question 12, calculate the converter efficiency and enter its numeric value below.

**Question 14**. For the conditions of Question 12, calculate the conduction loss of the IGBT and enter its numeric value (in watts) below.