Student ID:	22301689	**Lab Section:**	28
Name:	TASNIM RAHMAN MOUMITA	**Lab Group:**	03

Experiment No. 8

Study of the Transient Behavior of RC Circuit Using Software (LTSpice) Simulation.

Objective

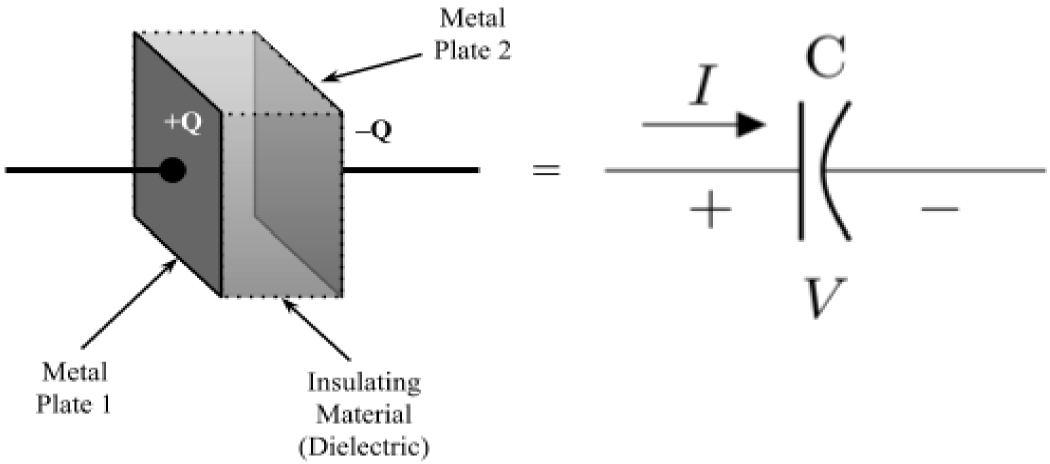
The objective of this experiment is to study the Transient Response of the first order RC circuit with step input. In this experiment, we shall apply a square wave input to an RC circuit separately and observe the respective wave shapes and determine the time constant, τ.

Theory

The word 'transient' means something that only lasts for a short time *(short-lived)*. In circuit theory, transient response is the response of a system to a change from an equilibrium or a steady state. In the context of RC circuits *(a circuit only consisting of resistors and capacitors but no inductor)*, we will study how the voltage and current in an RC circuit change due to external excitation, such as switching or sudden change in input. In today's experiment, we will construct RC circuits and observe their response due to sudden changes in input voltage.

Capacitor

Capacitors are passive elements that can store energy within its own electric field. A capacitor can be as simple as an insulating material *(dielectric)* consisting of two parallel conductive plates. Charges can build up within these plates which creates an electric field across the plates and a voltage difference between them.



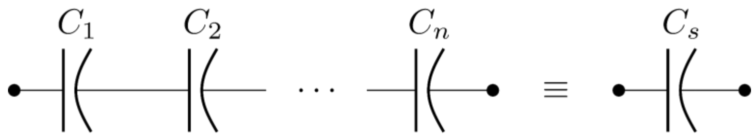
The amount of charge accumulated in each plate is directly proportional to the voltage difference applied across the two plates of a capacitor. If the voltage across the capacitor is v_C and the accumulated charge is Q, then we can write,

$$Q \propto V \Rightarrow Q = CV \Rightarrow \frac{dQ}{dt} = \frac{d}{dt}(CV) = C\frac{d}{dt}(V) \Rightarrow \boxed{I = C\frac{dV}{dt}}$$

This boxed equation dictates the behavior of a capacitor. Here, I is the current through the capacitor and C is the **capacitance** [*S.I. unit is **Farad (F)***]. As we can see, there is a current through the capacitor if and only if the voltage across the capacitor changes over time.

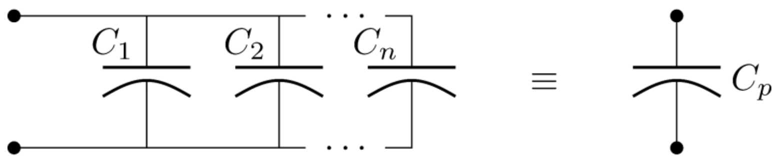
From this equation, we can find the equivalent series and parallel capacitance.

➢ Series combination:



$$\frac{1}{C_s} = \sum \frac{1}{C_n} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots + \frac{1}{C_n}$$

➢ Parallel combination:

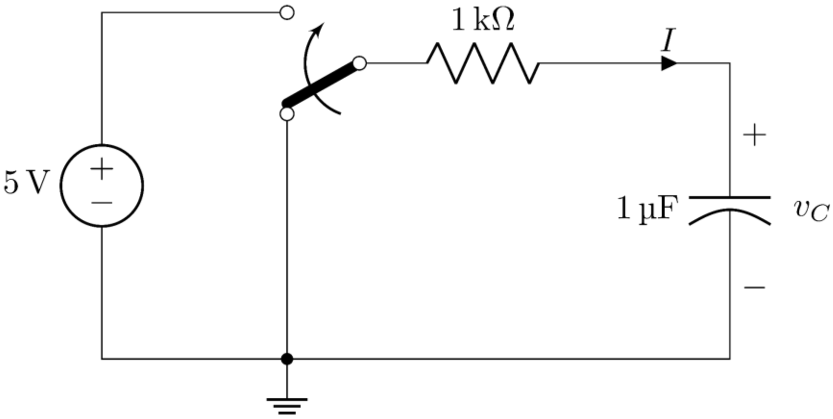


$$C_p = \sum C_n = C_1 + C_2 + \cdots + C_n$$

RC circuit

An RC circuit is an electric circuit composed of resistors and capacitors as the only passive components (may contain other active components). Such circuits exhibit transient behaviors if the input voltage is suddenly changed.

