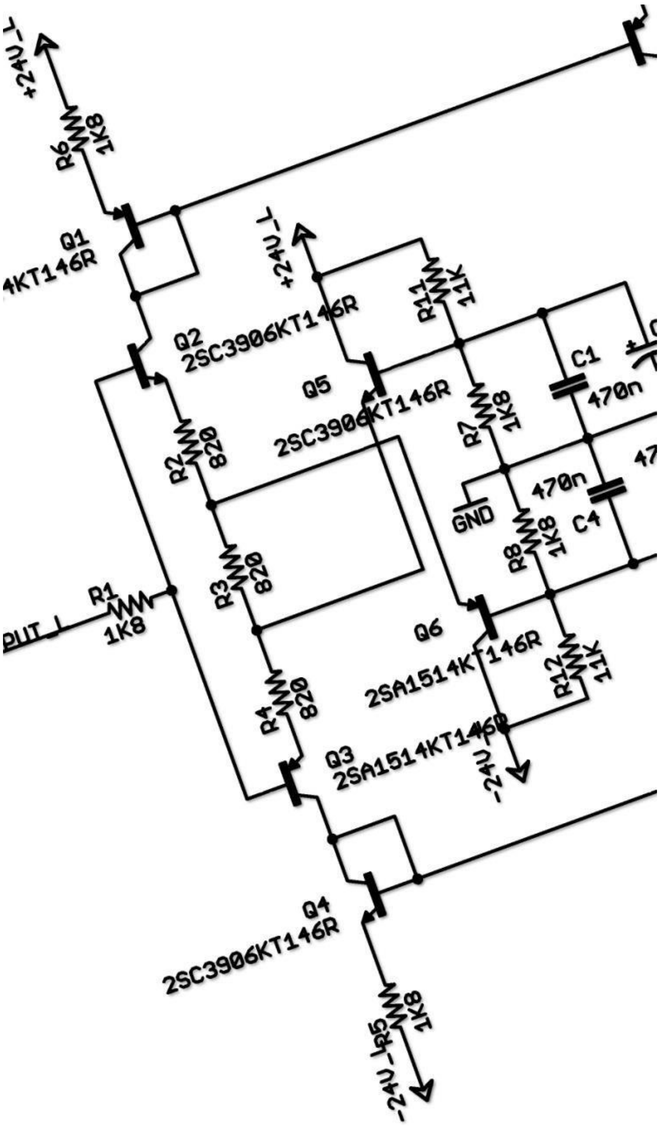
MONASH University
Engineering

ECE2131

Electrical Circuits

Laboratory Notes



2022 Edition

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2022

2 Transient Responses of First Order Circuits

2.1 Learning Objectives and Introduction

This experiment is intended to provide some practical experience of and familiarity with the step-responses of several simple series circuits containing one energy-storage element (an inductor or a capacitor). These circuits can be described by a first-order differential equation with either a zero or a constant forcing function (referred to as zero state or zero input).

By the end of the lab you should:

- Understand how voltage and current behave in first order circuits
- Be able to find τ in first order circuits
- Note the effect of frequency on first order circuits

The components provided for this experiment have a range of fixed or variable parameters so that the time response can be observed in different operating conditions. The physical sizes of the components used should be compared with their values and ratings (see Appendix 2 on how to read a resistor's nominal value). For example, the important factors determining the size of a capacitor are its capacitance and voltage rating, while a given variable resistor must have adequate power rating and suitable resistance range.

The voltages across and currents flowing through the elements of these circuits are to be measured by displaying on channels of a digital storage oscilloscope (DSO). Consult Appendix 1 for the operation of the DSO in general.

In this series of experiments the **transient behaviour** of RC and RL circuits, in two distinct configurations, labelled A and B, are constructed and measured with a unit-step square wave source excitation at the input port. Applications of these circuits as integrators and differentiators are also proposed.

STEP VOLTAGE SOURCE

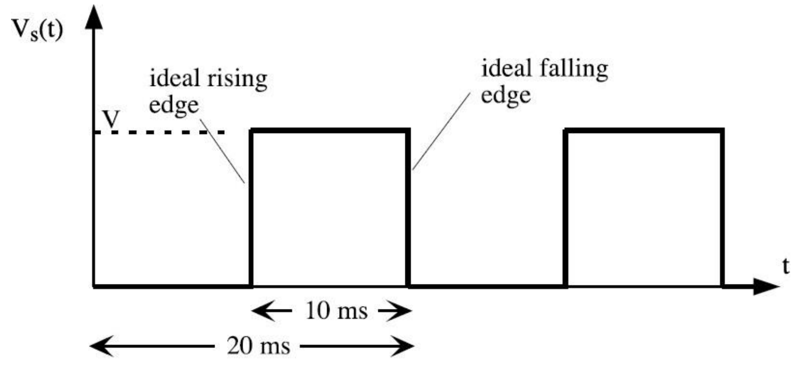


Figure S1.1: A typical and ideal square-wave voltage waveform.

A function generator is to be used as the source of step voltages. The generator should be set up to produce a 50 Hz square wave that has amplitude of V volts during one-half period of the waveform and zero during the other half-period as shown in Figure S1.1. Please ensure that your function generator is set to high impedance (Z) mode. The reasons for this will be discussed in a later lab.

The peak-to-peak voltage amplitude V can be adjusted between zero and approximately 15 V using the amplitude menu. The vertical and horizontal scales of the DSO channels should be adjusted appropriately to observe the square wave waveform.

The time constants of the circuits must be much less than the half-period of the square wave (10 ms). This is to ensure that the circuits have reached their steady state within each half-period of the square wave. The step response we are interested in is then repeated over the periodic intervals at a repetition rate equal to the period of the input voltage waveform, and should appear stationary on the screen.

