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1. INTRODUCTION

This assignment is an investigation of transient behaviour in resistor capacitor R-C and resistor inductor R-L circuits whilst charging and discharging under DC conditions. Determining the time constant using calculations, simulation and practical experiments to study the exponential growth and decay of voltage and current in these circuits.

2. RESEARCH

The time constant of a circuit as a function of time is represented by the Greek letter tau, or τ . Time constant is measured in seconds and proves the time in which the circuit charges and discharges.

This is how the units (seconds) of the time constant are achieved from the product $\tau = R(\Omega) \times C(F)$.

The units for resistance is ohms (Ω) and capacitance is farads (F).

$$(\Omega) = \frac{\text{Voltage}(V)}{\text{Current}(A)} \text{ also } F = \frac{\text{Coulombs, Charge}(C)}{\text{Voltage}(V)}$$

As there is voltage at the numerator and denominator, simplify as:

$$(\Omega)(F) = \left(\frac{V}{A}\right)\left(\frac{C}{V}\right) = \left(\frac{C}{A}\right)$$

Amps is a unit of current (number of coulombs over seconds),

this now can now be written as:

$$RC = \left(\frac{C}{C \div sec}\right) = \left(C \cdot \frac{C}{sec}\right) = \text{Seconds}$$

Equation 1 - Tau in Seconds

The transition from one steady state to another occurs at a rate indicated by the circuit's time constant, which is an exponential value. The time constant of a circuit thus defines how the transient response of the circuit's voltages and currents change during a each time period.

3. TRANSIENT BEHAVIOUR FOR THE CHARGING OF A CAPACITOR

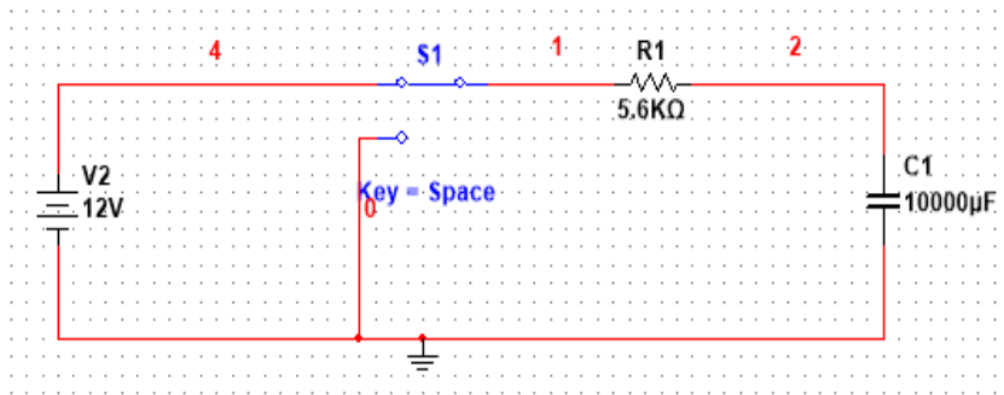


Figure 1 - RC Charging Circuit

Shown above is the first circuit that was under investigation. This image displays an RC charging circuit connected across a 6v DC battery supply with a switch and a 10000μF capacitor in series with a 5.6kΩ resistor.

In an R-C circuit the time constant is a product of the resistance (of the resistor) and the capacitance (of the capacitor). Using the values from this circuit the time constant (Tau, τ) can be found by using the formula:

$$\begin{aligned} \text{Tau } (\tau) &= R \times C \\ &= 5.6k\Omega \times 10000\mu = (5.6 \times 10^3) \times (10000 \times 10^{-6}) \end{aligned}$$

$$\text{When } \tau = 56\text{sec} \qquad 5 \times \tau = 280\text{sec}$$

Equation 2 - Tau in a RC Circuit

3.1. RC CHARGING CALCULATIONS

In this experiment the time constant value, which is 56 seconds. Along with two random and unique time values, 20 seconds and 110 seconds. Then using the exponential equations, the voltage and current values can be calculated.

