



Transient in first order circuit

Contents

- A. Objectives
- B. Introduction
 - 1. Basic background in first order circuit
 - 2. Inductors and capacitors
 - 3. The transient response of step function
 - 4. Time constant
- C. Experiments
 - 1. Resistive circuit
 - 2. R - L circuit
 - 3. R - C circuit
 - 4. R - L and R - C circuit design

A. Objectives

1. To study the behaviors of the currents and voltages in first order circuits.
2. To learn how to construct a first order circuit whose responses are identical to responses from a black box.

B. Introduction

1. Basic background in first order circuit.

A first order circuit is a circuit which its behaviors can be described with a (set of) first order differential equation(s). The circuit usually contains only one (equivalent) inductor or one (equivalent) capacitor with unlimited resistors and sources. The resistors and sources, by Thevenin-Norton Theorem, can be simplified to a Thevenin resistor in series with a Thevenin voltage source or in parallel with a Norton current source. Examples of some simple first order circuits are illustrated in **Fig. 1**.

The time-varying currents and voltages resulting from the sudden application of sources, usually due to switching, are called transients. In resistive circuits, the resulting currents and voltages change simultaneously following the sudden change of sources. However, since the current flowing through an inductor and the voltage across a capacitor cannot change immediately, the resulting current from R - L circuit and resulting voltage from R - C circuit will not change immediately following the sudden change of sources. Therefore, if a capacitor or an inductor is added into the resistive circuit, by writing circuit equations, we obtain integrodifferential equations.

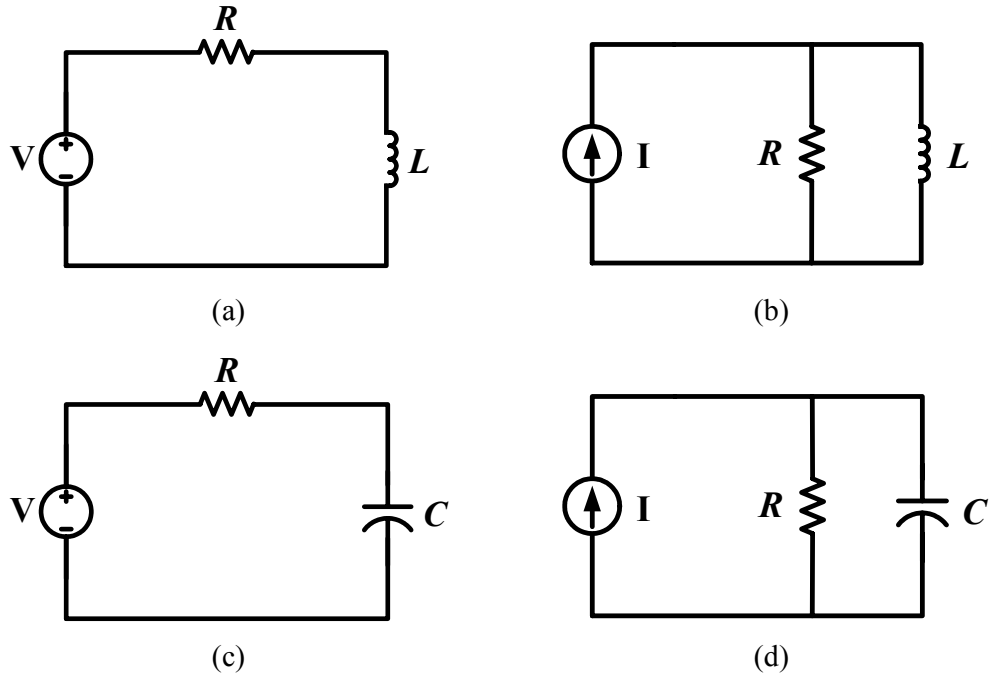


Figure 1. Simple first order circuits. (a) *R-L* series circuit, (b) *R-L* parallel circuit, (c) *R-C* series circuit and (d) *R-C* parallel circuit

2. Inductors and capacitors

2.1. Inductor

An **inductor** is a passive electrical element employed in electrical circuits for its property of inductance.

Overview

Inductance (measured in henries) is an effect which results from the magnetic field that forms around a current carrying conductor. Electrical current through the conductor creates a magnetic flux proportional to the current. A change in this current creates a change in magnetic flux that, in turn, generates an electromotive force (emf) that acts to oppose this change in current. Inductance is a measure of the generated emf for a rate of change in current. For example, an inductor with an inductance of 1 Henry produces an emf of 1 V when the current through the inductor changes at the rate of 1 ampere per second. The inductance of a conductor is increased by coiling the conductor such that the magnetic flux encloses (links) all of the coils (turns). Additionally, the magnetic flux linking these turns can be increased by coiling the conductor around a material with a high permeability.

Stored energy

The energy (measured in joules, in SI) stored by an inductor equals to the amount of work required to establish the current flowing through the inductor, and therefore the magnetic field. This is given by:

$$E_{\text{stored}} = \frac{1}{2}LI^2 \quad (1)$$

where L is inductance and
 I is the current flowing through the inductor.

In electric circuits

While a capacitor opposes changes in voltage, an inductor opposes changes in current. An ideal inductor would offer no resistance to direct current. However, all real-world inductors have non-zero electrical resistance.

In general, the relationship between the time-varying voltage $v(t)$ across an inductor with inductance L and the time-varying current $i(t)$ passing through it is described by the differential equation:

$$v(t) = L \frac{di(t)}{dt} \quad (2)$$

2.2. Capacitor

A capacitor is a passive electrical element that can store energy in the electric field between a pair of closely spaced conductors (called 'plates'). When current is passed through the capacitor, electric charges of equal magnitude, but opposite sign, build up on each plate.

Capacitors are used in electrical circuits as energy-storage devices. They can also be used to differentiate between high-frequency and low-frequency signals and this makes them useful in electronic filters.