The transient response associated with the **falling edge** of the square wave is the **zero-input response**, because the circuit was initially in a steady state, under the influence of the preceding constant voltage level, before the applied voltage drops to zero. The instant at which the applied voltagesuddenly becomes zero is considered to be the origin of the zero-input response.

Similarly, the transient response associated with the **rising edge** of the square wave is the **zero-state response**, because the circuit is 'initially' in its zero-state from the preceded half-period.

The circuit response due to a unit-step voltage source, often just called the step-response for short, is the zero-state response with V = 1.0 volt.

The zero-state and zero-input responses for each circuit in this experiment exhibit an exponential function with the same time constant, so it is sufficient to study only one response, namely the zero-input or "natural response", in detail.

2.2 EQUIPMENT AND COMPONENTS

For this lab, you will be using the DSOs, the signal generators, and:

- Breadboard
- 10 kΩ, 5.6 kΩ, 820 Ω, 560 Ω resistors (see colour codes at back of manual)
- 100 nF capacitor (marked '104' → 10×10^4 pF)
- 100 mH inductor (marked '104' → 10×10^4 μH)

2.3 EXPERIMENTAL WORK

2.3.1 CIRCUIT CONFIGURATIONS

Since the **common terminals** on the square wave generator and on the DSO may be connected together inside the equipment (ie through earth pins), it is necessary to use configuration A as shown in Figure S1.2(a) to monitor the waveform of the voltage across the energy storage element (the capacitor or the inductor). Use configuration B as shown in Figure S1.2(b) to observe the waveform of the voltage dropped across the resistor, and hence the current through the circuit. See Appendix 1 (page 99) for a more detailed explanation of this.

We recommend that you use one of these configurations and either the on-board math functions of the oscilloscope, or your knowledge of KVL to infer the waveforms over the passive circuit element that you are not actively probing.

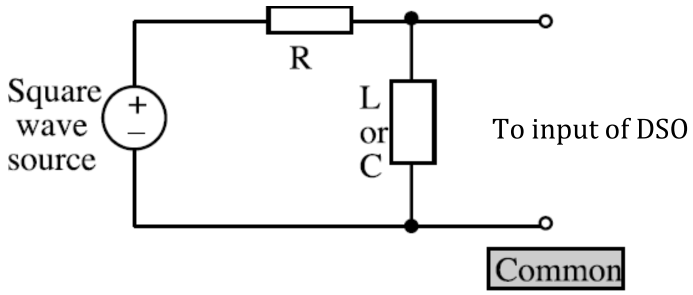


Figure S1.2(a) Circuit Configuration A

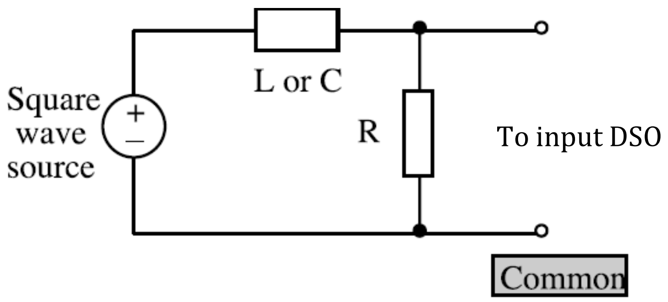


Figure S1.2(b) Circuit Configuration B .

2.3.2 SERIES RC CIRCUIT

Construct the series RC circuit using the 100 nF capacitor provided and test the circuit by using various resistances R=10 kΩ and, 5.6 kΩ. Set your input to 50 Hz square wave voltage, 0V as the low level, and between 1V to 2.5V for the high level of your square wave. For each resistor setting, measure the time constant (using theories learnt from lecture notes). Mark these time constant in your graphs. Calculate the theoretical time constants. Compare the experimental and theoretical time constants.

By using either (or, if you'd like, both) configurations A and B, examine the train of exponential risingand falling waveforms. Make sure that the observed waveforms reach a steady–state within the half- period of the monitored waveform. If they do not, change the resistance setting.

Sketch the following to scale on the same linear-linear graph paper provided overleaf, for each of thetwo resistance settings above. Each graph must have the following, and properly labelled:

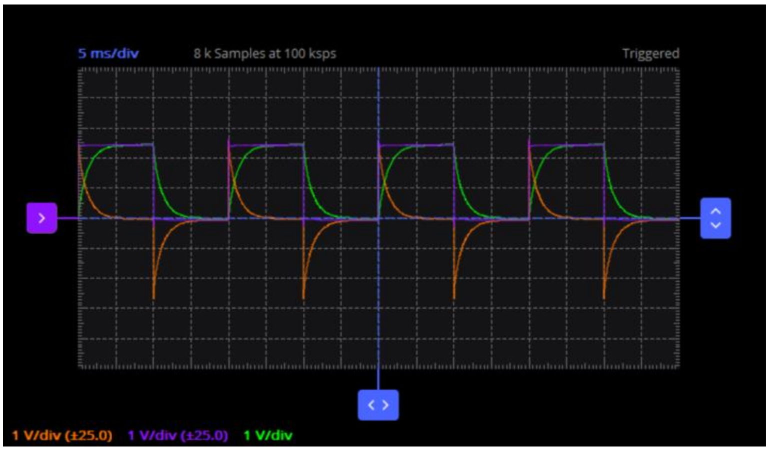
a) the input voltage waveform

b) resistor current waveform

c) the capacitor voltage waveform

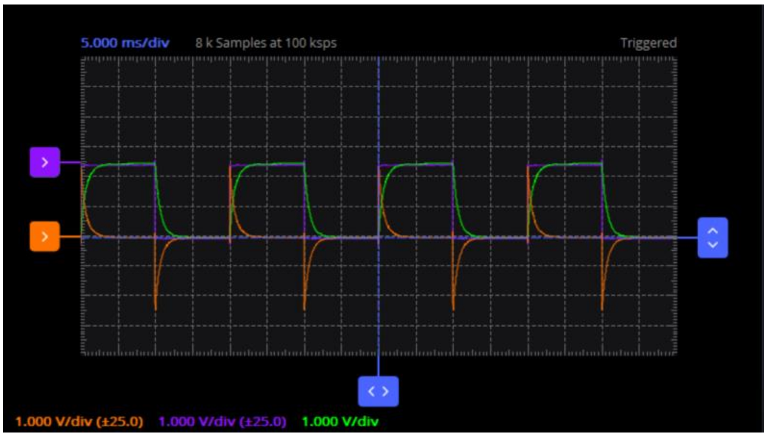
Oscilloscopes cannot measure currents through components. However, you can measure voltage across the component using oscilloscope, and divide the voltage by its resistance to get current (I = V/R).

For the third resistor setting, your demonstrator will provide a random resistor value during your laboratory session assessment.



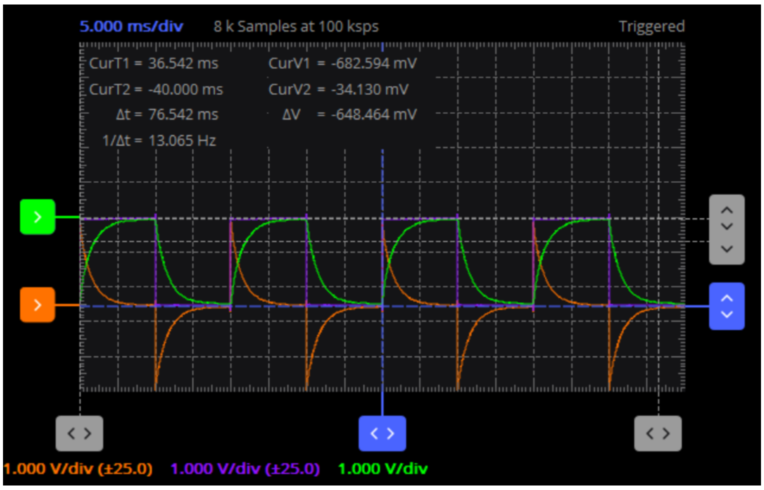
10 kΩ

Legend for 10 kΩ: Purple – The input voltage source, Green – The capacitor voltage waveform, Orange – The zero-input current waveform



5.6 kΩ

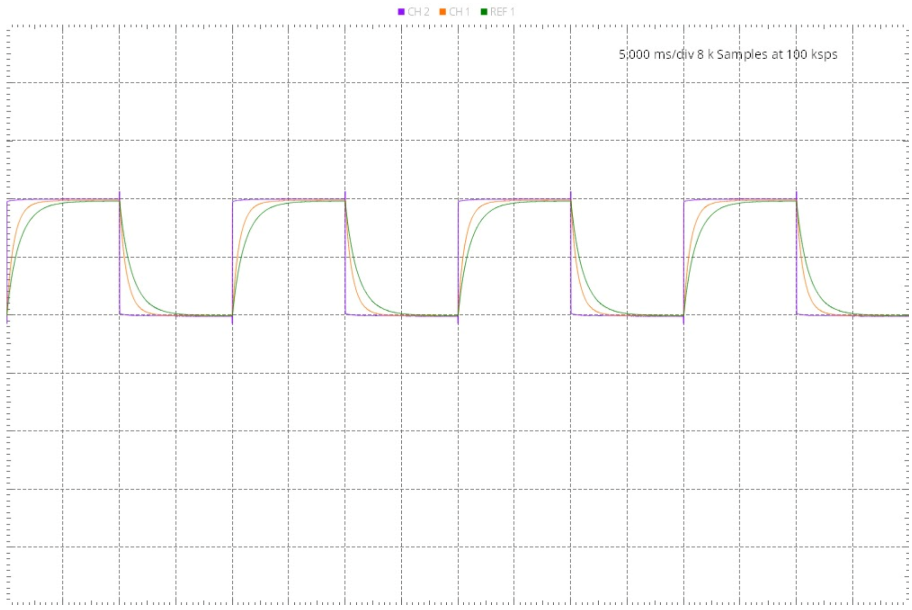
Legend for 5.6 kΩ: Purple – The input voltage source, Green – The capacitor voltage waveform, Orange – The zero-input current waveform



13kΩ

Legend for 13 kΩ: Purple – The input voltage source, Green – The capacitor voltage waveform, Orange – The zero-input current waveform

Visual Observation Made:



Legend for 10kΩ and 5kΩ : Purple – The input voltage source, Orange – The 5.6kΩ capacitor voltage waveform , Green – The 10kΩ capacitor voltage waveform

As it can be seen in the two-above graph, the 5.6kOhm resistor will reach steady state faster than the 10kOhm resistor. When the resistance is lower, steady state will be achieved faster. As the resistance is lower, more voltage will be divided to the capacitor due to the voltage divider rule.

☐ CHECKPOINT: Get a demonstrator to check your answers, and initial here:

Note that the capacitor voltages are continuous, with no jumps or discontinuities. Explain the theoretical reason behind this observation, linking to the V-I relationship for capacitors:

The current across the capacitor is linked by the equation Ic = C(dVc/dt) based on the lecture notes. When there is a discontinuous change in voltage, this would theoretically mean that an infinitely small amount of time is required for the change in voltage. This would mean we will need an infinite amount of current to pass through component which is not possible. Thus, the capacitor voltages must be continuous as it takes time for the capacitor to charge and discharge.

