ECE 214 - Virtual Lab #7
Boost Converter Circuit
Modified for Simulation Only

27 March 2020

Introduction: In this lab, you will design and simulate a boost converter based on the switched capacitor circuit shown in Figure 1. You will analyze how the output voltage changes over the temperature range between -50° and +60° C.

In this circuit, the two switches operate simultaneously and in opposite directions. When switch S_1 closes, switch S_2 opens; when switch S_1 opens, switch S_2 closes. In the ideal circuit, switches S_1 and S_2 are never both open or both closed at the same time. Switches S_1 and S_2 are continuously opened and closed by a function generator (FG), or oscillator circuit, not shown in the figure.

When switch S_1 is closed and S_2 is open, the 12 V supply voltage and the inductor form one circuit, and the capacitor and the resistor form a second circuit. These circuits are isolated and not connected to each other. The voltage across the capacitor when switch S_2 opens will begin to decrease as the capacitor is discharged through resistor R_o. This decrease in voltage will depend on how long the switch is open and the value of the resistor R_o. As the voltage across the capacitor decreases, the energy stored in the capacitor also decreases. At the same time, current through the inductor increases. The maximum current flow will depend on how long switch S_1 is closed and on the series resistance of the inductor and the switch S_1. As the current through the inductor increases, the energy stored in the inductor increases. The maximum current through the inductor should never exceed 0.6 A.

When switch S_1 is opened and S_2 is closed, the two circuits are connected, and the energy in the inductor will flow through switch S_2 and be supplied to the capacitor. The voltage on the capacitor will increase and drive current through the resistor R_o.

A steady-state output voltage is reached when the energy transferred from the inductor to the capacitor, with switch S_1 open and switch S_2 closed, is equal to the energy lost from the capacitor,

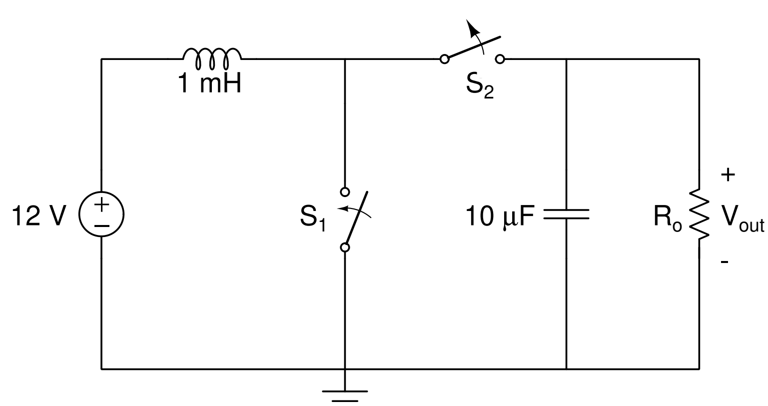

Figure 1: A boost converter circuit containing two synchronized switches.

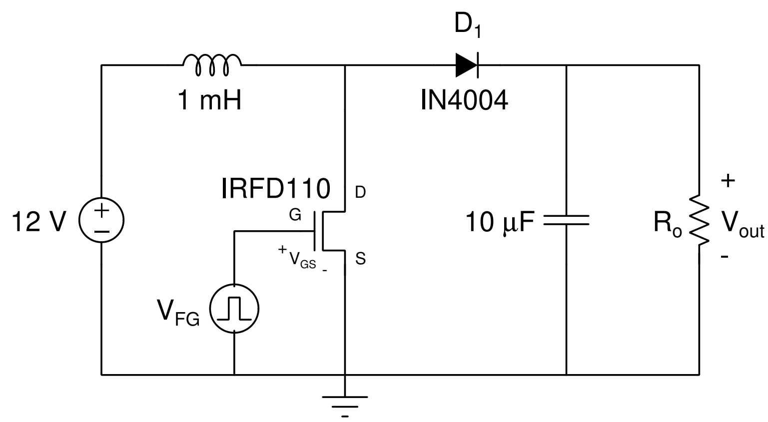

Figure 2: Boost converter circuit implemented with an NMOS transistor driven with a function generator (FG) to represent the switch S_1 and a junction diode to represent the switch S_2 in Figure 1.

with switch S_1 closed and switch S_2 open.

Rather than use two switches, you will implement the boost converter circuit using an IRFD110 NMOS transistor to represent switch S_1, and a 1N4004 junction diode to represent switch S_2. The schematic of the circuit is shown in Figure 2.

