Transient Response and Power Conversion

Goals:

1. Examine transient response of first-order RC circuit.
2. Examine transient response of second-order RLC circuit.
3. Build and test a mystery circuit.

Preparation:

1. Carefully review this document.
2. Review lecture slides on RC and RLC circuits.

Experiments:

1. Transient Response of a First-Order RC Circuit

(a) **Get Parts.** Obtain a 50 nF capacitor from the parts bins. Measure the capacitor using the LCR meter next to the parts bins. Make sure the meter is reading capacitance and select measurement frequency of 1 kHz and a drive voltage of 1 V - get help from a TA if needed. Record the measurement.

(b) **Setup Function Generator and Scope**. Remove the 50 Ω coaxial load termination from the coaxial T-splitter connected at the output of the function generator. Make sure that the function generator is not set to the "High-Z" mode – if High-Z appears on its LCD display, restore the settings of the function generator (press the store/recall button, then press the third from the left gray button which has recall written above it), or ask TA for help. Set the function generator to produce a square wave (push the button with the word "Square" and a squareish shape on it), and set its frequency (Freq) to 1 kHz, its low voltage (LoLev) to 0 V, its high voltage (HiLev) to 5 V (the function generator will actually generate a voltage twice these levels, i.e., 0 V and 10 V), and its duty cycle (DtyCyc) to 50%. The function generator is like a Thevenin voltage source v_S with a Thevenin resistance (output impedance) $\mathrm{R_S}$ (see Fig. 1).

Turn the function generator's output on, and use the oscilloscope to view and confirm the output voltage of the function generator. The following guidance regarding oscilloscope settings may be helpful: attach the oscilloscope probe so that channel 1 measures the function generator's output voltage; set channel 1 trigger (under the trigger menu, use the level knob under trigger to adjust the little yellow arrow until your waveform stabilizes); use DC coupling for the channel; set time base scale to be able to see at least one complete cycle of the square wave (try 250 $\mu\mathrm{sec/div}$); set channel 1 scale and position channel 1 vertical offset to be able to see the full waveform clearly (try 2 volts/div); enable averaging (under the ACQUIRE menu) to remove noise from the waveforms; enable peak-to-peak measurements (push the measure button, then use the buttons next to the screen to select Ch1, Pk-Pk). You may want to record your settings for future reference. You can also transfer waveforms to the computer using the OpenChoice Desktop software. Following is the procedure for opening OpenChoice Desktop with scope already connected: power on the desktop computer, then turn on the scope (without opening OpenChoice); OpenChoice will then open automatically and the device will be detected automatically. You probably also want to grab+save a screenshot as back-up.

(c) **Assemble Circuit**. Using a proto-board connect the 50 nF capacitor across the output of the function generator, forming the driven RC circuit shown in Fig. 1. Connect oscilloscope probe so that channel 1 measures the voltage v_{OUT} across the capacitor.

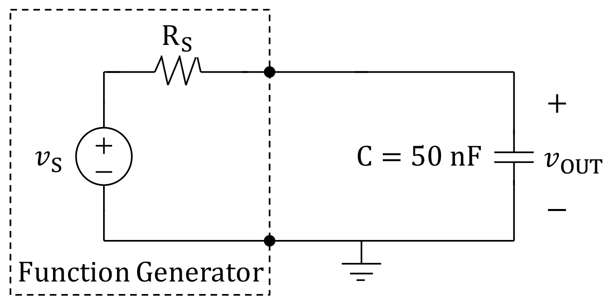

Fig. 1. Function generator with capacitor connected at its output, forming a driven RC circuit.

(d) **Record Waveforms and Measure the Time Constant Using the Oscilloscope**. Enable the cursor function of the oscilloscope (depress the CURSOR key), select "Time" and set source to Ch1. With this cursor mode active, the difference (denoted by Δ) in time and voltage between the dual cursors is displayed on the scope. Also the voltage at the current cursor position is displayed. Each cursor can be moved using the large round knob on the upper left.

Expand the time scale of the oscilloscope to be able to clearly see the low-to-high transition of the output voltage v_{OUT}. The output voltage response of this circuit to a step excitation of height V_0 is of the form:

$$v_{\text{OUT}}(t) = \text{V}_0\left(1 - e^{-t/\tau}\right)u(t)$$

where τ is the time constant of the circuit. At $t = \tau$, the output voltage is:

$$v_{\text{OUT}}(\tau) = \text{V}_0(1 - e^{-1}) = 0.632\text{V}_0$$

So for the 10-V step, v_{OUT} would be 6.32 V at time $t = \tau$. Place cursor 2 at the point in time giving this value (you may need to zoom-in on the vertical scale to improve measurement resolution). Now place cursor 1 at the leading step edge. The difference in time (between the two cursors) is now displayed and is the time constant τ. Record the measured time constant. You will use this measured time constant to determine the Thevenin resistance (output impedance) of the function generator. Transfer the low-to-high output voltage waveform to the computer and save an image for use in your lab report (a screenshot as back-up is a good idea). Also observe and record for your lab report the high-to-low transition of the output voltage. You can use the high-to-low transition to double check the value of the time constant.