The equation to calculate the voltage accross the charging capacitor:

$$V_c = V_{max}(1 - e^{-t/\tau})$$

$$\text{At } 20\text{sec} = 6(1 - e^{-20/56}) = 1.801v$$

$$\text{At } 56\text{sec} = 6(1 - e^{-56 \div 56}) = 3.792\text{v}$$

$$\text{At } 110\text{sec} = 6(1 - e^{-110 \div 56}) = 5.158\text{v}$$

Equation 3 - Charging Capacitor Voltage

Before the charging current values, the I_{max} (maximum current) was calculated using the formula:

$$I_{\text{max}} = V_s \div R = 5.6(6.6 \times 10^{-3}) = 1.071\text{mA}$$

Equation 4 - I_{max} Calculation

Once the I_{max} had been achieved, the current of the charging capacitor was calculated by using the random unique time values together using the Instantaneous equation:

$$I_c = I_{\text{max}}(e^{-t \div \tau}).$$

$$\text{At } 20 \text{ sec} = (1.071 \times 10^{-3}) \times (e^{-20 \div 56}) = 0.749\text{A}$$

$$\text{At } 56 \text{ sec} = (1.071 \times 10^{-3}) \times (e^{-56 \div 56}) = 0.393\text{A}$$

$$\text{At } 110 \text{ sec} = (1.071 \times 10^{-3}) \times (e^{-110 \div 56}) = 0.150\text{A}$$

Equation 5 - Charging Capacitor Current

3.2. CHARGING PRACTIAL EXPERIMENT

It is important to carry out the practical experiment to prove or disprove the hypothesis. Using real life conditions and changing variables to understand how that will alter the behaviour of the charging circuit., the circuit was built to mimic the circuit in question. Once the experiment was ready one team member would close the 1PDT switch to begin the charging process, simultaneously another would start the stopwatch and the last engineer would be holding the multi meter in place across the capacitor to take the readings. Starting in increments of 5 seconds until 60 seconds, then after that every 10 seconds, stopping at 300 seconds. The voltage and current from the transient circuit were collected as data in relation to these time periods, 56 seconds is the time taken to reach 1T and 280 seconds is the time it took to reach the steady state.

The table of the results was recorded ([Appendix, Table 4](#)).

These charts provide the data of the charging current and voltage curve across the capacitor to a base of time. The time constant of 1T and the unique time values have been plotted.

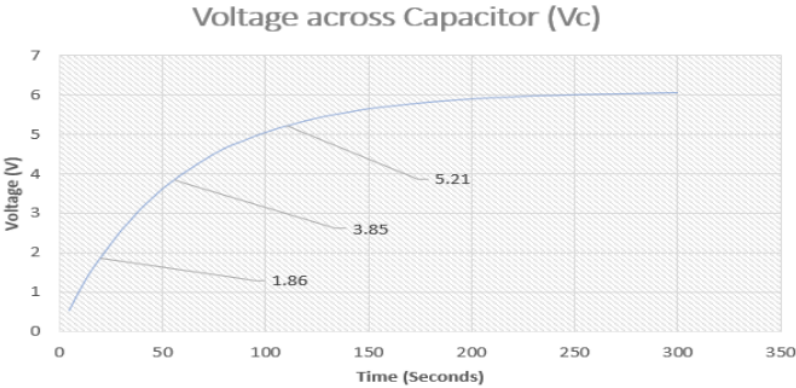


Figure 2 - Practical Charging Voltage Chart

The voltage increases exponentially until it reaches its steady state of 5T at 280 seconds. The capacitor is considered fully charged at this stage.

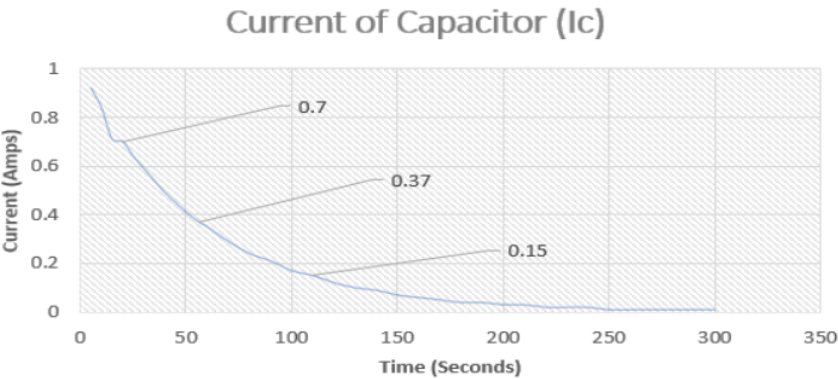


Figure 3- Practical Charging Current Chart

The charging current exponential curve moves in an opposite direction to the voltage as the current across the capacitor starts higher and decreases as until it reaches its steady state at 5T and will be close to 0 amps.