Consider this RC circuit with a switch (arrow indicates the direction of switching):

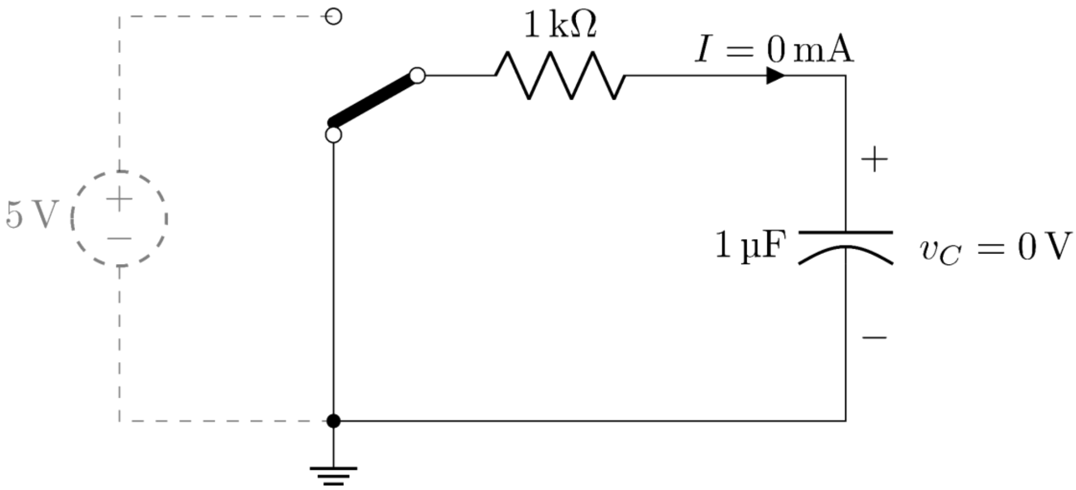


We can break this circuit into two separate circuits:

- ➢ Initial circuit
- ➢ Final circuit

The initial position of the switch indicates the voltage source was open and the resistor was grounded. Since there is no source in the circuit, the elements will have no current. Furthermore, **at steady-state conditions, a capacitor acts like an open circuit.** As a result,

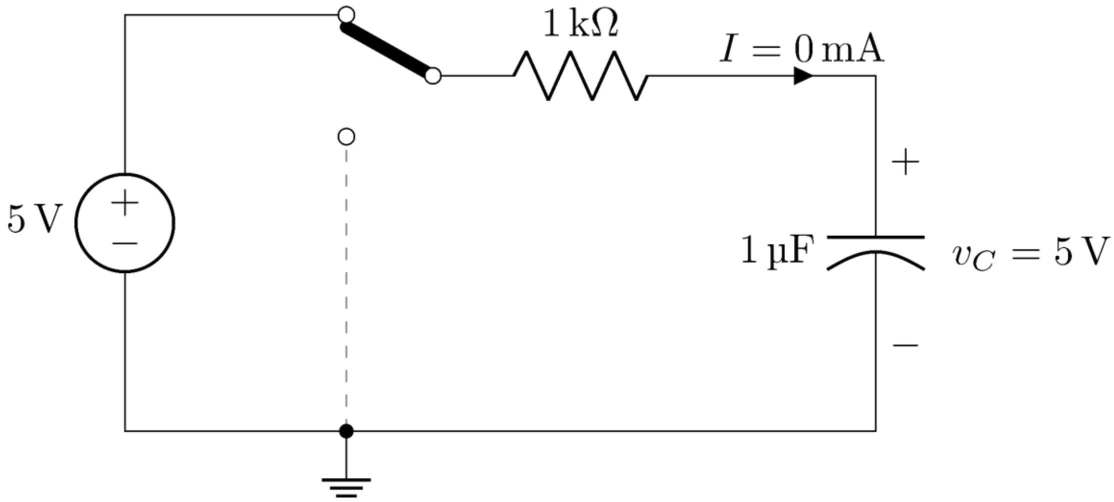
c



the voltage across the capacitor v will be 0V.

Initial Circuit

On the other hand, the final position of the switch indicates that the voltage source will now supply voltage. However, **after reaching a steady-state condition, the capacitor will again act like an open circuit.** As a result, the voltage across the capacitor v_C will be 5V.

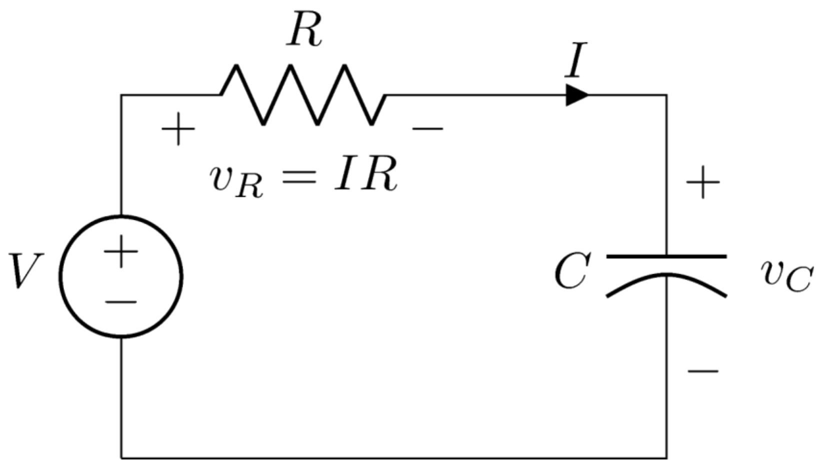


Final Circuit (after reaching steady-state)

Transient Behavior

Inresistors,the previousit takescircuit,a significantthe voltageamountacrossof timetheforcapacitorthe voltagev^C risesacrossfroma capacitor0V to 5toV.change.Unlike

This behavior is called transient behavior. We can figure out how the voltage will change over time using KVL and KCL.



