ECE445/545
Power Electronics I
Project

Task 1: Steady state and efficiency analysis using V-s and charge (I-s) balance

Modelling inductors with their ESR (equivalent series resistance), i.e. inductors L_1 and L_2 have series resistances r_1 and r_2, respectively, and the switch and diode have finite resistances, r_S and r_D, respectively, when ON and are open circuit when OFF. For simplicity, all other forms of losses are neglected. Using the concept of zero volt-second (flux) balance in inductors and zero charge (Amp-second) balance in capacitors find the average values of inductor currents I_1, I_2 and capacitor voltages V_1, V_2 when the converter is operating in steady state. Given these results find an expression for the power efficiency, η, of the converter.

Task 2: Steady state and ripple analysis using SSA (State Space Averaging)

During subintervals DT_s and $D'T_s$ the converter can be described by the following state equations:

$$DT_s: \qquad \frac{dx}{dt} = A_1 x + B_1 V_g,$$

and

$$D'T_s: \qquad \frac{dx}{dt} = A_2 x + B_2 V_g,$$

Where x is the state (we will use inductor currents and capacitor voltages as the state variables), and V_g is the input voltage.

Using SSA the averaged state space model becomes:

$$\frac{dx}{dt} = Ax + BV_g, \quad \text{where}$$

$$A = DA_1 + D'A_2$$
$$B = DB_1 + D'B_2$$

Subsequently the steady state vector X can be determined:

$$X = -A^{-1}BV_g \tag{1}$$

Also peak-to-peak amplitude values for first order and second order ripple can be determined using:

First order ripple: $\qquad \Delta x = (A_1 X + B_1 V_g)DT_s \tag{2}$

Second order ripple: $\qquad \Delta^2 x = \frac{A \, \Delta x T_s}{8} \tag{3}$

Note that second order ripple values only need to be determined when a first order ripple value is zero.

To do: For your ideal converter (i.e. for simplicity, do not include any losses) determine:

    i.   The state matrices A_1, B_1, A_2 and B_2

    ii.   Use these to find the averaged matrix, A, and vector, B

    iii.   Use (1) to find the steady state value of the state vector

    iv.   Use (2) to find the first order state ripple

    v.   Use (3) to find the second order state ripple

Task 3: Determine component values, based on ripple requirements

Using your results obtained from Task 2, we will now determine the component values of the converter. The specifications of the converter are:

    Input voltage: $V_g = 10\ V$

    Output voltage: $V_2 = 5\ V$

    Load resistance: $R = 5\ \Omega$

    Switching frequency: $f_s = 100\ kHz$

Complete the table with the requested information. As a first step in component value determination we will require that the peak to peak amplitude of state ripple, $x_{i_{pk-pk}}$, is a certain fraction, α, of the steady state value, X_i, that is

$$|x_{i_{pk-pk}}| = \alpha\,|X_i|\ , \text{ for } x_i = i_1, i_2, v_1 \text{ use } \alpha = 0.15 \text{ and for } x_i = v_2 \text{ use } \alpha = 0.05$$

Note that the component values determined here may be modified when we consider the control design, but they do represent a lower bound on their values.

Construct your converter in PECS using the values found, and show all the steady state waveforms.

Hand in the following:

    i.   completed table

    ii.   your PECS schematic

    iii.   steady state waveforms showing 5 or so cycles of each state ripple. Use a simulation step size which results in smooth waveforms

Task 4: Derive the control to output transfer function, $\frac{\widehat{v_2}}{\hat{d}}(s)$, of the converter

Having already derived the state equations for the converter, in preparation for undertaking the controller design, we can now derive the control to output transfer function using the SSA small signal model:

$$\dot{\hat{x}} = A\hat{x} + B_d\hat{d}$$

$$\hat{y} = C\hat{x}$$

Given that $C = [0\ 0\ 0\ 1]$, for the lossless converter, and $x = [i_1,\ i_2,\ v_1,\ v_2]^T$, the transfer function can be determined, as shown in class, using Cramer's rule to be the result of the simplification of two determinants. The denominator determinant is given by $|sI - A|$. To obtain

the numerator polynomial the following procedure is given. Since the output voltage is the fourth element of the state vector, replace the fourth column of the matrix $sI - A$ by the vector B_d. For the resulting matrix obtain its determinant. This is the numerator polynomial for the transfer function.