3.3. CHARGING SIMULATED METHODOLOGY

The charts below were created using NI MultiSim. The circuit was created and then simulated via interactive analysis on transients. The charging current and voltage can be seen across the capacitor. The unique time values have again been plotted against a base of time.

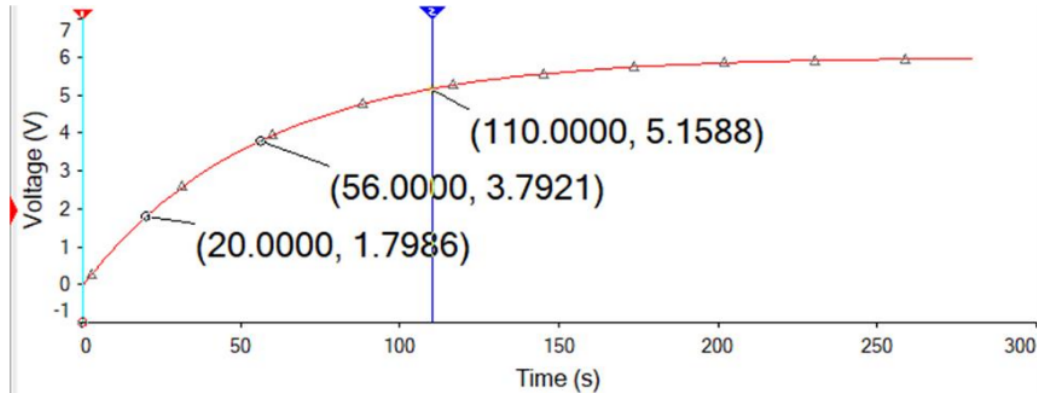


Figure 5 - Simulated Charging Voltage Chart

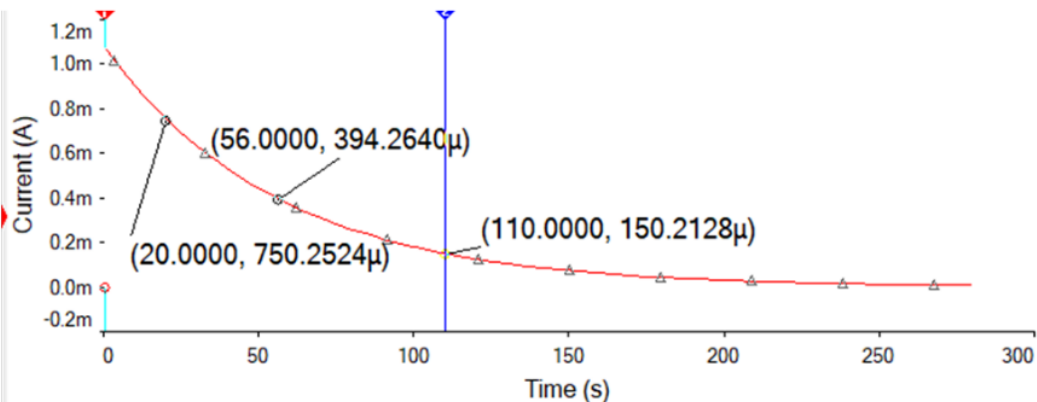


Figure 4 - Simulated Charging Current Chart

3.4. RC CHARGING ANALYSIS

The data below shows the charging currents and voltages recorded respectively from each experiment using the instantaneous time values.

Time (S)	Charge Vc (volts)		
	Practical	Calculated	Simulated
20	1.86	1.801	1.798
56	3.85	3.792	3.792
110	5.21	5.158	5.158

Table 1 - RC Charging Voltage Results

Times (S)	Charge Ic (current)		
	Practical	Calculated	Simulated
20	0.7	0.749	0.75
56	0.37	0.393	0.394
110	0.15	0.15	0.15

Table 2 - RC Charging Current Results

There are small disparities in results, there are many reasons for this. The practical experiment, some of the discrepancies can be attributed to resistance of the test leads, readings of the ammeter not at exact times and rounding of numbers. These discrepancies will have been expected, there is not a lot you can do to fix this. The charging and simulated results are much closer as these are the expected values from set equations, calculations, and simulations with no external influences.

The capacitors maximum charging voltage and current for a specified time constant can be seen in the accompanying table.