Overview

A capacitor consists of two conductive electrodes, or plates, separated by an insulator or *dielectric*. When the capacitor is in its minimum-energy state, each plate contains equal densities of electrons and protons and is therefore, overall, electrically neutral. When an electric field is applied across the terminals by an external circuit, excess electrons are forced into one plate, giving it a net negative charge, and some are forced out of the other plate, giving it a net positive charge. Assuming that the entire circuit is electrically neutral, as is usually the case, the number of electrons added to one plate is equal to the number removed from the other. Thus, the net charge on the capacitor remains zero even when it is energized. Even though one plate is now electrically positive, and the other plate is electrically negative, the capacitor as a whole remains electrically neutral.

When charging the capacitor (by connecting the capacitor to a battery), the plate on the capacitor that attaches to the negative terminal of the battery accepts electrons that the battery is producing, and the plate on the capacitor that attaches to the positive terminal of the battery loses electrons to the battery. Because of the electric field between the two plates of an energized capacitor, and since the electrons cannot cross the dielectric, their concentration is highest on the side of the negative plate facing the gap. Conversely, the electrons in the positive plate are repelled to the negative plate by the electric field. Their concentration is

lowest on the side of the positive plate nearest the gap. The protons in both plates are fixed in position by the atomic structure of the material.

Capacitance in a capacitor

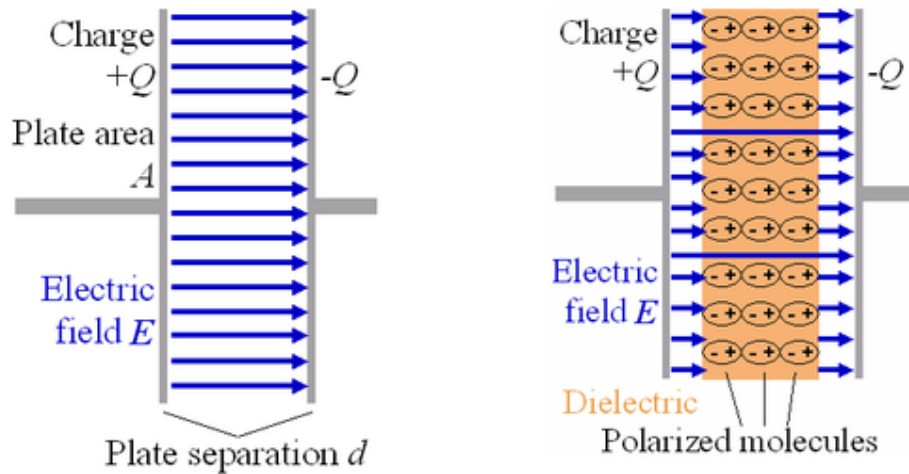


Figure 2. Parallel plate capacitor

When electric charge accumulates on the plates, an electric field is created in the region between the plates that is proportional to the amount of accumulated charge. This electric field creates a potential difference $V = E \cdot d$ between the plates of this simple parallel-plate capacitor.

The electrons within dielectric molecules are influenced by the electric field, causing the molecules to alter slightly from their equilibrium positions. The air gap is shown for clarity; in a real capacitor, the dielectric is in direct contact with the plates.

The capacitor's capacitance (C) is a measure of the amount of charge (Q) stored on each plate for a given potential difference or *voltage* (V) which appears between the plates:

$$C = \frac{Q}{V} \quad (3)$$

In SI units, a capacitor has a capacitance of one farad when one coulomb of charge causes a potential difference of one volt across the plates. Since the farad is a very large unit, values of capacitors are usually expressed in microfarads (μF), nanofarads (nF) or picofarads (pF).

The capacitance is proportional to the surface area of the conducting plate and inversely proportional to the distance between the plates. It is also proportional to the permittivity of the dielectric (that is, non-conducting) substance that separates the plates. The capacitance of a parallel-plate capacitor is given by:

$$C \approx \frac{\epsilon A}{d}; \quad A \gg d^2 \quad (4)$$

where ϵ is the permittivity of the dielectric

A is the area of the plates and
 d is the spacing between them.

Stored energy

As opposite charges accumulate on the plates of a capacitor due to the separation of charge, a voltage develops across the capacitor owing to the electric field of these charges. Ever-increasing work must be done against this ever-increasing electric field as more charge is separated. The energy (measured in joules, in SI) stored in a capacitor is equal to the amount of work required to establish the voltage across the capacitor, and therefore the electric field. The energy stored is given by:

$$E_{\text{stored}} = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}VQ \quad (5)$$

where V is the voltage across the capacitor.

The maximum energy that can be (safely) stored in a particular capacitor is limited by the maximum electric field that the dielectric can withstand before it breaks down. Therefore, all capacitors made with the same dielectric have about the same maximum energy density (J/m^3).

Capacitors in electric circuits

Circuits with DC sources

Electrons cannot easily pass directly across the dielectric from one plate of the capacitor to the other as the dielectric is carefully chosen so that it is a good insulator. When there is a current through a capacitor, electrons accumulate on one plate and electrons are removed from the other plate. This process is commonly called 'charging' the capacitor -- even though the capacitor is at all times electrically neutral. In fact, the current through the capacitor results in the separation of electric charge, rather than the accumulation of electric charge. This separation of charge causes an electric field to develop between the plates of the capacitor giving rise to voltage across the plates. This voltage V is directly proportional to the amount of charge separated Q . Since the current I through the capacitor is the rate at which charge Q is forced through the capacitor (dQ/dt), this can be expressed mathematically as:

$$I = \frac{dQ}{dt} = C \frac{dV_c}{dt} \quad (6)$$

where I is the current flowing in the conventional direction, measured in amperes
 dV/dt is the time derivative of voltage, measured in volts per second.
 C is the capacitance in farads

For circuits with a constant (DC) voltage source, the voltage across the capacitor cannot exceed the voltage of the source. (Unless the circuit includes a switch and an inductor, as in SMPS (switched-mode power supply), or a switch and some diodes, as in a charge pump). Thus, an equilibrium is reached where the voltage across the capacitor is constant and the

current through the capacitor is zero. For this reason, it is commonly said that capacitors block DC current.