Applying KVL on the circuit we get, example,$\tau = RC\tau = 1k\Omega \times 1\mu F = 1ms$. Time constant

$$v_R + v_C - V = 0.$$

$$\Rightarrow IR + v_C - V = 0$$

$$\Rightarrow \left(C \frac{d}{dt} v_C\right) \cdot R + v_C - V = 0$$

$$\Rightarrow v_C + RC \frac{d}{dt} v_C - V = 0$$

$$\Rightarrow v_C + \tau \frac{d}{dt} v_C - V = 0$$

Let, . This quantity is called the ~~**time constant**~~ and the S.I unit is **seconds (s)**. In this has physical significance. It determines how fast the transient response dies out.

Solving the above differential equation, we get,

$$\boxed{v_C(t) = v_C(\infty) + \left[v_C(0) - v_C(\infty)\right] \text{ at time } . \; e^{-t/\tau}}$$

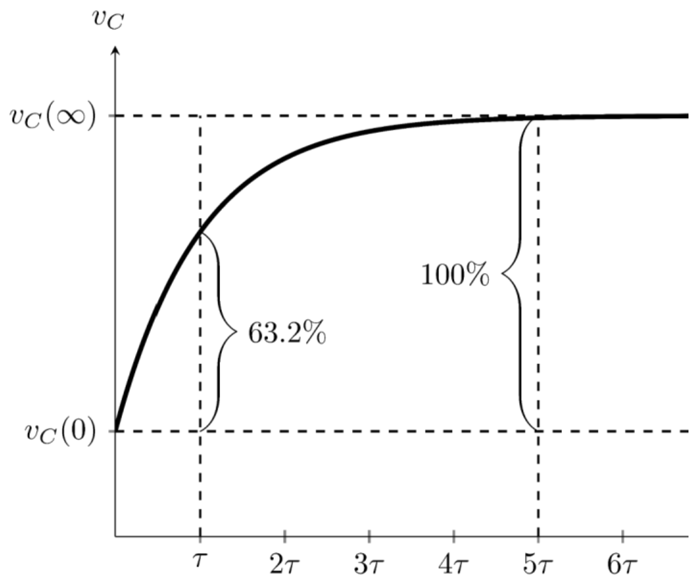
Here,**capacitor**$v^C(t$**voltage**) is the**of**voltage**the initial**across**circuit**the capacitor**and** **refers**t **to**Therefore,**the capacitor**$v^C(0)$ **voltagerefers toof thethe**

final circuit after it has reached steady- $_C(0) < v_C(\infty)$ **state.**v^CIf(∞), then the RC circuit is said circuit is in

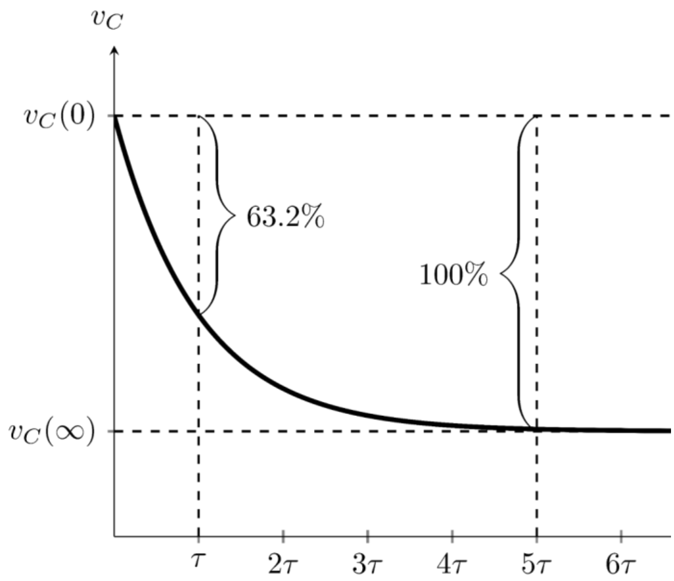
v

to be in the **charging phase**. And the RCthe **discharging phase** if

$v_C(0) > v_C(\infty)$.



Charging Phase



Discharging Phase

Time Constant

However, it is also possible to find the time constant from the plot of transient response. For a given circuit with a resistance of R and a capacitance of C, the time constant is $\tau = RC$. Higher the value of time constant, the longer it takes for the voltage to reach steady-state. At time $t = \tau$,

$$v_C(\tau) = v_C(\infty) + \left[v_C(0) - v_C(\infty)\right]e^{-\tau/\tau} = v_C(\infty) + \left[v_C(0) - v_C(\infty)\right]e^{-1}$$

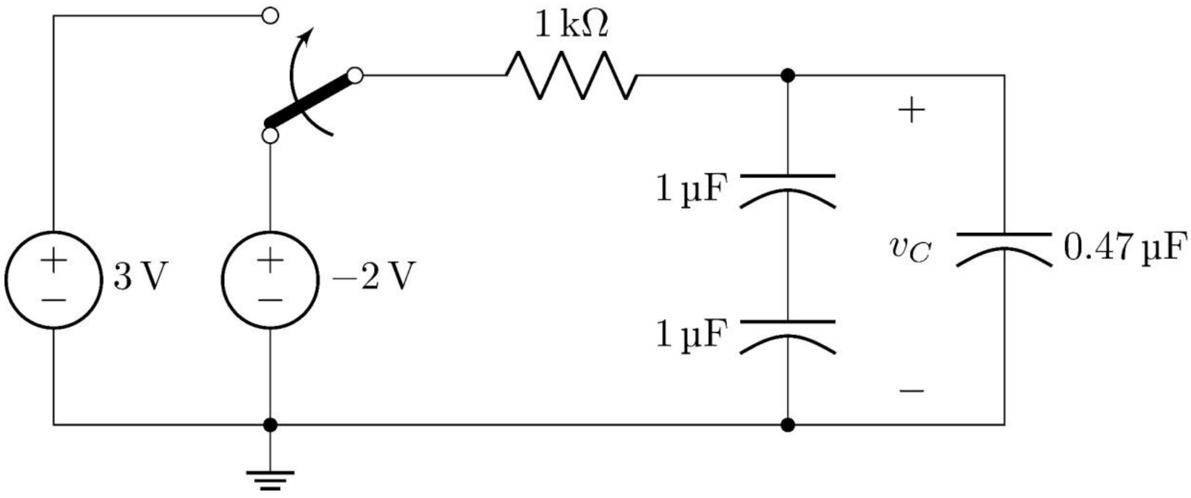
$$\therefore \frac{v_C(\infty) - v_C(\tau)}{v_C(\infty) - v_C(0)} = 1 - e^{-1} \approx 0.632 = 63.2\%$$