Time Constant	Charge Percentage	
	Voltage	Current
1	63.20%	36.80%
2	86.50%	13.50%
3	95.00%	5.00%
4	98.20%	1.80%
5	99.30%	0.70%

Table 3 - Maximum Charging Percentage

This table shows the percentage of the charge that will be achieved at each time constant in a charging circuit.

4. TRANSIENT BEHAVIOUR FOR THE DISCHARGING CAPACITOR

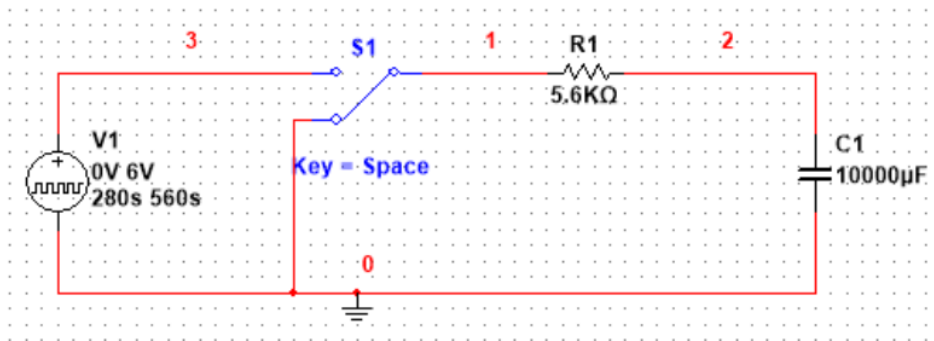


Figure 6 - RC Discharging Circuit

The image above displays an RC charging circuit connected across a 6v DC pulse supply with a switch and a 10000μF capacitor in series with a 5.6kΩ resistor.

4.1. DISCHARGING CALCULATED PREDICTIONS

The same time constant value at 1T was taken, along with the two random and unique time values. Then using the exponential equations, the voltage and current values were calculated. 3 unique instantaneous voltage values:

$$V_c = V_s(e^{-t/\tau})$$

$$\text{At } 20 \text{ Sec} = 6(e^{-20/56}) = 4.198v$$

$$\text{At } 56 \text{ Sec} = 6(e^{-56/56}) = 2.207v$$

$$\text{At } 110 \text{ Sec} = 6(e^{-110/56}) = 0.841v$$

Equation 6 - Discharging Capacitor Voltage

$$I_c = -I_{max}(e^{-t/\tau})$$

$$\text{At } 20 \text{ Sec} = -1.071 \times 10^{-3}(e^{-20/56}) = -0.749A$$

$$\text{At } 56 \text{ Sec} = -1.071 \times 10^{-3}(e^{-56/56}) = -0.393A$$

$$\text{At } 110 \text{ Sec} = -1.071 \times 10^{-3}(e^{-110/56}) = -0.150A$$

Equation 7 - Discharging Capacitor Current

4.2. DISCHARGING PRACTIAL EXPERIMENT

The discharge results from the practical experiment recorded in the same manner as the charging RC circuit but now discharging, then used in excel to create a table (Appendix – Table 8) and chart (below) that shows the voltage and current discharge. In the charts the circuit is discharging until the steady state at 5T is achieved. The time constant and unique time values have been plotted on their axis.