Circuits with AC sources

The capacitor current due to an AC voltage or current source reverses direction periodically. That is, the AC current alternately charges the plates in one direction and then the other. With the exception of the instant that the current changes direction, the capacitor current is non-zero at all times during a cycle. For this reason, it is commonly said that capacitors 'pass' AC current. However, at no time do electrons actually cross between the plates, unless the dielectric breaks down or becomes excessively 'leaky'. In this case it would probably overheat, malfunction, burn out, or even fail catastrophically possibly leading to explosion.

Since the voltage across a capacitor is the integral of the current, as shown above, with sine waves in AC or signal circuits this results in a phase difference of 90 degrees, the current leading the voltage phase angle. It can be shown that the AC voltage across the capacitor is in quadrature with the AC current through the capacitor. That is, the voltage and current are 'out-of-phase' by a quarter cycle. The amplitude of the voltage depends on the amplitude of the current divided by the product of the frequency of the current with the capacitance, C .

3. The transient responses of step function

3.1. An R - L circuit

Consider **Fig. 1(a)**, if the input V is a step function and the current that flows in the circuit is $i_L(t)$. Given the initial condition, I_0 , using KVL, the complete response of this circuit is:

$$i_L(t) = (I_0 - \frac{V}{R})e^{-\frac{Rt}{L}} + \frac{V}{R} \quad (7)$$

The first term in the right hand side of equation (7) is called **Natural Response**, which reflects the nature of the circuit. The second term in the right hand side of equation (7) is called **Forced Response**, which depends on the source that is given to the circuit.

For **Fig. 1(b)**, the current source and the resistor (in parallel) can be transformed into a voltage source connected in series with a resistor and its response can also be expressed with equation (7).

3.2. An R - C circuit

Consider **Fig. 1(c)**, if the input V is a step function and the voltage across the capacitor in the circuit is $v_C(t)$. Given the initial condition, V_0 , using KVL, the complete response of this circuit is:

$$v_C(t) = (V_0 - V)e^{-\frac{t}{RC}} + V \quad (8)$$

The first term in the right hand side of equation (8) is called **Natural Response**, which reflects the nature of the circuit. The second term in the right hand side of equation (8) is called **Forced Response**, which depends on the source that is given to the circuit.

For **Fig. 1(d)**, the current source and the resistor (in parallel) can be transformed into a voltage source connected in series with a resistor and its response can also be expressed with equation (8).

3.3. Time constant

In physics and engineering, the **time constant** usually denoted by the Greek letter τ , (tau), characterizes the frequency response of a first-order, linear time-invariant (LTI) system, e.g., in electrical RC circuits and RL circuits. It is also used to characterize the frequency response of various signal processing systems (e.g., magnetic tapes, radio transmitters and receivers, record cutting and replay equipment, and digital filters) which can be modeled or approximated by first-order LTI systems.

Physically, the time constant represents the time it takes for the step response of the system to reach about 63.2% of its final value (**Fig. 3(b)**). It indicates how fast the step response of the system can reach its final value. The higher the time constant is, the longer time the response needs to reach its final value (as shown in **Fig. 4**).

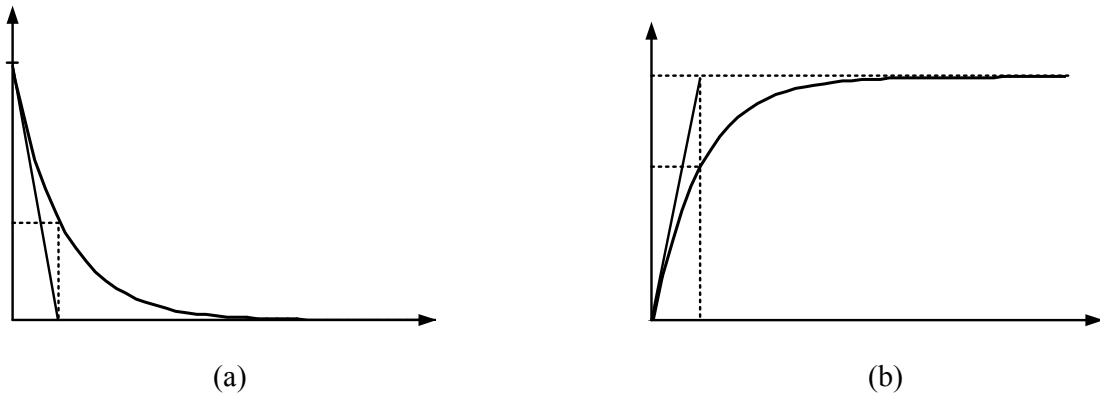


Figure 3. The step responses of the first order circuit. (a) zero-input response and (b) zero-state response.

If $y(t)$ represents the complete response, $i_L(t)$ or $V_C(t)$.
 Y_0 represents the initial condition, $i_L(0) = I_0$ or $V_C(0) = V_0$.
 Y_{SS} represents the steady state, $i_L(\infty)$ or $V_C(\infty)$

Then the complete response of a first order circuit is:

$$y(t) = Y_0 e^{-\frac{t}{\tau}} + Y_{SS} (1 - e^{-\frac{t}{\tau}}) \quad (9)$$

$$= y_{zi}(t) + y_{zs}(t) \quad (10)$$

$y_{zi}(t)$

Y_0

From **Fig. 3(a)**, we can calculate for τ by:

$$y_{zi}(\tau) = Y_0 e^{-1} = 0.368 Y_0 \quad (11)$$

Or, the slope of the zero input response at $t = 0$ s.:

$$\left. \frac{dy_{zi}(t)}{dt} \right|_{t=0} = -\frac{Y_0}{\tau} \quad (12)$$

Or from **Fig. 3(b)**:

$$y_{zs}(\tau) = Y_{SS}(1 - e^{-1}) = 0.632 Y_{SS} \quad (13)$$

Or, the slope of the zero state response at $t = 0$ s.:

$$\left. \frac{dy_{zs}(t)}{dt} \right|_{t=0} = \frac{Y_{SS}}{\tau} \quad (14)$$

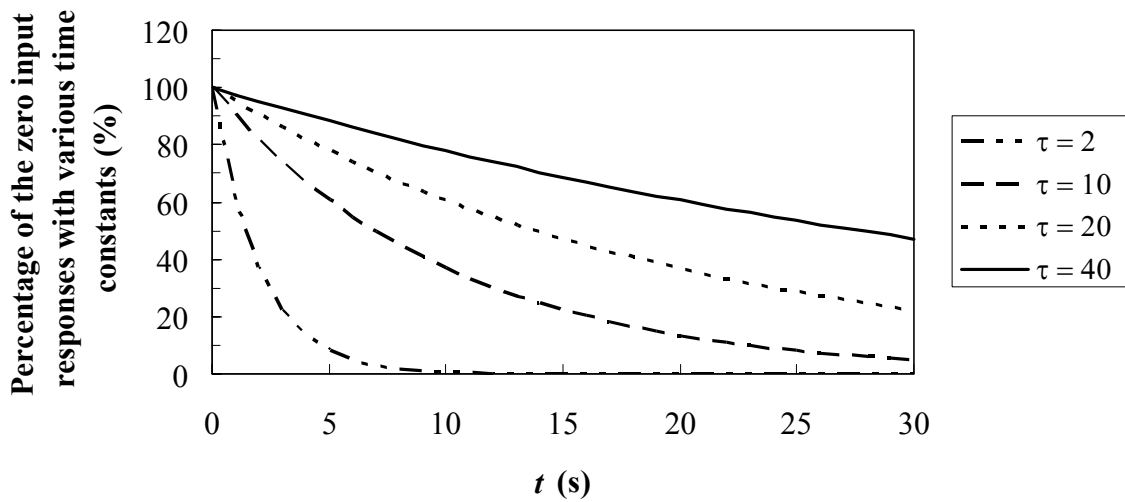


Figure 4. The zero input responses with various time constants.

3.4. Time constants in electrical circuits

In an R - L circuit, the time constant τ (in seconds) is

$$\tau = \frac{L}{R} \quad (15)$$

where R is the resistance (in ohms) and L is the inductance (in henries).

Similarly, in an R - C circuit, the time constant τ is:

$$\tau = RC \quad (16)$$

where R is the resistance (in ohms) and
 C is the capacitance (in farads).

C. Experiments

To understand how a capacitor or an inductor changes the characteristic of a resistive circuit, the behaviors of a resistive circuit, an R - L circuit and an R - C circuit are studied.

Exp1 A resistive circuit

1.1 Construct a resistive circuit as shown in **Fig. 5** using a function generator and two adjustable resistors.

1.2 Before connecting the circuit, Set the output of the function generator, $V_S(t)$, to Square Wave, frequency at 1 kHz, amplitude 4 Vp-p. Check the output signal using CH1 of the oscilloscope. Then, set both adjustable resistors to 1 k Ω .

1.3 Without removing the CH1 probe of the oscilloscope from $V_S(t)$, connect the function generator to both 1-k Ω resistors. Measure $V_{R2}(t)$ using CH2 of the scope.

1.4 Set the time base of the scope properly so that you could see approximately 2 cycles of the square wave. Then, record the plots of $V_S(t)$ and $V_{R2}(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

1.5 Without removing the CH1 probe of the oscilloscope from $V_S(t)$, measure $V_{R1}(t)$ using CH2 of the scope. Make sure both CH1 and CH2 share the same reference point.

1.6 With similar time base, record the plots of $V_S(t)$ and $V_{R1}(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

- Did $V_{R1}(t)$ and $V_{R2}(t)$ change simultaneously following the change of $V_S(t)$?

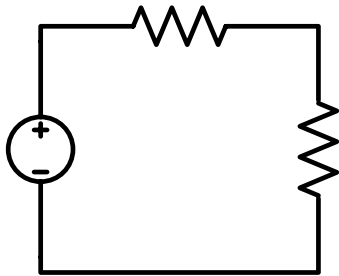


Figure 5. A resistive circuit.

Exp2 An R-L circuit

2.1 Construct an R - L circuit as shown in **Fig. 6(a)** using a function generator and an adjustable resistor and an inductor.

2.2 Before connecting the circuit, Set the output of the function generator, $V_S(t)$, to Square Wave, frequency at 1 kHz, amplitude 4 Vp-p. Check the output signal using CH1 of the oscilloscope. Then, set the adjustable resistor to 1 k Ω .

2.3 Without removing the CH1 probe of the oscilloscope from $V_S(t)$, connect the function generator to the 1-k Ω resistor and the inductor. Measure $V_R(t)$ using CH2 of the scope. Set the time base of the scope properly so that you could see approximately 2 cycles of the square wave.

2.4 Adjust the resistor until $V_R(t)$ looks like **Fig. 6(b)**. Record the value of R and L of this circuit.

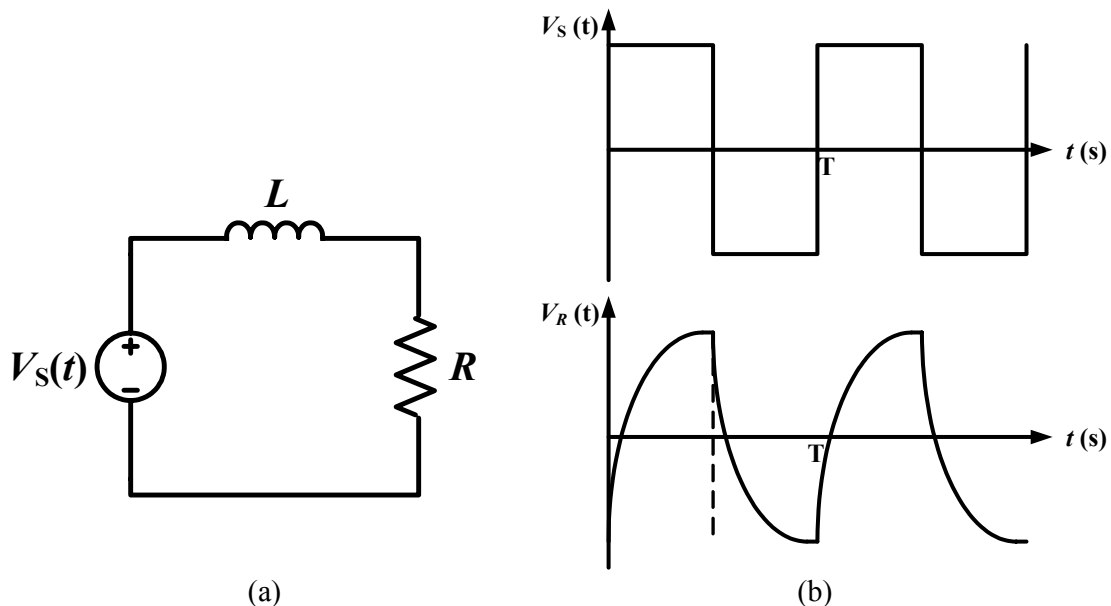


Figure 6. (a) An R - L circuit, and (b) Responses of an R - L series circuit.