2. Transient Response of a Second-Order RLC Circuit

(a) **Get Parts.** Save your capacitor from the previous experiment as it will be reused. Obtain a 1.2 mH inductor from the parts bin. Measure the inductor using the LCR meter. Make sure the meter is reading inductance and select measurement frequency of 1 kHz and a drive voltage of 1 V - get help from a TA if needed. Record the measurement. Next, measure the dc resistance of the inductor using the DMM. Record this value.

(b) **Function Generator and Scope Settings**. The function generator and scope settings stay the same as in previous experiment.

(c) **Assemble Circuit**. Using a proto-board assemble the driven series RLC circuit shown in Fig. 2. Connect oscilloscope probe so that channel 1 measures the voltage v_{OUT} across the capacitor.

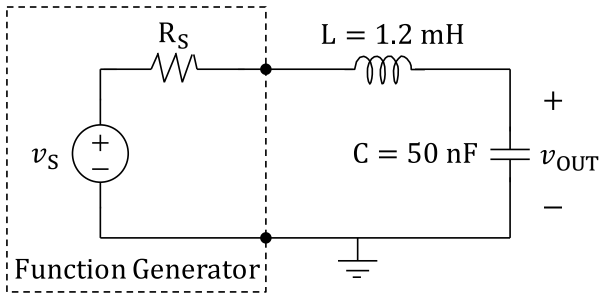

Fig. 2. Function generator with inductor and capacitor connected at its output, forming a driven series RLC circuit.

(d) **Record Waveforms and Measure Period and Number of Oscillations**. Adjust the time scale of the oscilloscope to be able to clearly see the low-to-high transition of the output voltage v_{OUT}. Using the cursors measure the period T of the oscillations in the output voltage. The period $\mathrm{T} = 2\pi/\omega_{\mathrm{d}}$ can be used to determine the undamped natural radial frequency ω_{d} of the circuit. Also count the number of oscillation that are visible. The number of visible oscillations is roughly equal to the quality factor Q of the circuit. Transfer the low-to-high output voltage waveform to the computer and save an image for use in your lab report (a screenshot as back-up is a good idea). Also observe and record for your lab report the high-to-low transition of the output voltage. You can use the high-to-low transition to double check the value of the period and the number of visible oscillations.

3. Build and Test a Mystery Circuit

(a) **Get Parts.** Save your capacitor and inductor from the previous experiment as they will be reused. Obtain a BS170 MOSFET, a IN4007 diode and a 1.2 kΩ resistor from the parts bin. Review the datasheet for BS170 to identify which lead is drain, which is gate and which is source. For the diode, the cathode lead is the one close to the dark ring, and the other one is the anode lead. Confirm this using the DMM (with one polarity the resistance of the diode will be close to zero and with the reverse polarity the resistance will be very large).

(b) **Function Generator and Power Supply Settings**. Change the function generator frequency to 100 kHz. The other settings of the function generator remain unchanged. You will be using a dc power supply to provide 5 V to the circuit in this experiment. Select the +6V option for the meter of the power supply (push the button with +6V written above it). Turn the power supply on and rotate the round knob with +6V written above it counterclockwise until the meter reads 0 V. Then turn off the power supply.

(c) **Assemble Circuit**. Using a proto-board assemble the mystery circuit shown in Fig. 3. The voltage source $\mathrm{V_{IN}}$ in Fig. 3 represents the dc power supply. Use the +6V and COM outputs of the power supply to connect it to the rest of the circuit. Do not turn on the power supply until after the circuit has been completely assembled and the output of the function generator turned on. Also do not inadvertently remove the load resistor R_{LOAD} from the circuit while the power supply is turned on. Connect oscilloscope probe so that channel 1 measures the voltage v_{OUT} across the capacitor and channel 2 measures the gate-to-source voltage of the MOSFET (same as output voltage of the function generator). Once the circuit is fully assembled and the function generator output is turned on (confirm this by observing channel 2 on the oscilloscope), turn on the power supply and gradually increase its voltage from 0 V to 5 V. You should see the output voltage v_{OUT} also increase gradually from 0 V.

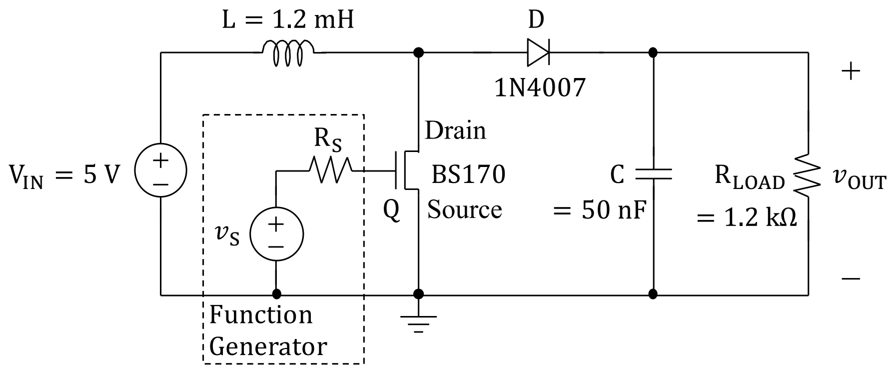

Fig. 3. The mystery circuit that combines an RLC circuit with a MOSFET Q and a diode D. The MOSFET and the diode act like ideal switches (either short circuit or open circuit) and switch in a complementary fashion (when MOSFET is on, the diode is off, and when MOSFET is off, the diode is on). The turn on and turn off of the MOSFET is controlled by the Function Generator.