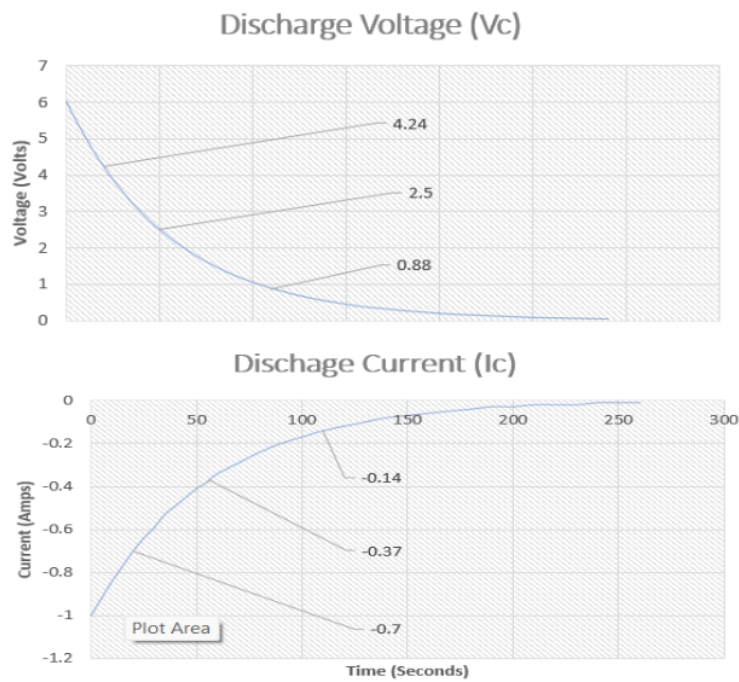


Figure 8 - Practical Discharging Current Chart

4.3. DISCHARGING SIMULATED METHODOLOGY

This Vc chart was created using MultiSim. Starting at 280 seconds, we can see the current rising until we reach the steady state at 5T. The unique time values have been clearly labelled at the X axis.

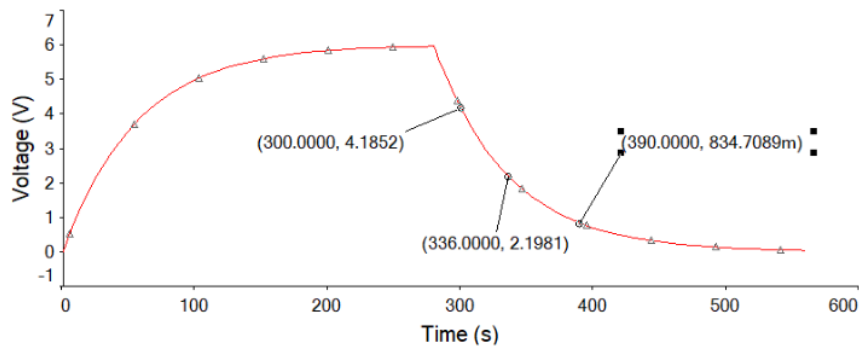


Figure 9 - Simulated Discharging Voltage Chart

These charts include one full time period of the pulse voltage and the time values have been included for the second transient period where the capacitor begins to discharge. When the V_{max} has been achieved, the V_c starts to dissipate as the supply is disconnected and capacitor discharges.

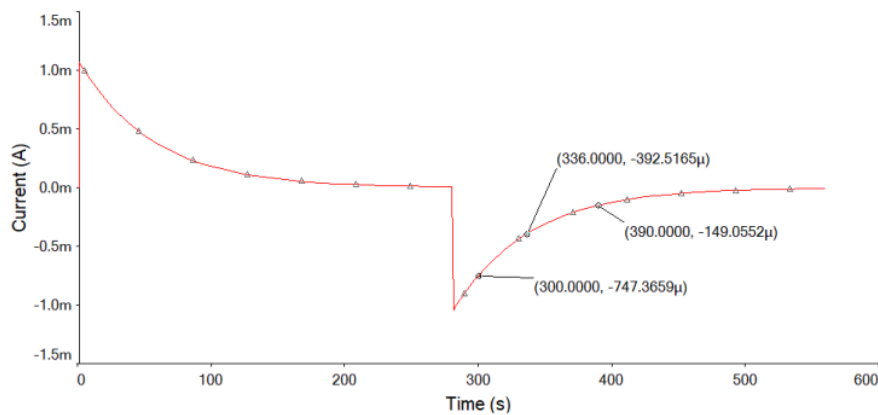


Figure 10 - Simulated Discharging Current Graph

When the supply is disconnected the polarity is reversed and the fully charged capacitor is now releasing its stored charge until the exponential charging curve reaches 0.

4.4. RC DISCHARGING ANALYSIS

For discharging there are many disparities in the results particularly in the practical experiment. The discrepancies can be attributed to the size of the capacitor may not be exact, possible loose connections or the calibration of the ammeter could affect the quality of the data.

Time (S)	Discharge I_c (current)		
	Practical	Calculated	Simulated
20	-0.7	-0.749	-0.747
56	-0.37	-0.393	-0.392
110	-0.14	-0.15	-0.149

Table 4 - Discharging Current Results

Time (S)	Discharge V_c (volts)		
	Practical	Calculated	Simulated
20	4.24	4.198	4.185
56	2.5	2.207	2.198
110	0.88	0.841	0.834

Table 5 - Discharging Voltage Results

Time Constant	Discharge Percentage	
	Voltage	Current
1	36.80%	63.20%
2	13.50%	86.50%
3	5%	95%
4	1.80%	98.20%
5	0.70%	99.30%

Table 6 - Maximum Discharging Percentage

This table shows the percentage of the discharge level that will be achieved at each time constant in a discharging circuit and these values can be used to compare the results.