2.5 Then, record the plots of $V_S(t)$ and $V_R(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

2.6 Find the time constant from the plot of $V_R(t)$. Then calculate for the value of L using the time constant you obtained.

2.7 Measure $V_L(t)$ using CH2 of the scope. Make sure both CH1 and CH2 share the same reference point.

2.8 With similar time base, record the plots of $V_S(t)$ and $V_L(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

2.9 Adjust the resistor to twice of what it is in 2.4. Record the value of the new R and record the plots of $V_S(t)$ and $V_R(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

2.10 Find the new time constant from the plot of $V_R(t)$. Then calculate for the value of L using the time constant you obtained.

2.11 Measure $V_L(t)$ using CH2 of the scope. Make sure both CH1 and CH2 share the same reference point. Then, record the plots of $V_S(t)$ and $V_L(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

- Did $V_R(t)$ change simultaneously following the change of $V_S(t)$?
- What is the relationship among $V_R(t)$, $V_L(t)$ and $V_S(t)$?
- Compare the time constant obtained from 2.6 and from 2.10.
- What happened when we increased R ?

Exp3 An R-C circuit

3.1 Construct an R - C circuit as shown in **Fig. 7(a)** using a function generator and an adjustable resistor and a capacitor.

3.2 Before connecting the circuit, Set the output of the function generator, $V_S(t)$, to Square Wave, frequency at 1 kHz, amplitude 4 Vp-p. Check the output signal using CH1 of the oscilloscope. Then, set the adjustable resistor to 1 k Ω .

3.3 Without removing the CH1 probe of the oscilloscope from $V_S(t)$, connect the function generator to the 1-k Ω resistor and the capacitor. Measure $V_C(t)$ using CH2 of the scope. Set the time base of the scope properly so that you could see approximately 2 cycles of the square wave.

3.4 Adjust the resistor until $V_C(t)$ looks like **Fig. 7(b)**. Record the value of R and C of this circuit.

3.5 Then, record the plots of $V_S(t)$ and $V_C(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

3.6 Find the time constant from the plot of $V_C(t)$. Then calculate for the value of C using the time constant you obtained.

3.7 Measure $V_R(t)$ using CH2 of the scope. Make sure both CH1 and CH2 share the same reference point.

3.8 With similar time base, record the plots of $V_S(t)$ and $V_R(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

3.9 Adjust the resistor to half of what it is in 3.4. Record the value of the new R and record the plots of $V_S(t)$ and $V_C(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

3.10 Find the new time constant from the plot of $V_C(t)$. Then calculate for the value of C using the time constant you obtained.

3.12 Measure $V_R(t)$ using CH2 of the scope. Make sure both CH1 and CH2 share the same reference point. With similar time base, record the plots of $V_S(t)$ and $V_R(t)$ with your digital camera. Make sure you write down the V/DIV and s/DIV of the scope.

- Did $V_C(t)$ change simultaneously following the change of $V_S(t)$?
- What is the relationship among $V_R(t)$, $V_C(t)$ and $V_S(t)$?
- Compare the time constant obtained from 3.6 and from 3.10.
- What happened when we decreased R ?

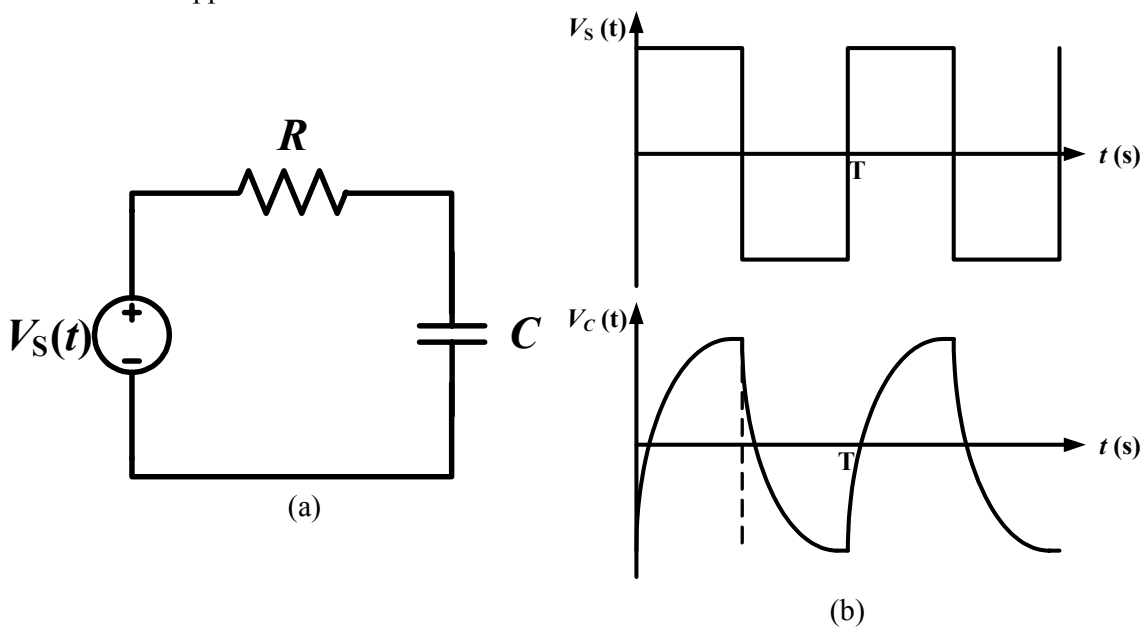


Figure 7. (a) An R - C circuit, and (b) Responses of an R - C series circuit.