Make sure your final transfer function expression are sufficiently simplified.

Hand in your derivation for the transfer function using the above outlined procedure.

Task 5: Simulate your closed loop design using LTspice (preferably) or PECS.

Task 6: Build a closed loop regulator with your assigned FOC (fourth order converter).

Demonstrate it to the instructor and the rest of the class. In particular, show the output voltage response to a step input voltage change. We will use the Capstone Lab (and the Circuits Lab, if needed) for the demonstration.

As previously detailed in class the specs for the converter are:

1)   10 V to 5 V, 1 Amp (i.e. use a 5 ohm load resistor)
2)   100 kHz switching frequency
3) $\geq$ 10 kHz unity loop gain crossover frequency
4) $60° \pm 3°$ phase margin

Requirements:

1)   Use an n-channel power MOSFET for the converter
2)   Use Schottky diodes for your converter and input voltage switching circuit
3)   Use an LTC7004 or LTC4440-5 gate driver
4)   Use a TL5001AIP (or its surface mount equivalent) PWM control IC
5)   Use the input voltage switching circuit discussed in class

All demonstrations must be completed by the end of the demonstration class.

The main components of your demonstration are:

1)   Presentation of a working, well-constructed circuit
2)   Demonstration of the output voltage response to input voltage switching. Have your oscilloscope show the waveform of the input power supply voltage switching between 10 V and 11 V (at around 100 Hz) and also show the output voltage response of the converter on another oscilloscope trace.
3)   All group members need to be present during the demonstration

Any non-functional circuits will receive at most a 50% score. In the case of a non-working circuit, you have until the end of the demonstration class to get your circuit to work. Accordingly, it would be wise to volunteer to demonstrate your circuit earlier in the demonstration class so as to have time, if you need it.

Task 7: Write a report.

The report should be in the form of an IEEE journal paper. (The requirements for these can be found in the 'guide to authors' of any of the IEEE journals.)

The format of an IEEE paper, is typically broken down into the following sections:
1) Abstract
2) Introduction
3) General overview
4) Design procedure
5) Constructed prototype
5) Conclusion
6) References (for your report this can be omitted, or minimized).
7) Appendices

Other sections may be added and each section may be further subdivided when appropriate.

Some general guidelines and requirements:
a) The presentation of the paper is very important. So, do not minimize your effort on this part.
b) Your aim in writing your paper is to 'sell' it to the reader. That is, you need to present a compelling case for using the converter.
c) Your derivations should, for the most part, be relegated to the appendices. Place all the Matlab code in an appendix.
d) Show a close-up photo of your constructed circuit.
e) Show a complete circuit schematic of your final system with all values of components shown. Also show the schematic of the input voltage switching circuit. The schematics should be drawn by appropriate software, such as, Easy EDA.
f) If possible, show a screenshot (in the same shot) of the inductor currents with the converter operating in steady state. Use small current sensing resistors if needed.
g) Show a screenshot of the output voltage response of your regulator to a step change in the input voltage. All screenshots should feature a white background.
h) Show PECS simulation results for (f) and (g)
i) For the power stage tabulate the inductors and capacitors and MOSFET and diode used, along with the cost. Your table should include the following information.
    i. Component value
    ii. Manufacturer and manufacturer part number
    iii. ESR, Rds (on) or Vf (forward diode voltage drop), as appropriate
    iv. Voltage rating for caps and current rating for inductors
    v. Price
j) Using the efficiency formula derived earlier this term, have Matlab sketch an efficiency vs d (duty ratio) plot using the values of the ESR and Rds(on) of your inductors and MOSFET, respectively.
k) Be sure to show the loop gain plot for your design, clearly showing the unity gain frequency (in Hz) and phase margin.

If possible, it is desirable to use Latex to format the report, as this is the de facto standard for academic papers.

Grading: Your report will be assessed based on, but not limited to, the following:
1) Completeness of the report
2) Accuracy and effectiveness of results presented
3) Effectiveness of the presentation and format

The report is an opportunity to present a compelling case for the use of your converter and design methodology.