For example, if $\tau = 1ms$, then 1 ms after switching, the voltage has already reached 63.2% of its way to the final steady-state voltage. A similar analysis shows that, after 5τ, the voltage almost reaches the final steady-state voltage. So we can conclude **it takes approximately $t = 5\tau$ time for a transient circuit to reach steady-state.**

Procedure

Simulation using LTspice

We will introduce the study of the Transient Behavior in LTspice by simulating the simple circuit shown below (**Circuit 1**). Let us visualize Vc(t) for both the charging (as shown in the circuit) and the discharging phase (switching in the opposite direction).



Circuit 1

An intelligent way to simulate the switching mechanism shown in Circuit 1 is to use a square wave that oscillates between the values of the two sources (3V & -2V) in place of the sources and the switch. That way, despite using a single AC source, it behaves as if it's switching between the two voltages supplied by the sources present in Circuit 1 (3V & -2V). Let us use this method and simulate the circuit step by step as described below:

➢ Open a new schematic window by clicking ***File → New Schematic***. Draw the circuit shown below in **Figure 1.**

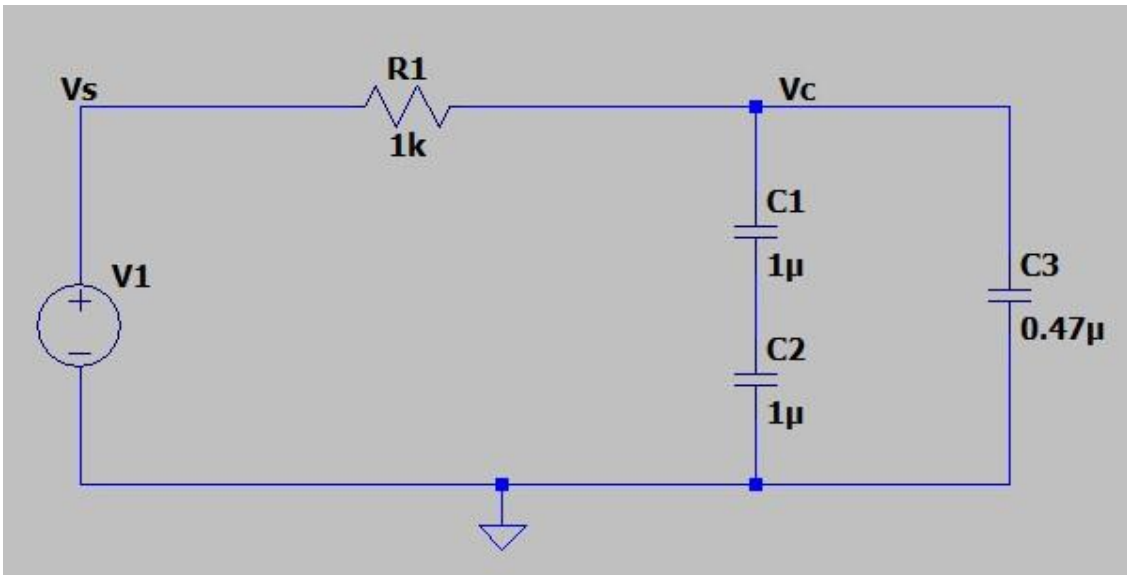
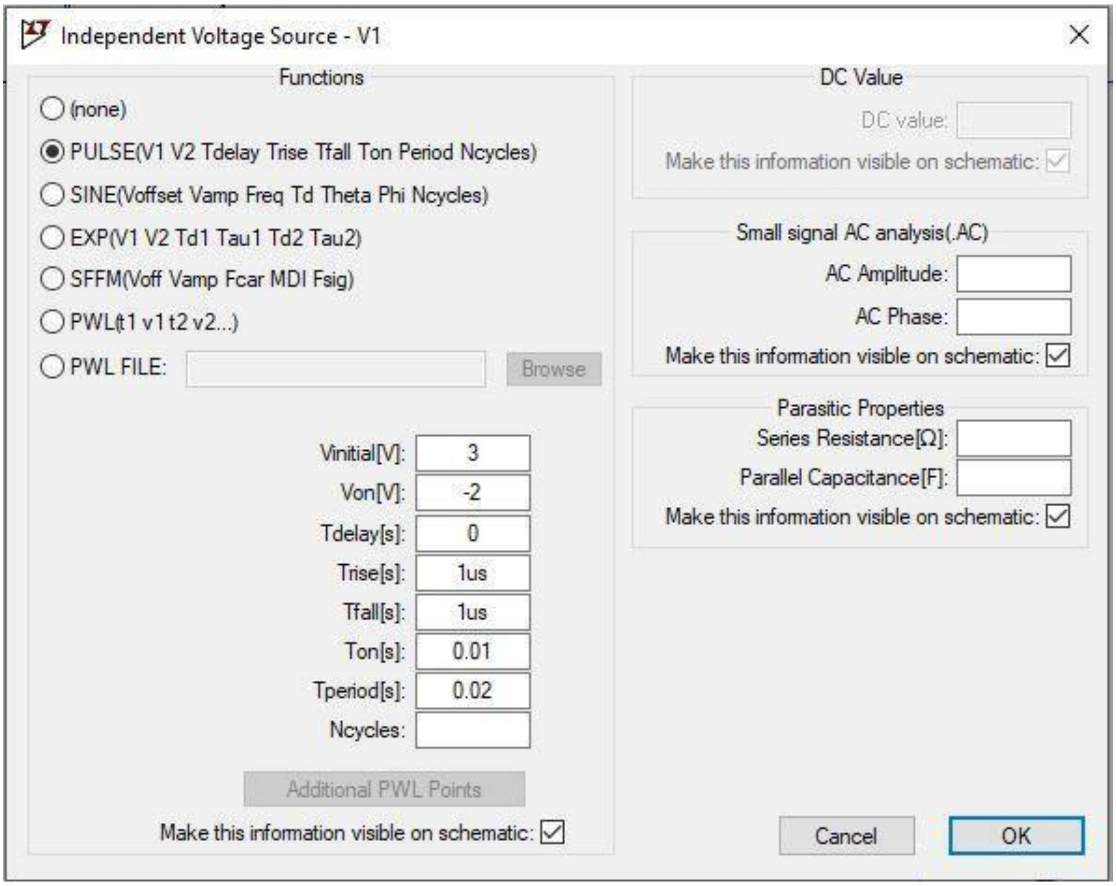