5. TRANSIENT BEHAVIOUR FOR A MORE COMPLEX CIRCUIT

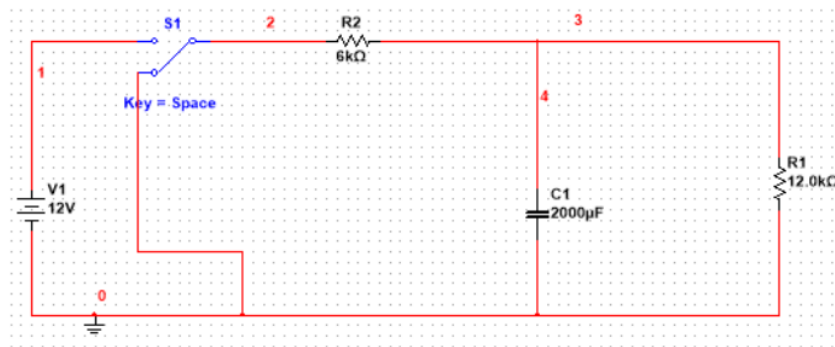


Figure 11 - Complex Circuit

This is the circuit that is we will be investigating in task 2, it is more complex and must be reduced in order to calculate the time constant. This can be achieved by the following calculations.

$$R_t = \frac{\text{Product}}{\text{Sum}} = \frac{R1 \times R2}{R1 + R2} = \frac{6 \times 12}{6 + 12} = 4k\Omega$$

Equation 8 - Total Resistance

$$V_{out} = \frac{R2}{R1 + R2} \times V_s = \frac{12}{6 + 12} \times 12 = 8v$$

Equation 9 - New Vs from Voltage Supply

$$t = R \times C = 4k \times 2000\mu = 4000 \times (2000 \times 10^{-6}) = 8sec$$

$$\tau, \tau(5t) = t \times 5 = 40sec$$

Once the circuit has been reduced and the total resistance that will be connected across the capacitor has been determined and the resistance is a parallel combination of R1 and R2, the time constant can now be calculated.

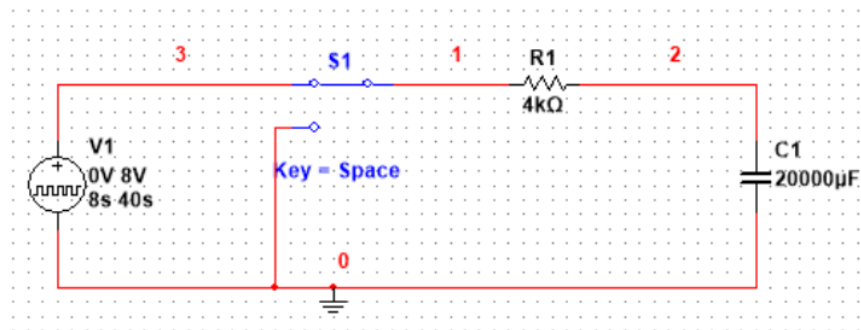


Figure 12 - Reduced Circuit

5.1. COMPLEX CIRCUIT SIMULATION

Now using this reduced circuit, the graphs were simulated for visual representation of the IC charging and discharging capacitor. The time constants $1T$ and $5T$ have been labelled which are 8 seconds and 40 seconds respectively.

