PURPOSE:

- To verify the validity of Thevenin and maximum power transfer theorems.
- To demonstrate the linear input-output relationship of a circuit graphically using the scope’s XY display mode.
- To observe and record the natural response of first order RC circuit.
- To observe and record the time-domain forced response of a 1st order RC circuit (ramp forcing function).

This experiment relates to the following course learning objectives of the course:

1. Ability to interconnect equipment and devices such as multimeter, counters, and oscilloscope to achieve required results.
2. Ability to relate practical laboratory results with lecture theory.
3. Ability to obtain and analyze time-domain response of 1st and 2nd-order circuits.
4. Ability to analyze and evaluate data.

LAB EQUIPMENT:

1. TPS-4000 Dual DC Regulated Power Supply or Agilent 3640A DC power supply
2. Agilent 54621A Oscilloscope
3. Agilent 33120A Function Generator (FG)
4. Decade Resistance Box, 1Ω step
5. Decade Capacitor Box, 0.1 μF step
6. Agilent 34410A Digital Multimeter/Timer/Counter
7. Resistive Network (containing a combination of two 1.5kΩ and one 1.0kΩ resistors)

STUDENT PROVIDED EQUIPMENT:

1. Bag of six short banana-to-banana leads
2. Banana-to-banana leads
3. Meter Lead set
4. Agilent Scope probes
5. BNC to BNC
6. BNC to banana
7. BNC T

Section 1) Maximum Power Transfer

a) Using the resistive network provided, and a decade box for $R_{\text{load}}$, construct the following circuit (first measure $R_x$, $R_1$, $R_2$, and $V_S$).

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1 Version 6, last revised 2/23/12 ,EE Dept., Cal Poly
b) In lab notebook, set up a table with the following column headings:

| column 1: $R_{\text{load}}$ | measured |
| column 2: $V_x$ | measured |
| column 3: $V_{\text{load}}$ | measured |
| column 4: $I_s$ | $V_x/R_x$ |
| column 5: $P_{\text{source}}$ | $V_s I_s$ |
| column 6: $P_{\text{load}}$ | $(V_{\text{load}})^2/R_{\text{load}}$ |
| column 7: % efficiency | $(P_{\text{load}}/P_{\text{source}}) \times 100$ |

c) Complete the table for $R_{\text{load}}$ values of 100, 160, 250, 400, 630, 1000, 1600, 2500, 4000, 6300, 10,000 $\Omega$. Calculate $I_s$ by using the measured resistance value $R_x$, the voltage dropped across it, and Ohm’s law.

d) Using the above table locate the region of maximum power transfer. Take one additional data point for $R_{\text{load}}$. Specifically, choose $R_{\text{load}}$ midway between —on logarithmic scale—the two values of $R_{\text{load}}$ in part c that attained the highest %-efficiencies. (Note: Given two values $a > 0$ and $b > 0$, the value midway between them on a logarithmic scale is given by their geometric mean $c = (ab)^{1/2}$)

e) Disconnect $R_{\text{load}}$ and measure the voltage across the terminals to which it had been connected. This is the open-circuit voltage or the Thevenin voltage $V_{\text{Th}}$.

f) Turn off and remove the power supply from the circuit and place a short across the terminals where the power was connected. Measure the resistance across the terminals, where the load resistor was connected. This is the Thevenin equivalent resistance ($R_{\text{Th}}$) of the circuit to the left of the load.

g) Using the measured values of $V_{\text{Th}}$ and $R_{\text{Th}}$, set up the circuit shown. This circuit is the Thevenin equivalent of the previous circuit. Use the Agilent E3640A DC power Supply to accurately set $V_{\text{Th}}$. Set $R_{\text{load}}$ equal to the value found in step (d) above. Note that instead of using a decade box, the resistance network can be configured to yield $R_{\text{Th}}$. Do so and describe how it was done.

h) By measuring the voltages across the load and the source (using a DMM), compute the percent power efficiency for this circuit. Note that the current in the circuit is the measured value of $V_{\text{Load}}$ divided by $R_{\text{Load}}$. The output impedance of the DC supply can be neglected for these measurements.

**Questions: Section 1**

1) Using the data in the table above, plot $P_{\text{load}}$ and %-efficiencies vs $R_{\text{load}}$ on log scale. Use a single graph to plot both $P_{\text{load}}$ and %-efficiencies (use vertical scales on both sides of the graph for $P_{\text{load}}$ and %-efficiencies). Also show a vertical line on the plot corresponding to $R_{\text{th}}$ (the value of $R_{\text{load}}$ at which $P_{\text{load}}$ is theoretically maximized).

2) How do the values of $R_{\text{load}}$ obtained from step (d) (for maximum power) and (f) compare? Calculate the percent difference and the state reasons for the difference.
3) Using the measured values of resistances in the circuit board used in step (a), calculate the value of \( R_{\text{Load}} \) for maximum power transfer. How does this value compare with \( R_{\text{Th}} \) in step (f)?

4) Observe from your plot in Question 1 that the power efficiency of the original circuit peaks versus \( R_{\text{load}} \). By contrast, show that the power efficiency of the Thevenin equivalent circuit is strictly increasing versus \( R_{\text{load}} \).