Figure S1.3 shows a sketch of a typical exponential waveform arising from a first-order differential equation. The 'decay' or 'time' constant τ can be found by calculating the voltage at time = τ, and then measuring the time in between the initial voltage and the calculated voltage. Make sure you use the DSO's cursor controls to enable you to measure the time constant as accurately as possible.

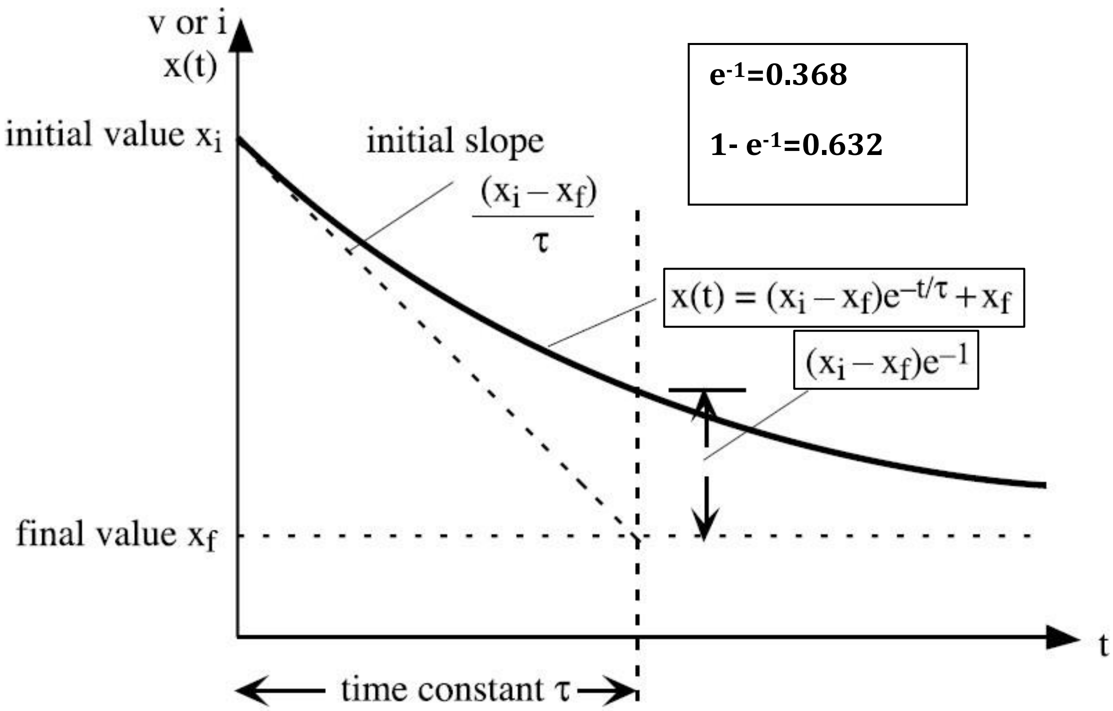


Figure S1.3 Sketch of a typical "first-order" exponential voltage.

Show your working for your calculations here:

For 10kOhm:

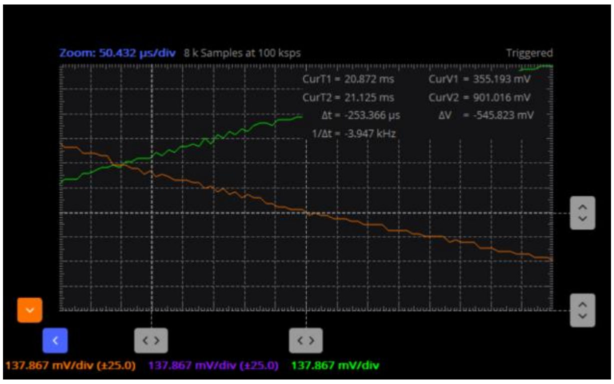
Measured Value obtained: Top Peak (20.037 ms ,2.453 V), Bottom Peak (0 V)

Let t = tau and using the formula x(t) = (xi - xf)e^(-t/tau) + xf

x(initial) = 2.453 V, x(final) = 0.242V

x(t) = (2.453 - 0) e^-1 + 0

= 0.902 V



The value above corresponds to 21.125 ms

Measured Value:

21.125 ms – 20.037 ms = 1.088 ms

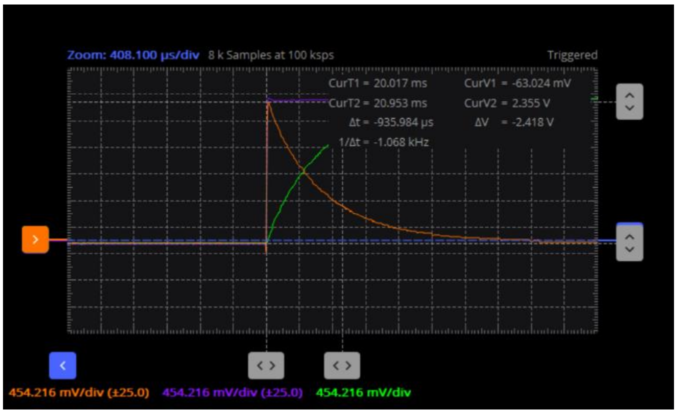
Calculated Value:

tau = RC = 10k x 100n

= 1 ms

Show your working for your calculations here:

For 5.6 kOhm:



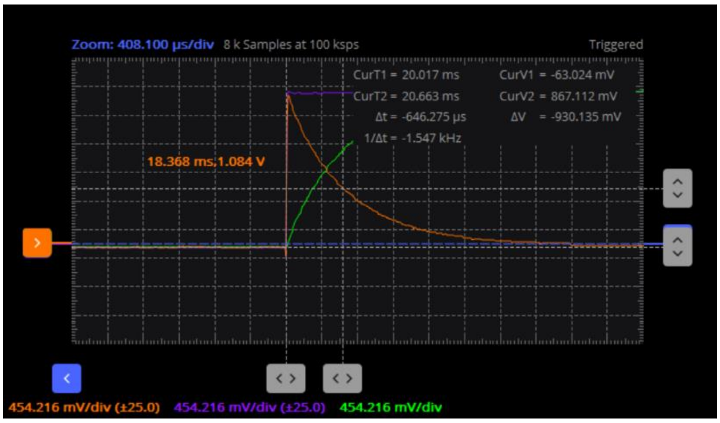
Measured Value obtained: Top Peak (20.017 ms ,2.355 V), Bottom Peak (0 V)

Let t = tau and using the formula x(t) = (xi - xf)e^(-t/tau) + xf

x(initial) = 2.355 V, x(final) = 0V

x(t) = (2.355 - 0) e^-1 + 0

= 0.866 V



The value above corresponds to 20.663 ms

Measured Value:

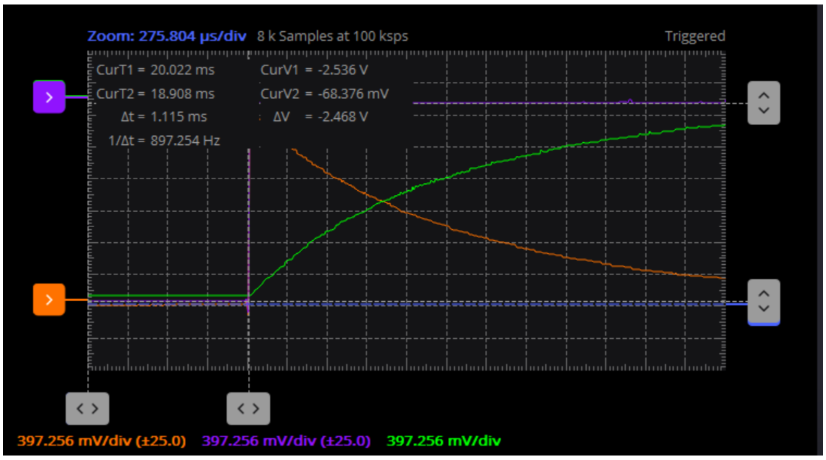
20.663 ms –20.017 ms = 0.646 ms

Calculated Value:

tau = RC = 5.6k x 100n

= 0.56 ms

For 13 kOhm:



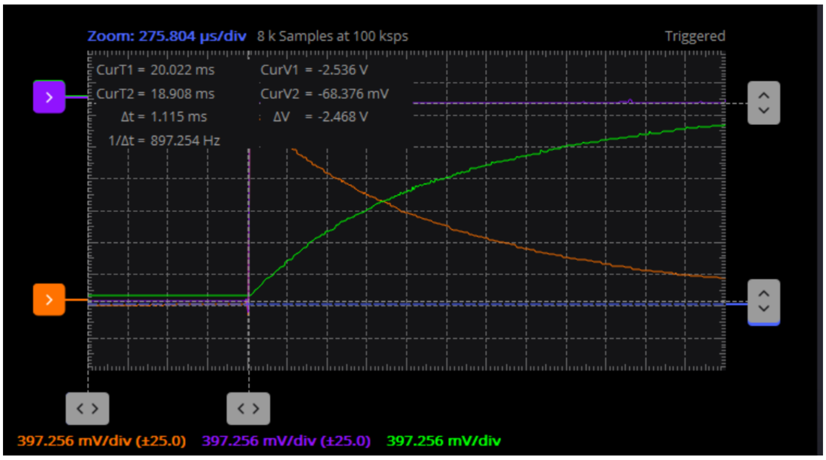
Measured Value obtained: Top Peak (20.022 ms ,2.436 V), Bottom Peak (0 V)

Let t = tau and using the formula x(t) = (xi - xf)e^(-t/tau) + xf

x(initial) = 2.436 V, x(final) = 0V

x(t) = (2.436 - 0) e^-1 + 0

= 0.896 V



The value above corresponds to 20.663 ms

Measured Value:

21.435 ms –20.022 ms = 1.413 ms

Calculated Value:

tau = RC = 13 k x 100 n

= 1.3 ms

Using this technique, measure and calculate the time constant for each pair of values of R and C fromboth the theoretical values and the experimental measurements.

Resistance used	Measured value of τ	Calculated value of τ
10kΩ	1.088 ms	10*10^3 * 100*10^-9 = 1 ms
5.6kΩ	0.646 ms	5.6*10^3 * 100*10^-9 = 0.56 ms
13 kΩ	1.413 ms	13*10^3 * 100*10^-9 = 1.3 ms

☐ CHECKPOINT: Get a demonstrator to check your answers, and initial here:

2.3.3 SERIES RL CIRCUIT

Now, construct a series RL circuit using the 100 mH inductor and potentiometer from the previous section (again using diagrams S1.2(a) and (b)). Test this circuit with the different resistances as before. Test with R=560 Ω and 820 Ω (Use 50Hz square wave voltage source as input for these experiments). Check and mark the time constants for each of these experiments on your graphs.

You might find the jumper leads useful when setting up this circuit. Go get some solid core wires from the trolley if you need … .
If you try to measure the input voltage waveform by measuring the voltage at the signal generator output with the circuit connected, what are you really going to measure (… what does the inductor produce when current is changed …)? What does this imply when you try to figure out the inductor voltage waveform?

Important Note: because inductors can have large instantaneous changes in voltage it is important that you restrict the amplitude of the applied voltage square wave to about 2.5 V peak-to-peak. This helps to ensure that the inductor will behave in its linear operational region (this just means the region where it behaves the way we are expecting it to in this unit).