Exp4 R - L and R - C circuit design

4.1 Set the output of the function generator, $V_S(t)$, to Square Wave, frequency at 1 kHz, amplitude 4 Vp-p. Then connect it to the input side of the black-box. Measure the output signal of the black-box, $X(t)$, using CH1 of the oscilloscope. Then find the time constant of $X(t)$.

4.2 Construct an R - L circuit using the same L and R used in the previous experiment. Supply the circuit with the same signal generator (as shown in **Fig. 8**). Then measure $V_R(t)$ with CH2 of the scope.

4.3 Adjust R so that $V_R(t)$ looks exactly like $X(t)$. You may use “Variable voltage scale” to help you adjust the size of both $X(t)$ and $V_R(t)$ so they look identical.

4.4 Find the time constant of the $V_R(t)$. Record the value of R and L and record the plots of $V_R(t)$ and $X(t)$ with you digital camera.

4.5 Replace the $R-L$ circuit with an $R-C$ circuit. Measure $V_C(t)$ with CH2 of the scope. Adjust R so that $V_C(t)$ is identical to $X(t)$. Find the time constant of $V_C(t)$. Record the value of R and C and record the plots of $V_R(t)$ and $X(t)$ with you digital camera.

- Find the complete response $i_L(t)$ and $v_C(t)$ from the circuit elements you used in this experiment.
- Compare the time constant obtained from the black-box with the ones obtained from the $R-L$ and $R-C$ circuit.

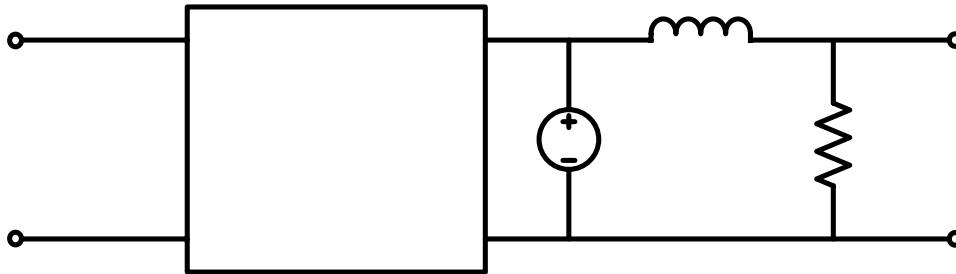
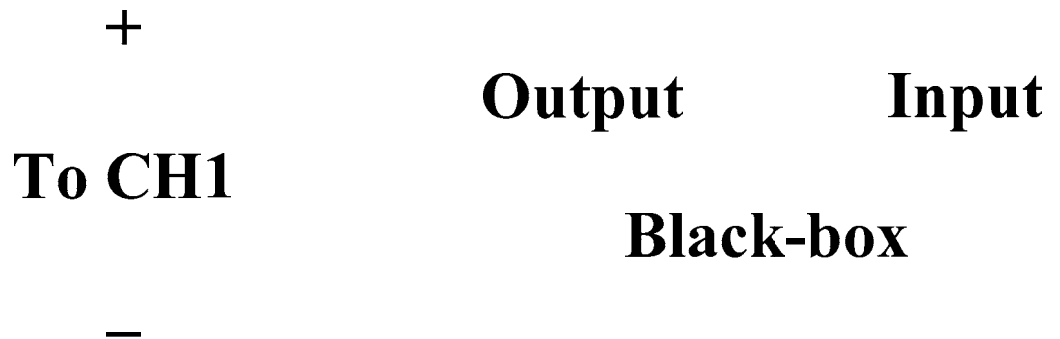


Figure 8. Experimental circuit using black-box and $R-L$ circuit.



Student Name: _____ ID: _____
Date: _____ Group: _____ Instructor signature: _____

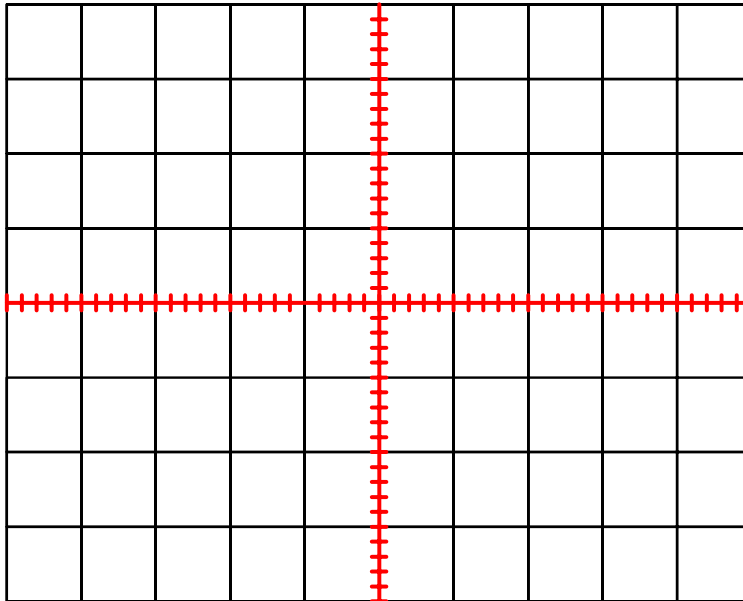
Experimental Report

Transient in first order circuit (TRC1)

Exp1 A resistive circuit

$V_S(t) =$ _____ V/DIV, $V_{R1}(t) =$ _____ V/DIV, $V_{R2}(t) =$ _____ V/DIV
Time Base = _____ s/DIV