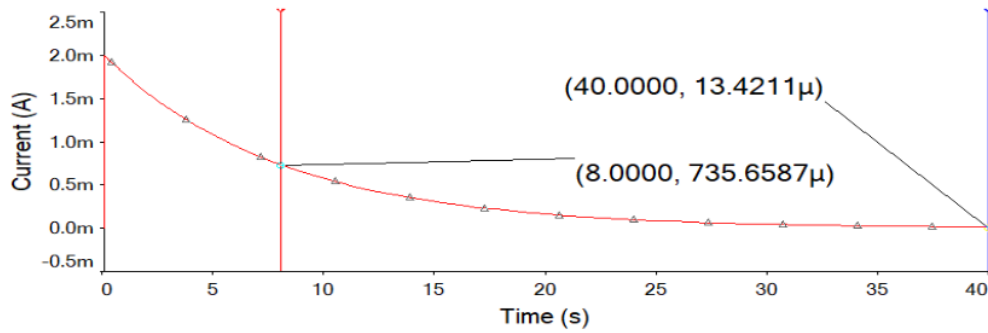


Figure 14 - Charging Current Complex Circuit

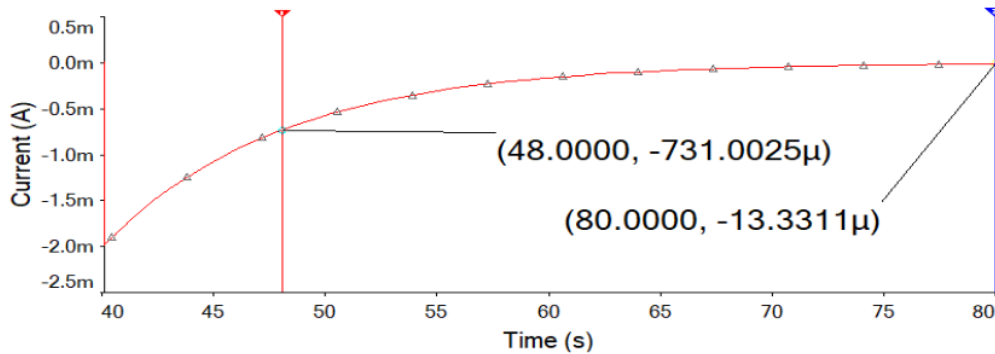


Figure 13 - Time Period Complex Circuit

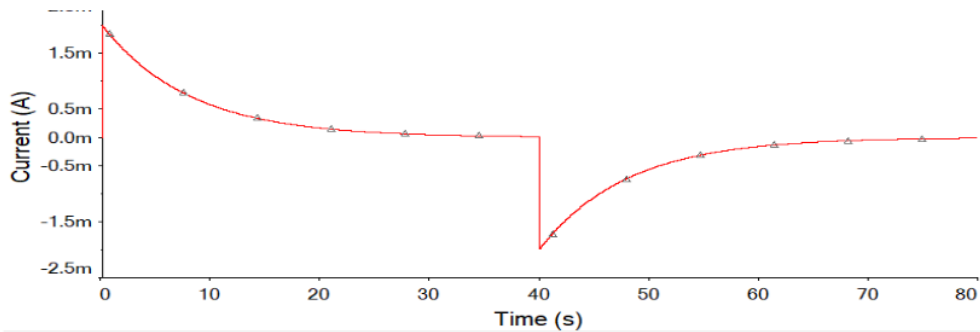


Figure 15 - Time Period for Current in a Complex Circuit

Figure 15 shows one full time period of 80 seconds, which includes both time transient periods of 40 seconds for the pulse supply of the circuit to equally reach its maximum charge and then discharge.

5.2. CALCULATED PREDICTIONS COMPLEX CIRCUIT

The I_{max} must be calculated in order to calculate the instantaneous current values.

$$I_{max} = V_s \div R = 8 \div 4000 = 2mA$$

Equation 10 - I_{max} #2

Time Constants current values

$$I_c = I_{max}(e^{-t \div \tau})$$

$$8 \text{ Sec} = 2 \times 10^{-3}(e^{-8 \div 8}) = 735.758\mu F$$

$$40 \text{ Sec} = 2 \times 10^{-3}(e^{-40 \div 8}) = 13.475\mu F$$

Equation 11 - Charging Capacitor Current #2

$$-I_{max}(e^{-t \div \tau})$$

$$\text{At } 8 \text{ Sec} = -2 \times 10^{-3}(e^{-8 \div 8}) = -735.758\mu F$$

$$\text{At } 40 \text{ Sec} = -2 \times 10^{-3}(e^{-40 \div 8}) = -13.475\mu F$$

Equation 12 - Discharging Capacitor Current #2

5.3. COMPLEX CIRCUIT CURRENT ANALYSIS

Charging IC (current)		
Time	Simulated	Calculated
8	735.658	735.758
40	13.421	13.475

Table 8 - Charging Current in Complex Circuit

Discharging IC (current)		
Time	Simulated	Calculated
8	-735.658	-735.758
40	-13.421	-13.475

Table 7 - Discharging Current in Complex Circuit

These calculated and simulated results are much closer as these are the expected values from set equations, calculations, and simulations with no external influences. Discrepancies in these values can be attributed to the rounding of figures.