For each resistance setting, sketch your measured waveforms on the graphs below, and label your graphs:

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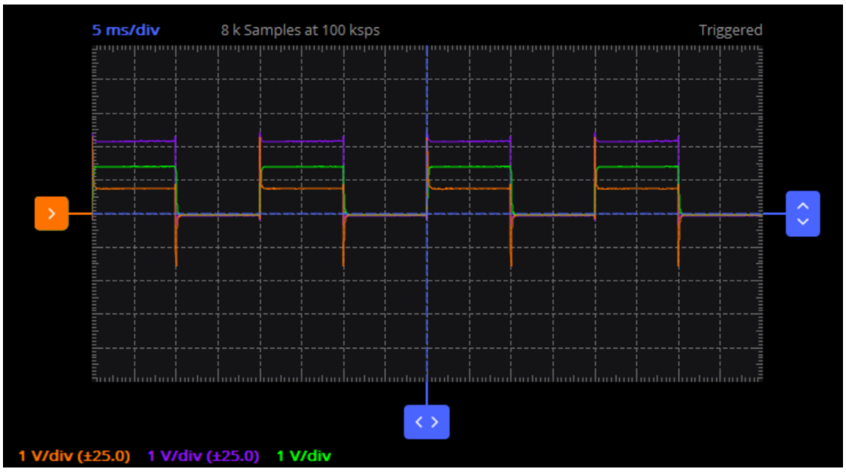
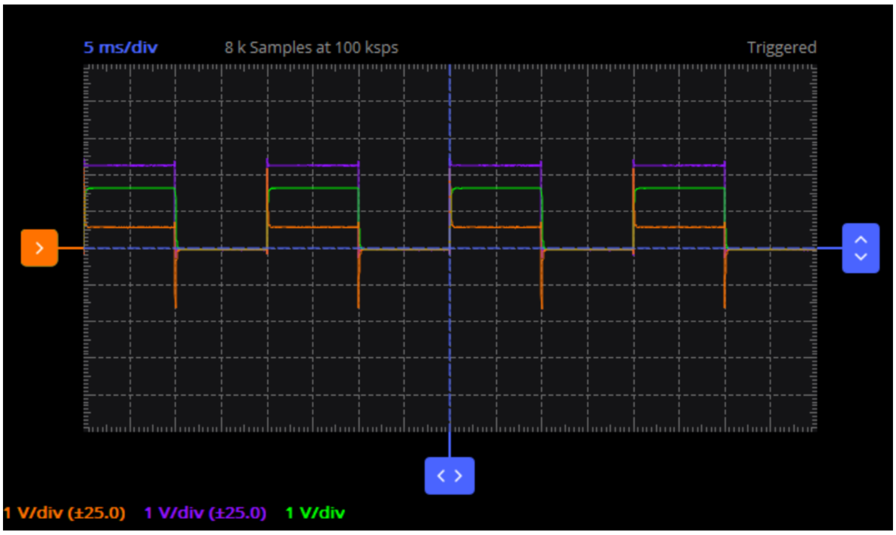
a. the zero-input current waveform (i.e. when the input changes from high to low)
b. the zero-state current waveform (i.e. when the input changes from high to low)
c. the inductor voltage waveform (i.e. what is the source voltage waveform? What is the voltage waveform over the resistor? So, from those, how can we get the inductor voltage waveform?)

For the third resistor setting, your demonstrator will provide a random resistor value during your laboratory session assessment.



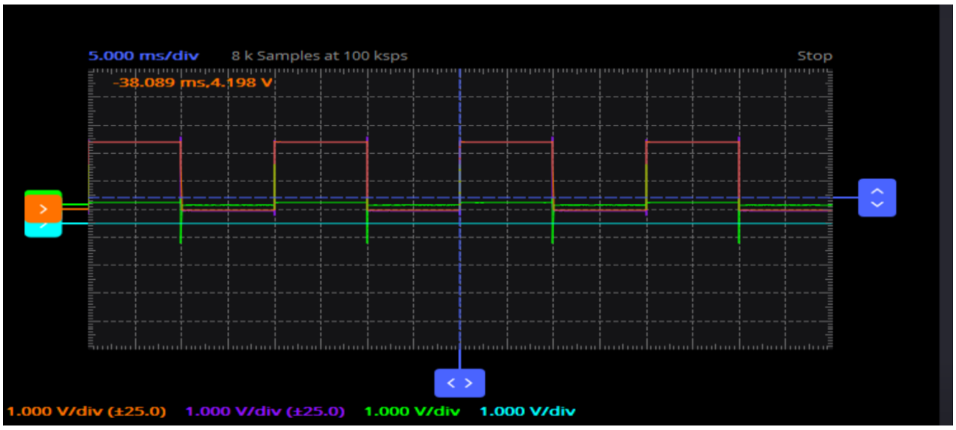
560 Ω

Legend for 560 Ω: Purple – The input voltage source, Green – The zero state/ zero input current waveform, Orange – The inductor voltage waveform



820 Ω

Legend for 820 Ω: Purple – The Input Voltage Source, Green – The zero state/ zero input current waveform, Orange – The inductor voltage waveform

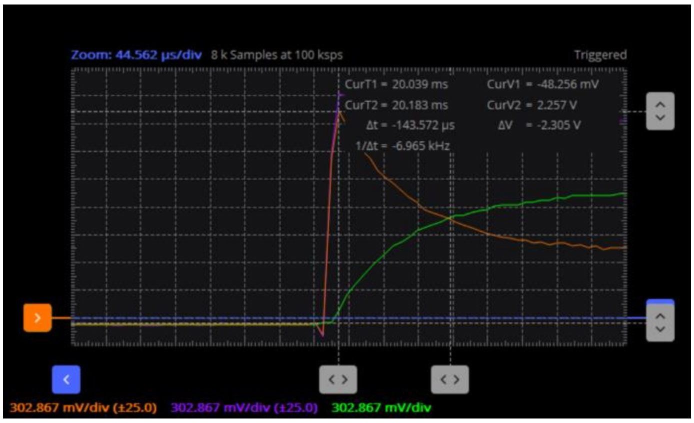


13 kΩ

Legend for 13 kΩ: Purple – The Input Voltage Source, Orange – The zero state/ zero input current waveform, Green – The inductor voltage waveform