The NMOS transistor acts as a voltage controlled switch. When V_{GS}, the voltage between the gate (G) terminal and the source (S) terminal, is greater than 4 V, the drain (D) and source (S) terminals are effectively shorted, and current flows between the drain (D) terminal and the source (S) terminal. When $V_{GS} = 0$, the connection between the D and S terminals of the transistor is open, and no current flows between the D and S terminals. Transistors have a maximum current rating. The maximum amount of steady-state current allowed through the IRFD110 transistor is 0.6 A, and the maximum instantaneous current is 1.2 A. The current through the transistor will be checked during the simulation.

When the D and S terminals of the NMOS transistor are open (switch S_1 open), the energy in the inductor causes charge to flow through the diode (D_1) to the capacitor. A diode allows current to flow in only one direction. Hence, the diode only allows current to flow from the inductor to the capacitor. Once the charge flows through the diode and onto the capacitor, it can not return back to the inductor side of the circuit.

The diode functions as an open circuit when the D and S terminals of the transistor are shorted (switch S_1 closed). Thus, anytime switch S_1 is closed, switch S_2 is open. The diode ensures that switches S_1 and S_2 are never both closed at the same time.

When the frequency and duty cycle of the FG are properly adjusted, as described below, switch S_1 will close when all of the energy is transferred from the inductor to the capacitor. In addition, switches S_1 and S_2 will never both be open at the same time.

Design Specifications: The nominal design temperature is 27° C. However, the boost converter should meet the design specifications over the temperature range from -40° to +60° C when simulated using models of real resistors..

1. Inputs: +12 V_{DC} and 12 V_{pp} square wave from a FG having frequency f and duty cycle δ.
2. Output: $V_{OUT} = 30 \pm 0.25$ V_{DC}

Circuit Design and Analysis: Follow the steps below to estimate the frequency (f), duty cycle (δ), and resistance (R_o) of the boost converter. These values will be used as a starting point for the boost converter simulation. Incorporate these calculations, in narrative form, into the circuit theory and design section of your report.

1. Let V_{OUT} decrease from 30.05 V to 29.95 V when switch S_1 is closed. How much energy must be supplied to the capacitor when switch S_1 opens to bring the voltage back to 30.05 V?
2. Let t_1 be the time duration that switch S_1 is closed. What is the value of t_1 that will allow the inductor to absorb this much energy?
3. What is the maximum current through the inductor just before switch S_1 opens? Ensure it is lower than the maximum allowed by the transistor.
4. What value of R_o is required such that the capacitor voltage drops from 30.05 V to 29.95 V during time t_1.
5. How much power is dissipated by this resistor? (Make sure to choose a resistor capable of handling this power when generating your bill of materials later in this lab.)
6. Let t_2 be the amount of time it takes for the current to stop flowing from the inductor to the capacitor after switch S_1 opens and S_2 closes. Calculate the value of t_2 by considering the series RLC circuit where R is the ESR of the inductor at a frequency of 10 kHz, determined in Lab #6. (Note: if you did not measure the Q of your inductor, pick a value between 18 and 22 for Q.)
   (a) What is the measured value of Q, and the calculated ESR, for your inductor at a frequency of 10 kHz?
   (b) Derive the equation of the current through the inductor as a function of time after switch S_1 opens and S_2 closes. Ignore the output resistance R_o in this calculation. Is this an under-damped, over-damped or critically-damped circuit?
   (c) Plot this current as a function of time.
   (d) What is the value of t_2?
7. The period of the square wave (T) used to drive switch S_1 is $t_1 + t_2$; the frequency (f) is $1/T$, and the duty cycle (δ) is t_1/T. What are the values of T, f, and δ for the FG?

Circuit Simulation: Simulate the boost converter circuit shown in Figure 3 at a temperature of 27° C using ideal resistors, inductors, and capacitors. Include the ESR of the inductor as an ideal resistance in series with the inductor. Also include a 1 Ω resistor between the S terminal of the transistor and ground to allow for the simulation of the current through the transistor.

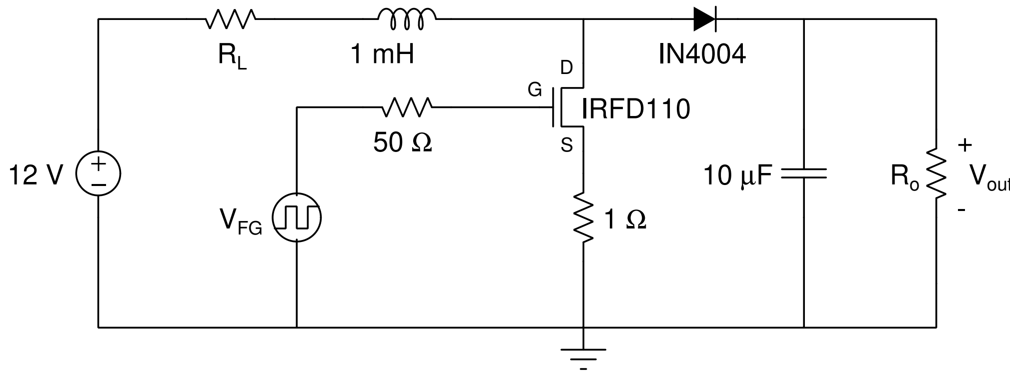

Figure 3: Boost converter circuit for NGspice simulation and for implementation.