Section 2) Linearity

Background

The defining characteristic of a linear system is that it exhibits a linear input-output relationship. That is, the system is both “homogeneous” — i.e., if \( y(t) \) is the output for the input \( x(t) \), and \( \alpha \) is a constant, then the input \( \alpha x(t) \) produces the output \( \alpha y(t) \) — and “additive” — i.e., \( y_1(t) \) and \( y_2(t) \) are the respective outputs for inputs \( x_1(t) \) and \( x_2(t) \), then the inputs \( x_1(t) + x_2(t) \) produces the output \( y_1(t) + y_2(t) \). A graphical method for verifying this linear relationship is to use the scope in the “XY” or “X-deflection” mode. We can then apply a ramp voltage waveform to the circuit to test for linearity. If the scope is placed in the XY mode, the input signal is connected to the X input (channel 1), and the circuit output is connected to the Y input (channel 2), a straight line should be displayed on the screen (if the circuit is linear). The ramp waveform generates a voltage that increases from low to high at a constant rate within each period. This causes the scope’s electron beam to move horizontally from left to right at a constant speed. If the circuit is linear, the output voltage will be proportional to the input voltage and will cause the electron beam to deflect from low to high (at a constant rate) while being driven from left to right by the input voltage. The net result is a linear upward sloping motion displayed by the scope. For further discussion of the X-Y mode, review the scope operation section of Experiment 2.

Procedure:

a) Using the same resistive network which was used in section 1, construct the circuit shown. Set the decade box \( R_L \) to 500Ω. Set the FG output termination to “HIGH Z” and select a 10.0 V pp ramp waveform @ 500 Hz with 0 V DC offset.

b) Connect the input signal to the channel 1 of the scope. Place the scope in the XY mode using the following steps: Autoscale, Main/ Delayed -> XY. A horizontal line representing the 10V peak to peak value of the ramp input waveform should appear. Set Chan 1 to 1.00V/Div.

c) Disconnect the probe from channel 1 of the scope. Connect the output signal, i.e., voltage across the decade box, to channel 2 of the scope. A vertical line representing the peak to peak value of the ramp output waveform should appear. Adjust the input sensitivity of Channel 2 manually to maximize the length, then record the length of this line in volts.

d) Reconnect the input waveform to channel 1. A straight line should be displayed. Adjust the vertical and horizontal scales and the position knobs as necessary to fit the line in the center of the screen (locate the point 0V, 0V at the center of the screen). Capture the display. Label axes and units appropriately.

e) Increase \( R_L \) to 1 kΩ and observe the change in slope and the length of the display. Measure the vertical displacement of the line (in volts). Disconnect the probe from channel 1 of the scope.
**Questions: Section 2**

1) In step (c), what is the expected length of the vertical line (i.e., peak to peak value of the output voltage) based on nominal circuit components? Record the percent difference between the measured and expected values.

2) In step (d), how would the display appear if the circuit was not linear?

3) In step (e), why does the slope of the displayed line change when $R_L$ is increased from 500Ω to 1 kΩ?

**Section 3) Natural response of an RC circuit**

**Background**

With a simple modification, the circuit of the previous section can be used to demonstrate the natural response of a first order RC circuit. If the same ramp input is applied to the circuit and the decade box is replaced with a capacitor, the resulting scope display will appear as a concave upward curve instead of a straight line. This is due to the response of the resulting RC circuit to a ramp function. As you recall, the output of a first order RC circuit is equal to the sum of the natural and forced responses. The natural response is an exponential decay with a time constant of $T = R_{\text{equivalent}} \times C$ where $R_{\text{equivalent}}$ is the Thevenin resistance as seen from the capacitor terminals.

For a constant DC input, the forced response will also be a constant that corresponds to the output at time $t \to \infty$, i.e., when the capacitor is fully charged. It can be shown that, for a ramp forcing function, the forced response will also be a ramp function that lags the input ramp by one time constant. Thus, the total response for this circuit will be the sum of the natural response, which is an exponential decay, and the forced response, which is a ramp with the same slope as the input but shifted to the right by one time constant. The resultant total response should appear as a concave upward curve composed of an initial exponential decay followed by a ramp function. The actual shape depends on the value of the time constant relative to the period of the input ramp waveform. Note that the response of the circuit will be identical for each period of the input waveform cycle, except for the first few cycles before steady state is reached.

**Procedure:**

a) Using the resistive network, construct the circuit shown. Set the capacitor decade box to 0.1 μF. Place the FG output termination to “HIGH Z” and set it at 10.0 Vpp ramp wave @ 500 Hz with 0 V DC.

b) Place the scope in the X-Y mode and connect the input signal to the channel 1 and the output signal, i.e., voltage across the capacitor, to channel 2. A curve should be displayed. Adjust the horizontal and vertical scales and the position knobs as necessary to fit and center the display in the screen (make the point (0 V, 0 V) correspond to the center of the screen). Capture the image to your report.

c) Vary the frequency from 50 Hz to 2 kHz and record any changes observed in the shape of the plot.

d) Reset the frequency to 500 Hz. Increase the capacitance from 0.1μF to 0.5μF in steps of 0.1μF and record any changes observed in the shape of the plot.
**Questions: Section 3**

In answering the following questions it may be useful to note that the scope displays one period of the output waveform, during which the input ramps upward. Therefore what you are effectively seeing is beginning of the output due to the ramp input, for some initial charge on the capacitor.

1) In step (c), explain why the displayed curve appears more like a straight line (sloping upward) as the frequency decreases. Hint: decreasing the frequency does not affect either the forced response or the natural response. It merely enlarges the observation window (period) which is used to capture the response and display it on the scope.

2) In step (c), explain why the displayed curve approaches a straight horizontal line as the frequency increases. Hint: increasing the frequency does not affect either the forced response or the natural response. It merely shortens the observation window (period) which is used to capture the response and display it on the scope.

3) In step (d), explain why the displayed curve appears more like a straight horizontal line as the capacitance increases. Hint: changing the value of capacitance impacts the time constant and hence changes the natural response (however, the ramp forced response does not change).