(d) **Record Waveforms and Measure Average Output Voltage**. Adjust the time scale of the oscilloscope to be able to clearly see the roughly triangular shape of the ripple (i.e., variation) in the output voltage v_{OUT}. Record the average value of the output voltage. Also record the peak-to-peak amplitude of the ripple in the output voltage. How does the average value of the output voltage compare with the 5 V input voltage (V_{IN}) supplied by the power supply. If the average value of the output voltage is greater than the input voltage, try and understand how this could be possible. Transfer the output voltage waveform to the computer and save an image for use in your lab report (a screenshot as back-up is a good idea). This output voltage corresponds to a square wave with 50% duty cycle.

Vary the duty cycle of the square wave produced by the function generator between 20% and 80% in steps of 20%. Observe and record the average value of the output voltage for each of these duty cycle values. For what value of duty cycle does the average output voltage reach its maximum value? Transfer the output voltage waveforms for the extreme duty cycles (20% and 80%) to the computer and save an image for use in your lab report (a screenshot as back-up is a good idea).

Reduce the frequency of the function generator to 50 kHz. Adjust the time scale of the oscilloscope to be able to clearly see the ripple in the output voltage v_{OUT}. Record the peak-to-peak amplitude of the ripple in the output voltage. Did the amplitude of the ripple increase or decrease relative to when the frequency of the function generator was 100 kHz? Transfer the output voltage waveform to the computer and save an image for use in your lab report (a screenshot as back-up is a good idea).

Wind down:

Clean up around your bench and return any components back to their storage bins. Be sure all data is collected and placed on your own storage media. Delete all files on your desktop or at least organize them in a folder. ECE makes no guarantee that these files left on your desktop will remain over time.

Analysis:

1. Plot the measured output voltage v_{OUT} waveforms (from the saved scope images) of the RC circuit. Include both the low-to-high and high-to-low transitions.
2. State the measured time constant of the RC circuit. Using the measured time constant, calculate the Thevenin Resistance (Output Impedance) $\mathrm{R_S}$ of the Function Generator. Compare your calculated value with the default/typical output impedance of the Function Generator as given in its data sheet or user manual (these are available on the Internet).
3. Plot the measured output voltage v_{OUT} waveforms (from the saved scope images) of the RLC circuit. Include both the low-to-high and high-to-low transitions.
4. State the measured time period of the underdamped RLC circuit. Using the measured time period, calculate the damped natural radial frequency ω_{d} of the RLC circuit. Compare your calculated value with a value calculated directly using the measured/calculated values of L, C and $\mathrm{R_S}$. The inductor you are using has a few ohms of series resistance (since it is made of thin wire). Would you get a better match in ω_{d} value if you included this resistance? How much inductor series resistance $\mathrm{R_L}$ would you need to include to get a perfect match? How does this value compare with the inductor series resistance that you measured using the DMM?
5. State the number of visible cycles (oscillations) in the natural response of the underdamped RLC circuit. This is a rough estimate of the quality factor Q of the circuit. Compare this value with a value calculated directly using the measured/calculated values of L, C and $\mathrm{R_S}$.
6. Plot the measured output voltage v_{OUT} waveform (from the saved scope images) of the mystery circuit when operating at 100 kHz with a duty cycle of 50%.
7. State the average value of output voltage v_{OUT} when the mystery circuit is operating at 100 kHz with 50% duty cycle. Is the average value of output voltage less than, equal to, or greater than the input power supply voltage of 5 V? If the output voltage is greater than the input voltage, try and explain how this may be happening. Hint: You can model the MOSFET and the diode as ideal switches that turn on and off in a complementary fashion (when the MOSFET is turned on, the diode turns off, and when the MOSFET is turned off, the diode turns on).
8. Plot the measured output voltage v_{OUT} waveforms (from the saved scope images) of the mystery circuit when operating at 100 kHz with duty cycles of 20% and 80%.
9. Using Excel, plot the average output voltage as a function of duty cycle in the range 20% to 80%. For what value of duty cycle do you get the highest value for average output voltage? What is this highest average output voltage?

10. Plot the measured output voltage v_{OUT} waveform (from the saved scope images) of the mystery circuit when operating at 50 kHz with a duty cycle of 50%. Comment on any observed differences in the output voltage waveform's ripple relative to when the circuit was operating at 100 kHz. If we wanted the output voltage to look more constant would we want to increase or decrease operating frequency?