1. Set the value of R$_o$ to the value calculated in step 4.
2. Set V$_{FG}$ to a square wave with a voltage from 0 to 12 V, a period T (calculated in step 7), and a pulse width of t_1 (calculated in step 2). Make the rise time and fall times $\ll$ pulse width.
3. Plot the simulated voltage across the capacitor as a function of time. Adjust the `.tran` statement so the simulation is long enough to reach a steady-state voltage. Also, make sure your initial time step is small enough that you capture an accurate representation of the ripple, and obtain an accurate steady-state response.

   To ensure that your time step is not too large, reduce the initial time step by a factor of four, and rerun the simulation. If your simulation results do not change, you have chosen your time step correctly. If the amount of ripple or the steady-state voltage change significantly, your initial time step is too large. In this case, continue to decrease the initial time step by a factor of four until the simulation results become nearly independent of the value of the initial time step. In the report, indicate the initial time step, final simulation time, and if you used a maximum time step in the simulation.
4. What is the steady-state output voltage V$_{out}$?
5. What is the peak-to-peak ripple?
6. Determine the current through the transistor by plotting the voltage across the 1Ω resistor as a function of time. Are the instantaneous and average currents through the transistor below the current ratings of the transistor?
7. Does the circuit satisfy the design specifications at a temperature of 26° C.
8. If not, adjust the duty cycle and/or frequency of the FG to meet the specification.
9. Include a table in your report listing the final values of t_1, t_2, R$_o$, f and δ for the design.

Operating temperature range: Modify the design to include a "real" resistor model of R$_o$. Simulate the design over the temperature range between -40° to +60° C.

1. Download the supplemental ECE214 device library from https://ece214.davidkotecki.com/docs/ngspice/ece214_device_sup.tar.gzip. Place this file in the `Import_Export` directory located within the `CppSim` directory structure. Import the library into `Sue2` by clicking: `Tools` → `Library Manager` → `Import Library Tool`. Select `ece214_devices_sup` as the `Source File/Library`, click `Import`, and then restart `Sue2`.

2. The `ece214_device_sup` library contains models for three types of real resistors: a wire-wound resistor, carbon thin film resistor (what you used in Labs 1-5), and metal film resistor. You can read about these types of resistors at: https://tinyurl.com/uueh5sq

   The temperature coefficient of resistance (TCR) for these three resistor types is given below:

   Table 1: Temperature Coefficient of Resistance.

Resistor Type	**TCR**
Wirewound	+ 800 ppm
metal thin film	+ 70 ppm
carbon thin film	- 400 ppm

3. Modify the design of the boost converter circuit by replacing the "ideal" resistor for R_o with a "real" resistor.

4. Simulate the boost converter circuit over the temperature range between -40° to +60° C, and plot the steady-state output voltage as a function of temperature.

5. Over what temperature range does the boost converter meet the specification?

6. By using combinations of real resistors with positive and negative TCRs, the effect of temperature on the circuit performance can be reduced. Try and improve the temperature range over which the boost covnerter meets spec by using a combination of "real resistors" to replace R_o. Describe the final design and performance in the report.

Bill of Materials. Start a Bill of Materials (BoM) as an Appendix in the report. The BoM is a list of parts needed for the construction of the power supply circuit. This should be represented in tabular format, as illustrated in the sample table below:

Table 2: Sample Bill of Materials.

Item	**Part No.**	**Description**	**Qty.**	**Unit Price**	**Total Price**	**Total Leads**
1	xxx-yy-zz	Resistor: $350\Omega \pm 5\%$, carbon film, 0.5W	1	\$0.07	\$0.07	2
2	jkj-jjk=53k	Capacitor: $10\mu F \pm 10\%$, ceramic, 50V	2	\$0.32	\$0.64	4

For now, only complete the Item, Description, and Quantity columns. Make sure the descriptions are complete. For resistors, include the type (carbon composition, carbon film, metal film, or wirewound), power rating and tolerance; for capacitors, include the type (film, ceramic, electrolytic), tolerance and voltage rating. See: `https://tinyurl.com/tx6rmp9` for a description of different types of capacitors. The remaining columns of the table will be discussed later during the semester.