Plot $V_S(t)$, $V_{R1}(t)$ and $V_{R2}(t)$



Discussion

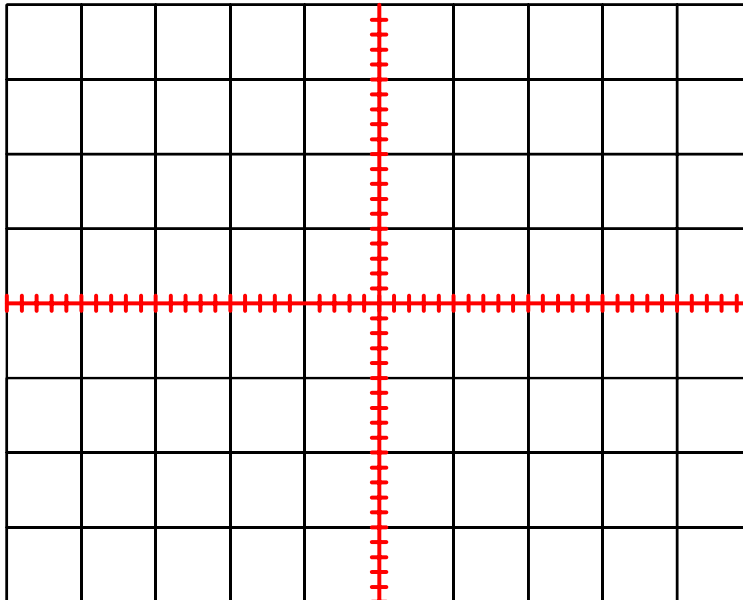
Exp2 An R-L circuit

$R = \underline{\hspace{2cm}}$ Ω , $L = \underline{\hspace{2cm}}$ H

$V_S(t) = \underline{\hspace{2cm}}$ V/DIV, $V_R(t) = \underline{\hspace{2cm}}$ V/DIV, $V_L(t) = \underline{\hspace{2cm}}$ V/DIV

Time Base = $\underline{\hspace{2cm}}$ s/DIV

Plot $V_S(t)$, $V_R(t)$, and $V_L(t)$



Time constant = $\underline{\hspace{2cm}}$ s

Calculated $L = \underline{\hspace{2cm}}$ H

Discussion

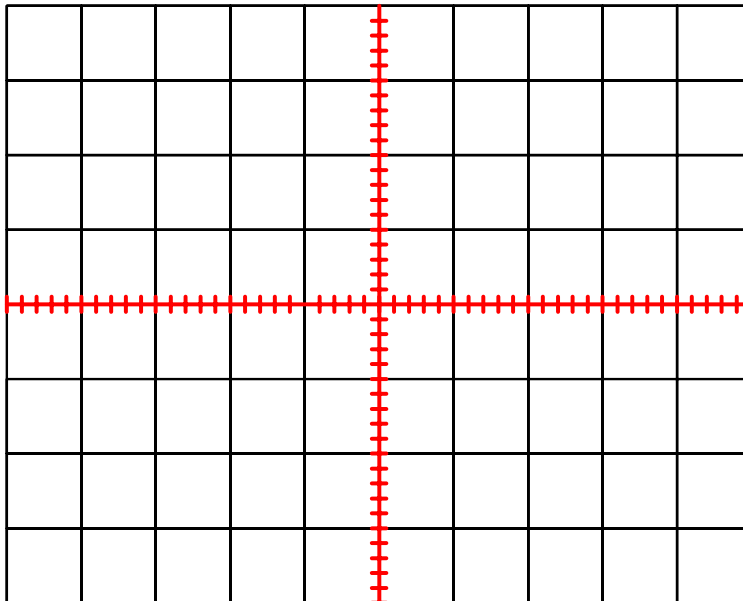
Double the value of R

$R = \underline{\hspace{2cm}} \Omega, L = \underline{\hspace{2cm}} \text{H}$

$V_S(t) = \underline{\hspace{2cm}} \text{V/DIV}, V_R(t) = \underline{\hspace{2cm}} \text{V/DIV}, V_L(t) = \underline{\hspace{2cm}} \text{V/DIV}$

Time Base = $\underline{\hspace{2cm}} \text{s/DIV}$

Plot $V_S(t)$, $V_R(t)$, and $V_L(t)$



Time constant = $\underline{\hspace{2cm}} \text{s}$

Calculated $L = \underline{\hspace{2cm}} \text{H}$

Discussion

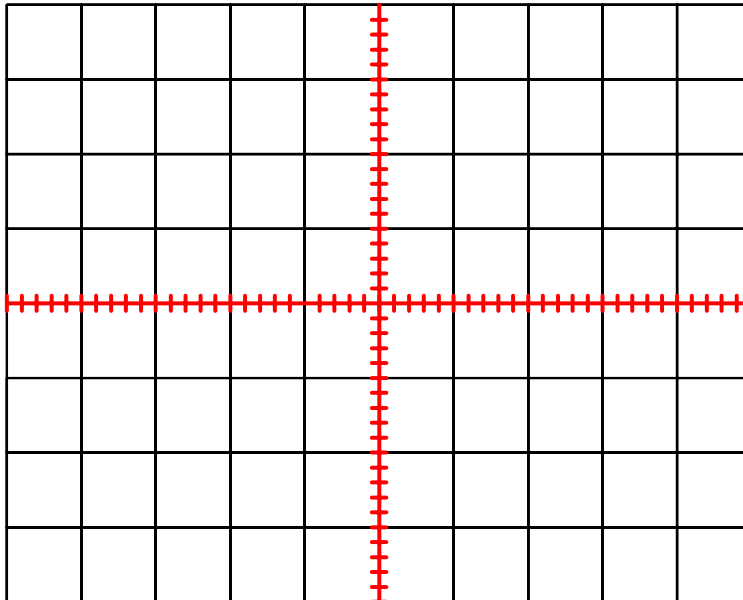
Exp3 An R-C circuit

$R = \underline{\hspace{2cm}} \Omega, C = \underline{\hspace{2cm}} \text{ F}$

$V_S(t) = \underline{\hspace{2cm}} \text{ V/DIV}, V_R(t) = \underline{\hspace{2cm}} \text{ V/DIV}, V_L(t) = \underline{\hspace{2cm}} \text{ V/DIV}$