Figure 1

➢ We have to modify the **V1** source so that it provides 3V and -2V alternatively in order to mimic the switching action illustrated in **Circuit 1.** We will use the source as a pulsating DC square wave generator. To do so, ***Right-click on the voltage source →***

Select Advanced → insert the values as below and click OK. It will generate a -2V 3V and **50 Hz** pulsating DC square signal.

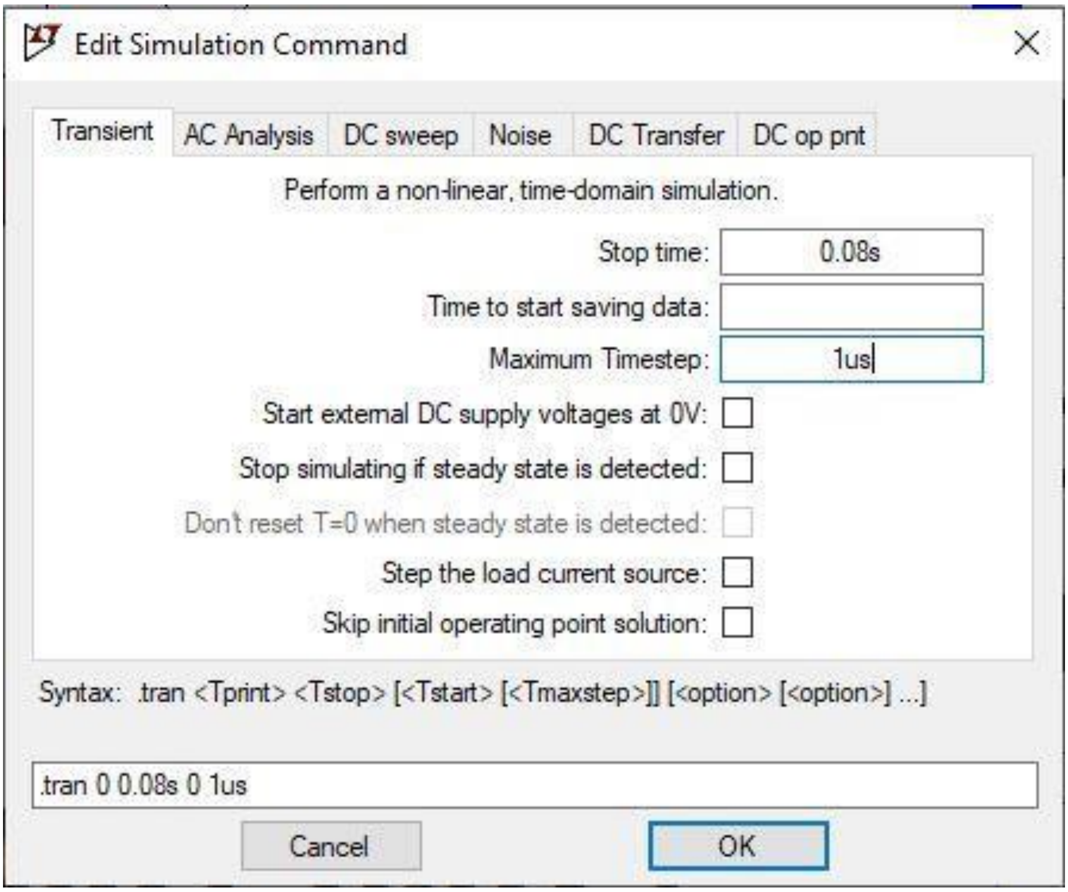


- To see the responses we have to do ***'Transient Analysis'***. The transient analysis calculates a circuit's response over a period of time.

  To run the 'Transient Analysis', we have to write the analysis command. First, find the ***'Spice Directives'*** option by ***Right-clicking on the schematic → Draft → Spice Directives*** or clicking on the "SPICE Directive" 

