Part I

Open-Loop Pulse-Width Modulated DC–DC Converters—Steady-State and Performance Analysis and Simulation of Converter Topologies

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Boost DC–DC Converter in CCM—Steady-State Simulation

Objectives

The objectives of this lab are:

- To design a pulse-width modulated (PWM) boost dc–dc converter operating in continuous-conduction mode (CCM) for the design specifications provided.
- To simulate the boost converter on a circuit simulator and to analyze its characteristics in steady state.
- To determine the overall losses and the efficiency of the boost converter.

Specifications

The specifications of the boost converter are as provided in Table 1.1.

Pre-lab

For the specifications provided, find the values of all the components and parameters for the boost dc–dc converter operating in CCM using the relevant design equations provided in Table A.1 in Appendix A.

Quick Design

Choose:

$L = 20$ mH, ESR of the inductor $r_L = 2.1\ \Omega$, $R_{Lmin} = 1.778\ \mathrm{k}\Omega$, $R_{Lmax} = 35.6\ \mathrm{k}\Omega$, $D_{min} = 0.579$, $D_{nom} = 0.649$, $D_{max} = 0.714$, $C = 1\ \mu\mathrm{F}$, ESR of the capacitor $r_C = 1\ \Omega$.

Laboratory Manual for Pulse-Width Modulated DC–DC Power Converters, First Edition.
Marian K. Kazimierczuk and Agasthya Ayachit.

Table 1.1 Parameters and their values

Parameter	Notation	Value
Minimum dc input voltage	V_{Imin}	127 V
Nominal dc input voltage	V_{Inom}	156 V
Maximum dc input voltage	V_{Imax}	187 V
DC output voltage	V_O	400 V
Switching frequency	f_s	100 kHz
Maximum output current	I_{Omax}	0.225 A
Minimum output current	I_{Omin}	5%ofI_{Omax}
Output voltage ripple	V_r	$< 0.01V_O$

MOSFET: International Rectifier IRF430 n-channel power MOSFET with $V_{DSS} = 500$ V, $I_{SM} = 4.5$ A, $r_{DS} = 1.8\ \Omega$ at $T = 25°$C, $C_o = 135$ pF, and $V_t = 4$ V.

Diode: ON Semiconductor MUR1560 with $V_{RRM} = 600$ V, $I_F = 15$ A, $R_F = 17.1$ mΩ, and $V_F = 1.5$ V.

Procedure

A. Simulation of the Boost Converter and its Analysis in Steady State

1. Construct the circuit of the boost converter shown in Figure 1.1 on the circuit simulator. Name the nodes and components for convenience. Enter the values of all the components.
2. Initially, simulate the converter at $V_I = V_{Inom} = 156$ V, $R_L = R_{Lmin} = 1.778$ kΩ, and $D = D_{nom} = 0.649$. Connect a pulse voltage source in order to provide the gate-to-source voltage at the MOSFET gate and source terminals. Set `time period = 10` μs, `duty cycle/ width = 0.649`, and `amplitude = 12 V`. Let the `rise time` and `fall time` be equal to zero (optional).
3. Set simulation type to `transient analysis`. Set `end time = 10 ms` and `time step = 0.1` μs. Run the simulation.
4. Plot the following waveforms after successful completion of the simulation. You may display the waveforms on different figure windows for better clarity.
   - Gate-to-source voltage v_{GS}, drain-to-source voltage v_{DS}, and diode voltage v_D.
   - Output voltage v_O, output current i_O, and output power p_O.
   - Inductor current i_L, diode current i_D, and MOSFET current i_S.
   Zoom in to display the steady-state region.

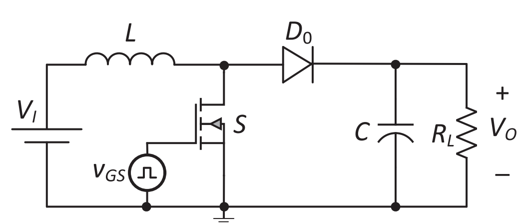

Figure 1.1 Circuit diagram of the PWM boost dc–dc converter.

5. Observe the inductor current waveform to ensure whether the current is in CCM. If the current is not in CCM, then increase the value of the inductor and repeat the simulation.
6. For the above-mentioned waveforms, measure:
   - The average and peak-to-peak values of the current through the inductor L.
   - The maximum and average values of the voltage across the MOSFET S.
   - The minimum and average values of the voltage across the diode D_0.
   - The maximum and average values of the currents through the MOSFET and the diode.

   Ensure that the values obtained above match the desired specifications. Should there be any deviation in the values, adjust the value of the duty cycle accordingly.
7. Repeat the steps above with duty cycle $D_{min} = 0.579$ and input voltage $V_{Imax} = 187$ V. Also, repeat for a duty cycle of $D_{max} = 0.714$ and an input voltage of $V_{Imin} = 127$ V.

B. Simulation of the Boost Converter to Determine the Power Losses and Overall Efficiency

1. Set up the converter to operate at the nominal operating condition, that is, at $D = D_{nom}$ and $V_I = V_{Inom}$. Let $R_L = R_{Lmin}$ such that the converter is delivering maximum output power.
2. Set the simulation type to transient analysis and perform the simulation.
3. Plot the waveforms of the input power p_I and the output power p_O. Zoom in to display the steady-state region.
4. Measure the average values of the input power and the output power. If the input power is negative, then consider only the magnitude of the average value of the input power.
5. Calculate the efficiency of the converter using $\eta = P_O/P_I$, where P_O is the average value of the output power and P_I is the average value of the input power, respectively.
6. This section may be repeated by plotting the power waveforms of all the components and then estimating their average values. All the power losses can be added to give the total power loss in the converter. Further, the efficiency can be estimated using $\eta = P_O/(P_{LS} + P_I)$, where P_O is the average value of the output power and P_{LS} is the sum of the average values of the power loss in individual components.
7. Repeat the above-mentioned activities in this section for $R_L = R_{Lmax}$ to determine the efficiency at minimum output power.

Post-lab Questions

1. Determine through simulations the maximum value of load resistance beyond which the converter operates in discontinuous-conduction mode?
2. Draw the waveforms of the inductor current for the input voltage at V_{Imin}, V_{Inom}, and V_{Imax}.
3. Draw the waveforms of the diode current, current through the filter capacitor, and current through the load resistor. Describe the nature of the three currents in terms of their shape and peak-to-peak values.
4. Draw the waveforms of the voltages across the capacitor and the equivalent series resistance of the capacitor.
5. Identify the component in the converter, which exhibits the highest power loss. Provide a proper reason for your answer.