Show your working for your calculations here:

For 560 Ohms:



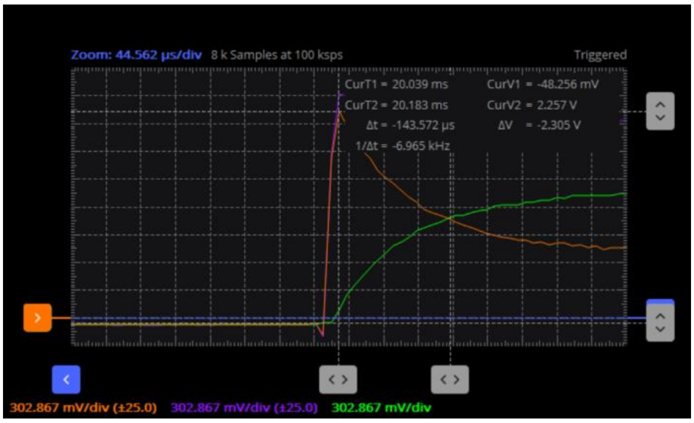
Measured Value obtained: Top Peak (20.039 ms ,2.257 V), Bottom Peak (0 V)

Let t = tau and using the formula x(t) = (xi - xf)e^(-t/tau) + xf

x(initial) = 2.257 V, x(final) = 0V

x(t) = (2.257 - 0) e^-1 + 0

= 0.830 V



The value above corresponds to 20.326 ms

Measured Value Obtained:

20.326 – 20.183 = 0.143 ms

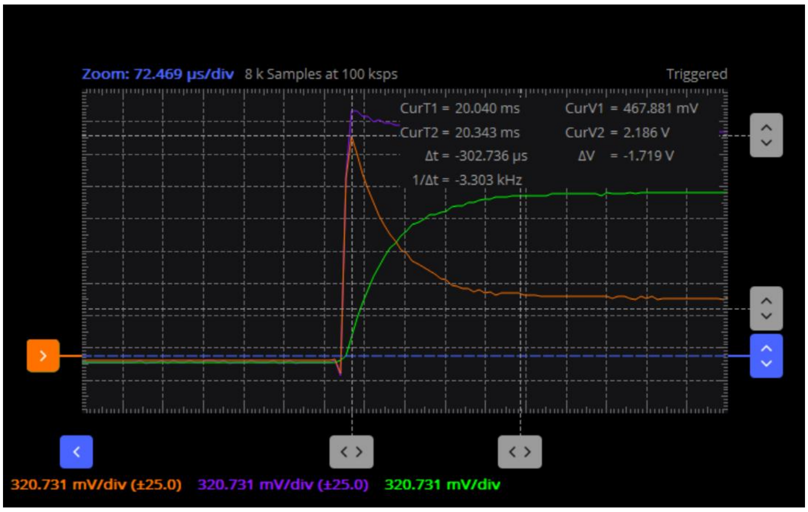
Calculated Value Obtained:

tau = L/R = 100m/ (560)

= 0.179 ms

Show your working for your calculations here:

For 820 Ohms:



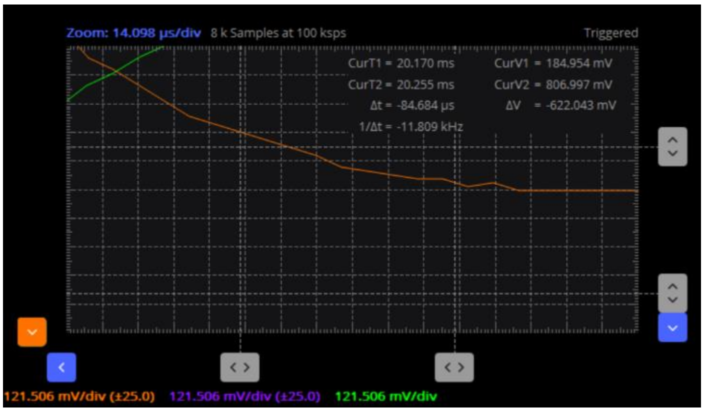
Measured Value obtained: Top Peak (20.040 ms ,2.186 V), Bottom Peak (0 V)

Let t = tau and using the formula x(t) = (xi - xf)e^(-t/tau) + xf

x(initial) = 2.186 V, x(final) = 0V

x(t) = (2.186 - 0) e^-1 + 0

= 0.804 V



The value above corresponds to 20.255 ms

Measured Value Obtained:

20.255 – 20.040 = 0.103 ms

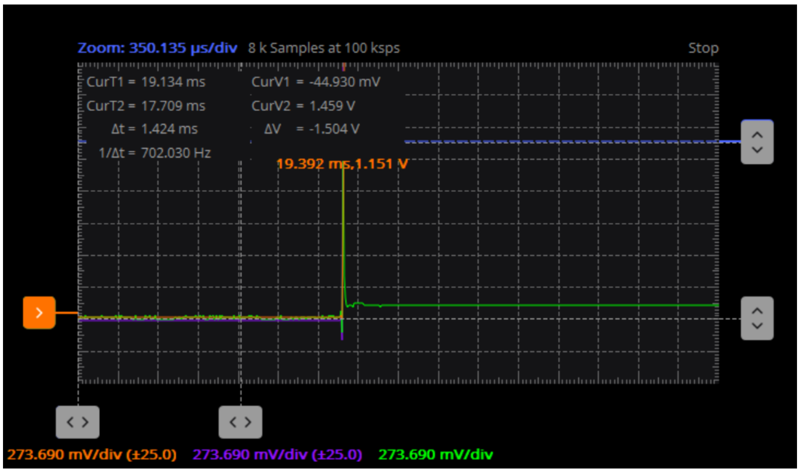
Calculated Value Obtained:

tau = L/R = 100m/(820)