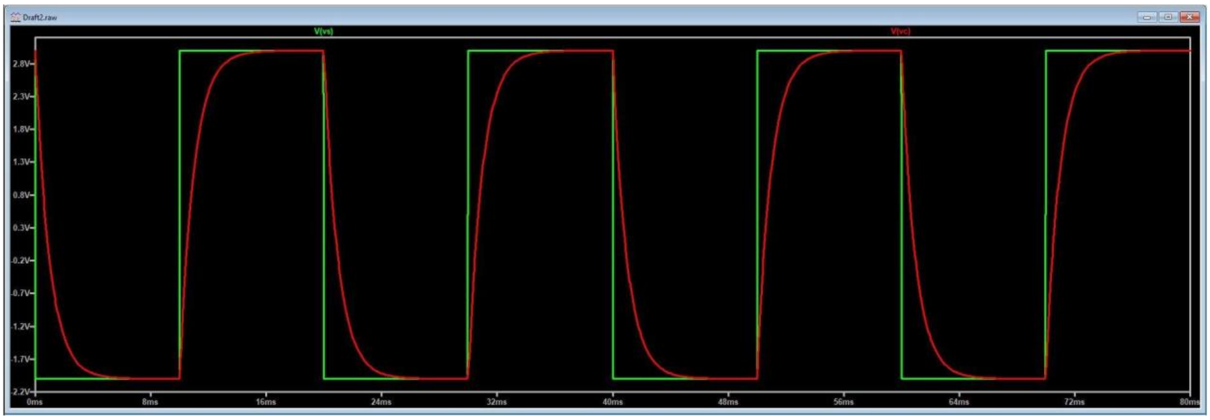
 icon from the toolbar **.**

- After clicking the ***'Spice Directives'***, the ***'Edit Text on the Schematic'*** window will appear. Now ***Right-click on the blank space on this window → Select 'Help me Edit' → Analysis Command.*** A window titled ***'Edit Simulation Command'*** will appear. Insert values in the boxes as below and click OK. It will generate a transient analysis command. Place the command somewhere on the schematic. [Notice the '.tran' syntax for transient analysis.]



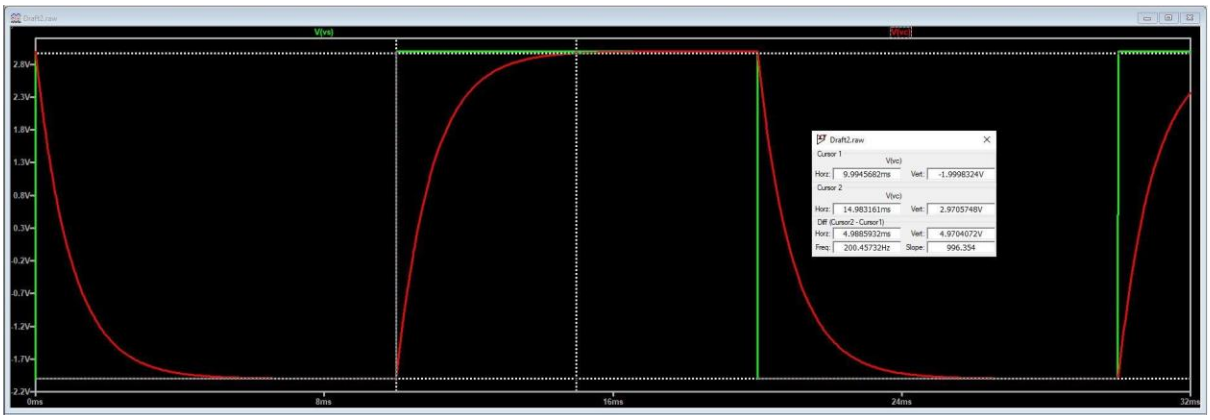
➢ To run the simulation, click ***'Run'***. Find the ***'Run'*** button  from the above toolbar or ***Right-click on the schematic →Run***.

➢ After clicking the ***'Run'*** button a plot window will appear. In this window we can see responses and waveshapes of voltage and currents with respect to time. To see a plot ***Right-click on the plot window → Add trace → Select any voltage or current → OK. [We can also add trace by simply using a marker on the schematic. When the run is complete a cursor will appear if we place the mouse cursor on a wire or component of the circuit.]***



The axes properties (Range) can be changed by **Right-clicking on the horizontal (x-axis) and the vertical (y-axis).**

- ➢ To extract data from a plot/response, use the data cursor. **A cursor for a particular trace will appear by clicking on the name of that trace. One click will produce one cursor, clicking twice will produce two.** The data point of the cursor can be moved by the arrow keys from the keyboard.



- ➢ A window will appear on the bottom right corner containing the values corresponding to the cursors. Note that it also shows the difference between the two cursors (data points) for both the vertical and the horizontal axes. Use this to find **Time constant τ.**

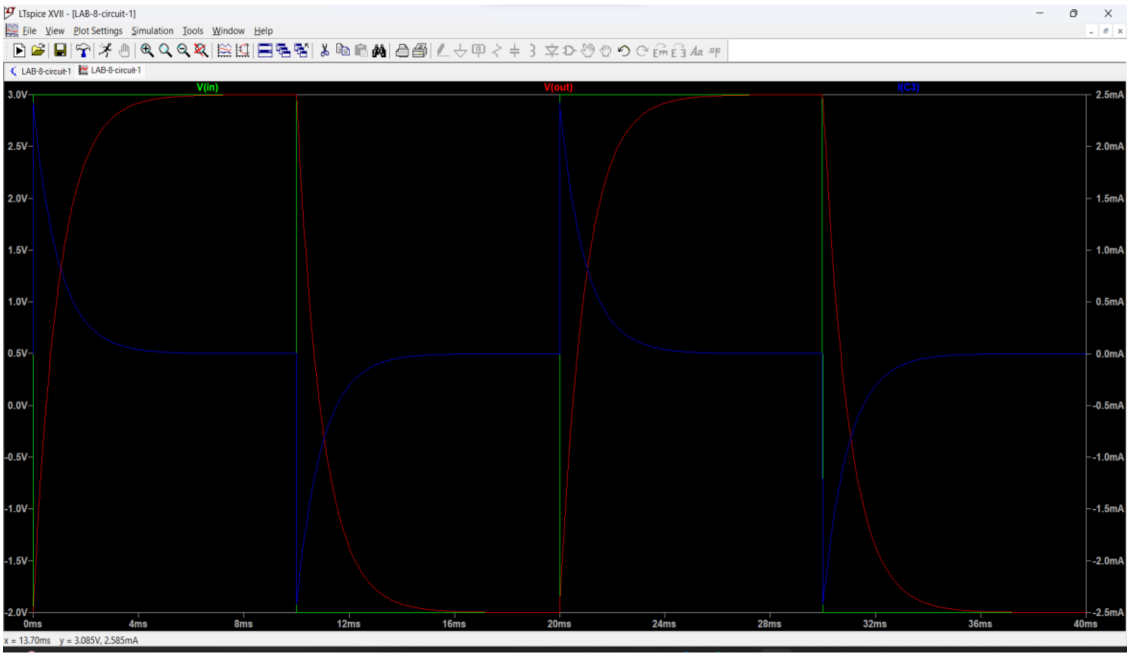
- ➢ Save the Schematic by clicking ***File → Save as → 'Name.asc'*** and the plots by clicking ***File → Save plot settings → 'Name.plt'*** for future use and analysis.