Time Base = $\underline{\hspace{2cm}} \text{ s/DIV}$

Plot $V_S(t), V_R(t),$ and $V_L(t)$



Time constant = $\underline{\hspace{2cm}} \text{ s}$

Calculated $L = \underline{\hspace{2cm}} \text{ F}$

Discussion

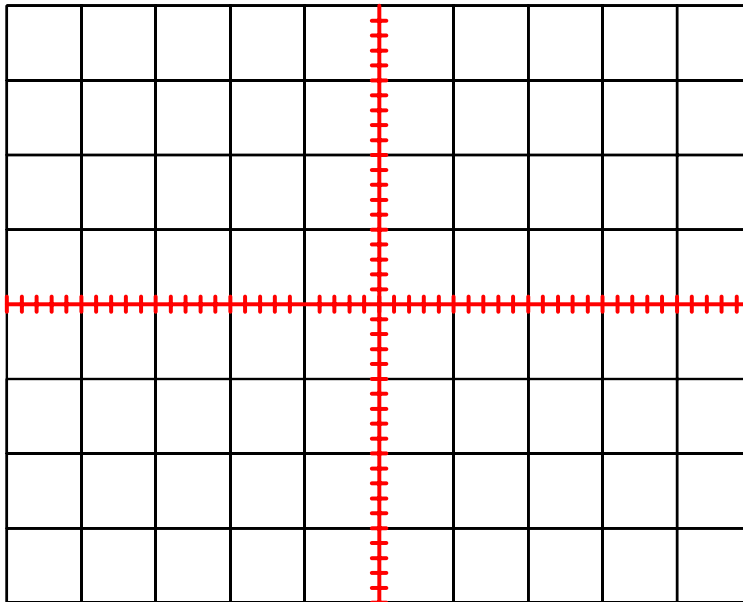
Reduce the value of R to $\frac{1}{2}R$

$R =$ _____ Ω , $C =$ _____ F

$V_S(t) =$ _____ V/DIV, $V_C(t) =$ _____ V/DIV, $V_R(t) =$ _____ V/DIV,

Time Base = _____ s/DIV

Plot $V_S(t)$, $V_C(t)$ and $V_R(t)$



Time constant = _____ s

Calculated $C =$ _____ F

Discussion

Exp4 R-L and R-C circuit design

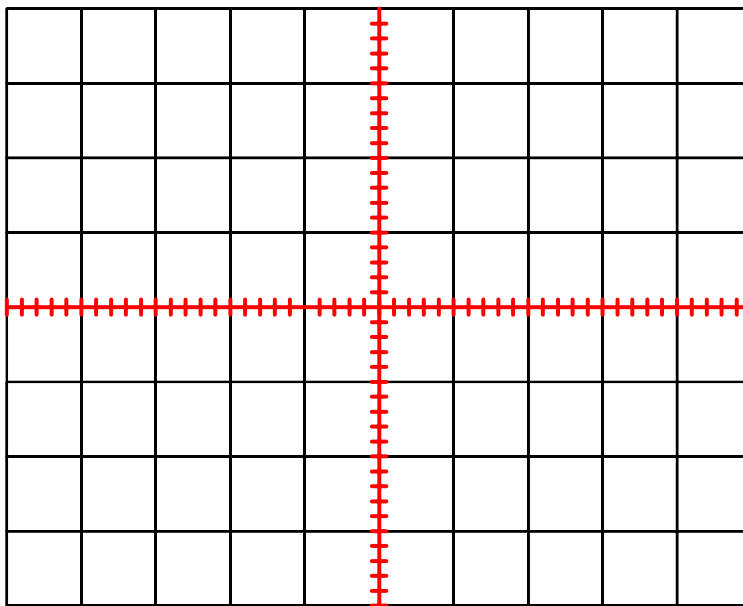
RL circuit design

$R = \underline{\hspace{2cm}} \Omega, L = \underline{\hspace{2cm}} \text{ H}$

O/P (CH I) = $\underline{\hspace{2cm}}$ V/DIV, $V_R(t)$ (CH II) = $\underline{\hspace{2cm}}$ V/DIV

Time Base = $\underline{\hspace{2cm}}$ s/DIV

Plot CH1 (O/P) and CH2 ($V_R(t)$)



Time constant of O/P = $\underline{\hspace{2cm}}$ s

Time constant of $V_R(t)$ = $\underline{\hspace{2cm}}$ s

Discussion

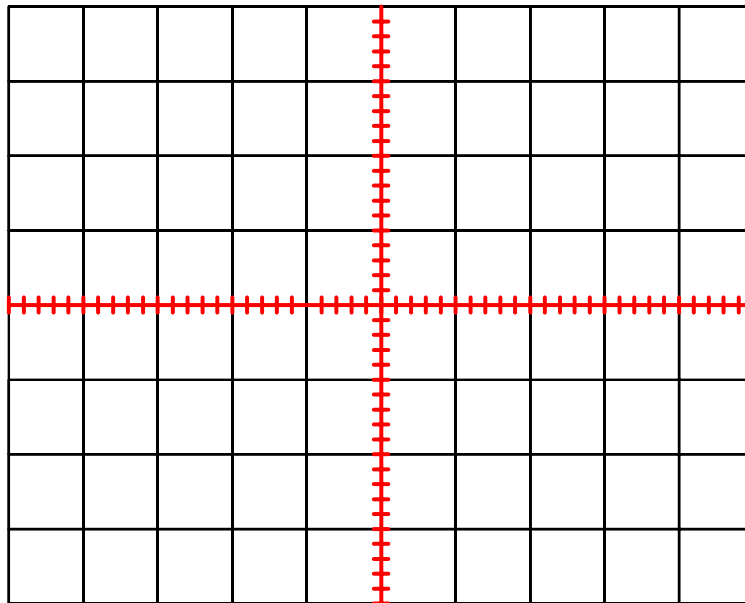
RC circuit design

$R = \underline{\hspace{2cm}} \Omega, C = \underline{\hspace{2cm}} \text{H}$

O/P (CH I) = $\underline{\hspace{2cm}}$ V/DIV, $V_C(t)$ (CH II) = $\underline{\hspace{2cm}}$ V/DIV

Time Base = $\underline{\hspace{2cm}}$ s/DIV

Plot CH1 (O/P) and CH2 ($V_C(t)$)



Time constant of O/P = $\underline{\hspace{2cm}}$ s

Time constant of $V_C(t)$ = $\underline{\hspace{2cm}}$ s

Discussion