= 0.122 ms

Show your working for your calculations here:

For 13 kOhms:



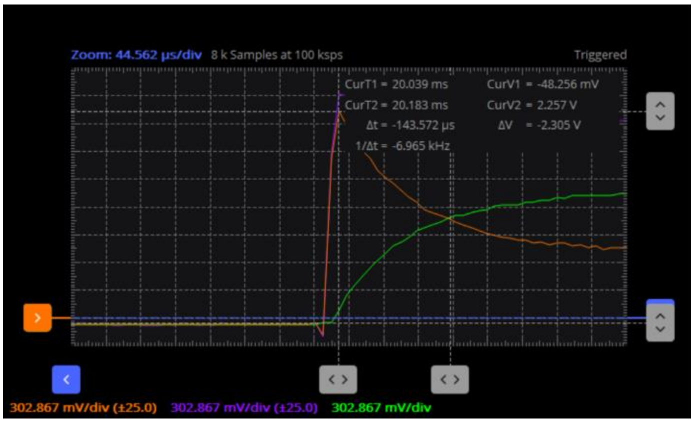
Measured Value obtained: Top Peak (19.134 ms , 1.459 V), Bottom Peak (0 V)

Let t = tau and using the formula x(t) = (xi - xf)e^(-t/tau) + xf

x(initial) = 1.459 V, x(final) = 0V

x(t) = (1.459 - 0) e^-1 + 0

= 0.537 V



The value above corresponds to 20.286 ms

Measured Value Obtained:

19.13535 ms – 19.12824 ms = 7.11 µs

Calculated Value Obtained:

tau = L/R = 100m / (13k)

= 7.69 µs

☐ CHECKPOINT: Get a demonstrator to check your answers, and initial here

Note that the inductor current waveform is continuous. Measure the value of the time constant and its uncertainty from the observed waveforms. Compare these values with the theoretically expected values.

Resistance used	Measured value of τ	Calculated value of τ
560Ω	0. 143 ms	0.179 ms
820Ω	0.103 ms	0.122 ms
13 kΩ	7.11 µs	7.69 µs

☐ CHECKPOINT: Get a demonstrator to check your answers, and initial here

2.3.4 SERIES RC AND RL CIRCUITS USED AS INTEGRATORS AND DIFFERENTIATORS.

RC INTEGRATORS

So far, the time constant of the series circuits (RC or L/R) have been chosen deliberately to be much less than the half-period (T=10 ms) of the applied square wave voltage source, so that a steady-state is reached within each half period. Consider the series RC circuit as shown in Figure S1.2(a). If the time constant RC is now made very much larger than the half-period T, then the voltage dropped across the capacitor barely changes within each half-period and, except for a DC offset equal to the average value of the applied voltage, its waveform would be proportional to the integral of the applied voltage waveform.

Observe this behaviour by changing the period of the square wave source so that it is now much smaller than the time constant (T<<RC). Describe what you see as you change the square wave frequency from a low to high value.

The capacitor will reach a transient state when the square wave frequency goes from low to high. However, the capacitor will be unable to reach the steady state for zero-input and zero-state responses. As a result, the graph of the capacitor voltage will be changed into a triangular waveform that oscillates around the offset voltage. If the input period is more than 5 time constant, the capacitor voltage will still oscillate between 0V to 1V as we can see in the typical capacitor voltage graph above. However, when we select our frequency such that the time period is equal to our time constant, we will obtain a triangular curve that does not oscillate fully from 0V to 1V. This means that the capacitor does not reach steady state between charging and discharging. As the frequency is increased further, we will soon have a capacitor voltage that will oscillate very close to 0.5V, almost making the capacitor voltage to have a constant value of 0.5V.

Hence give a physical (rather than mathematical) explanation of the behavior of the RC integrator:

The RC integrator is a series-connected RC circuit that changes a capacitor voltage with an exponential waveform to a triangular waveform that will oscillate at a smaller amplitude compared to the input voltage. This triangular waveform is caused by the circuit being unable to reach to steady state before the input voltage changes as the input time is less than the required time to reach steady state. Thus, at higher frequencies, the RC integrator capacitor will always be in transient state response. An RC integrator can also act as a low pass filter. As the frequency of the square wave source increases, RC circuit with large time constant greater than the period of the square wave source does not sufficient time to charge and discharge. This will cause the higher frequency voltage to be filtered out as the amplitude of the voltage will converge until the offset voltage.

☐ CHECKPOINT: Get a demonstrator to check your answers, and initial here

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REFERENCES

J. D. Irwin, and R. M. Nelms, Basic Engineering Circuit Analysis, 9th Ed, John Wiley, NJ, 2008.

James W. Nilsson and Susan Riedel, Electric Circuits, 8th Edition, Prentice Hall, 2008.

ASSESSMENT

Student Statement:

I have read the university's statement on cheating and plagiarism, as described in the *Student Resource Guide*. This work is original and has not previously been submitted as part of another unit/subject/course. I have taken proper care safeguarding this work and made all reasonable effort to make sure it could not be copied. I understand the consequences for engaging in plagiarism as described in *Statue 4.1 Part III – Academic Misconduct*. **I certify that I have not plagiarized the work of others or engaged in collusion when preparing this submission.**

Student signature: Tan Jin Chun Date: 16/3/2022

TOTAL: ________(/7)

ASSESSOR: ________