Lab Work

1. Measure the **Time constant** τ from the plot you just generated.

From the Circuit we simulated, the **Time constant**, τ = 20.97479 ms

2. Perform similar analysis to visualize the current supplied to the capacitor and observe whether it's a discontinuous graph or not.



we can see from the graph that, here all the points are connected without any breaks or gaps. So, it is not a discontinuous graph. Rather it is a discontinuous graph.

3. Observe the shapes of the capacitor voltage & current and also compare the value of the Time Constant to the theoretical value $\tau = RC_{eq}$, and state your opinion on whether your observations match the theory or not.

Observations:

The capacitor voltage:

When the capacitor was charging and discharging, its voltage behaved as it should have.
The voltage rose exponentially in the **charging phase** in relation to the source voltage and progressively got closer to a steady state.
The voltage dropped exponentially in the **discharging phase**, eventually reaching zero (0).

Current:

The waveform of current displayed was typical of an RC circuit. When charging, there was a sudden increase that curved off gradually, and when discharging, the current flow was reversed.

Comparison of the value of the Time Constant to the theoretical value $\tau = RC_{eq}$:

From the observations of LTspice 's graph plot,

Time constant, $\tau = RC_{eq} =$ 20.97479 ms

Again,
From theory,
$\tau = RC_{eq} =$ 20.97479 ms

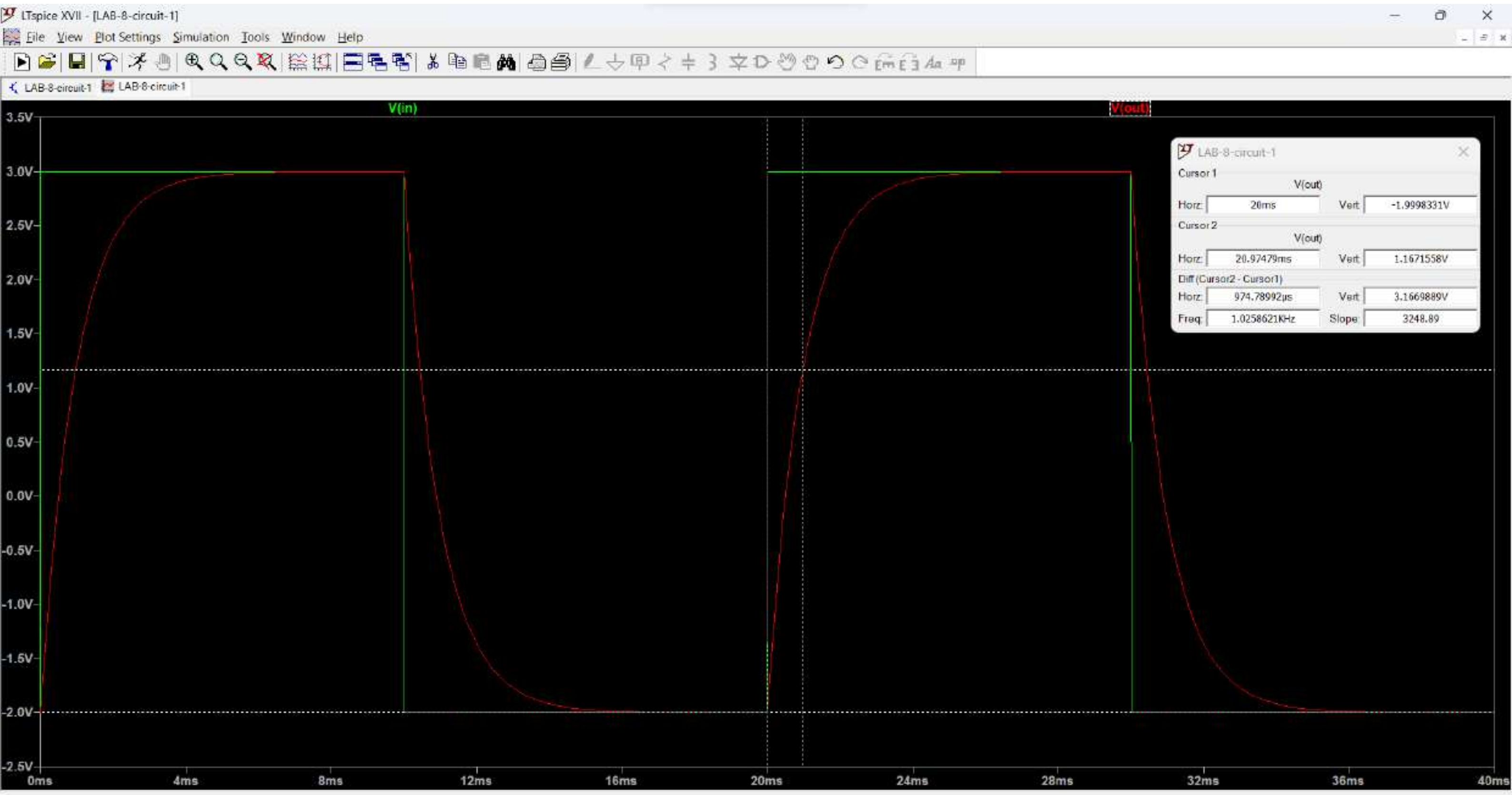
so, The observed waveforms of the capacitor's voltage and current matched the theoretical model's behavior quite well.

Report

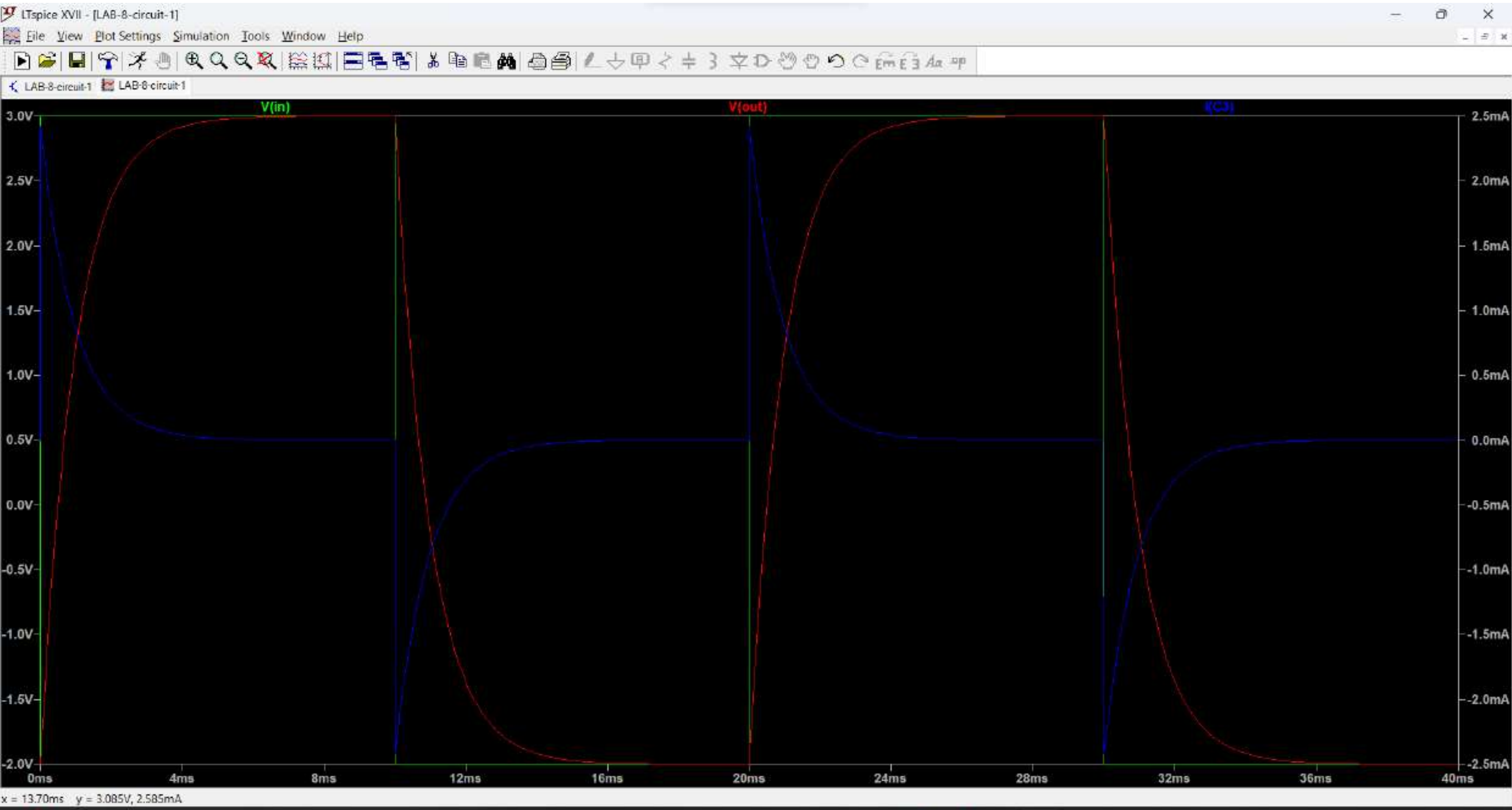
1. **1.** Answer to questions and Complete the Lab work sections.
2. **2.** Save all your .asc and .plt files and make a zip file. You need to submit it with the report.
3. **3.** Discussion *[comment on the obtained results and discrepancies]*. Add pages if necessary.

Discussion :

The transient behavior of the RC circuit as predicted by theory and the LTSpice simulation results matched effectively. The observed patterns could be seen in the waveforms of the capacitor's voltage and current, and the simulation's determined time constant was quite similar to the theoretical value. This match demonstrates that the mathematical equation used to explain the transient response of the investigated RC circuit is valid. Any small differences could be explained by actual variables like simulation limitation or component limitations.



LTspice XVII - [LAB-8-circuit-1]
File View Plot Settings Simulation Tools Window Help
LAB-8-circuit-1
LAB-8-circuit-1
V(in)
V(out)
LAB-8-circuit-1
Cursor 1
V(out)
Horz: 20ms Vert: -1.9998331V
Cursor 2
V(out)
Horz: 20.97479ms Vert: 1.1671558V
Diff (Cursor2 - Cursor1)
Horz: 974.78992µs Vert: 3.1669889V
Freq: 1.0258621KHz Slope: 3248.89
3.5V
3.0V
2.5V
2.0V
1.5V
1.0V
0.5V
0.0V
-0.5V
-1.0V
-1.5V
-2.0V
-2.5V
0ms 4ms 8ms 12ms 16ms 20ms 24ms 28ms 32ms 36ms 40ms



LTspice XVII - [LAB-8-circuit-1]
File View Plot Settings Simulation Tools Window Help
LAB-8-circuit-1
LAB-8-circuit-1
V(in)
V(out)
3.0V
2.5V
2.0V
1.5V
1.0V
0.5V
0.0V
-0.5V
-1.0V
-1.5V
-2.0V
2.5mA
2.0mA
1.5mA
1.0mA
0.5mA
0.0mA
-0.5mA
-1.0mA
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-2.0mA
-2.5mA
0ms
4ms
8ms
12ms
16ms
20ms
24ms
28ms
32ms
36ms
40ms
x = 13.70ms y = 3.085V, 2.585mA