The charging current at 1T rises to 66.2% of the I_{max} . When the fully charged capacitor is disconnected from its source the current starts at $-I_{max}$ and is released at the same rate of 66.2% by the time of 1T, this means there is 33.8% of the charge left. This is the reason for the results being the same bar charging current is positive and discharging current is in the minus.

6. TRANSIENT BEHAVIOUR IN AN INDUCTIVE CIRCUIT.

The circuit in question is now an RL circuit where the previous capacitors have been replaced with an inductor of 3H, in series with a 15Ω resistor, and a 12v DC battery supply are connected.

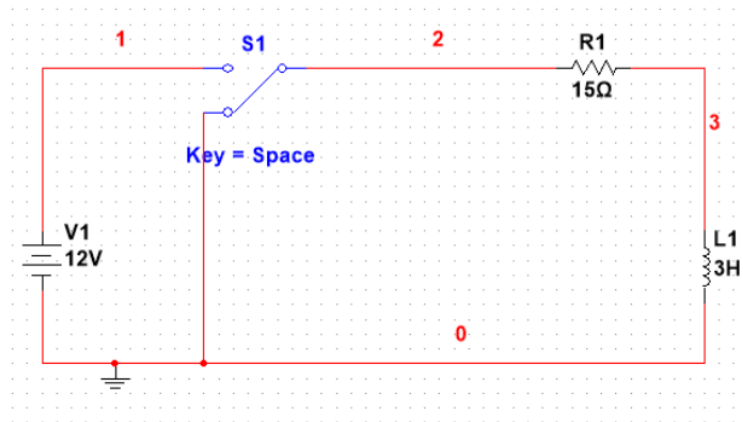


Figure 16- Inductive Circuit

The time constant in an R-L circuit can be determined using the following formula with the values from this circuit:

$$T = \frac{L}{R} = \frac{3}{15} = 0.2 \text{ Sec}$$

When 1T= 0.2 Sec

5T= 1 Sec

Equation 13 - Tau in Inductive Circuit

In this circuit 0.2 seconds is 1T. One second, 5T, is known as the transient period. This is the time when the circuit is considered fully charged and is also regarded as the steady state.

6.1. SIMULATED INDUCTIVE CHARGING CURRENT

This chart shows the current growth of the transient period which is 1 second, after the voltage source is applied to it. Cursors have been placed at 1T where it is at 63.2% charge and 5T and labelled.

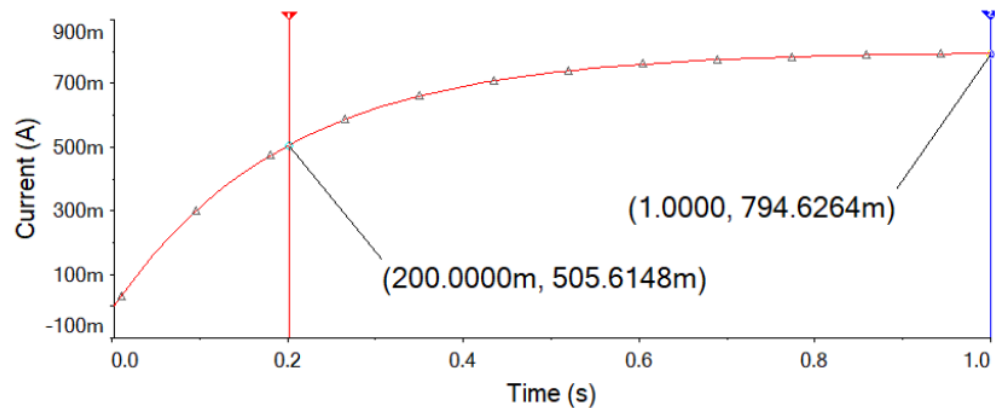


Figure 17 - Simulated Inductive Circuit

6.2. INDUCTIVE CIRCUIT CHARGING CALCULATIONS

IMAX must be determined prior to finding instantaneous current values. The circuit's maximum current is determined using the following equation:

$$I = \frac{V}{R} = \frac{12}{15} = 0.8A$$

Equation 14 - I_{max} #3

Charging Time Constants current values:

$$I_c = I_{max}(1 - e^{-t \div T})$$

$$\text{At } 0.2 \text{ Sec} = 0.8(1 - e^{-0.2 \div 0.2}) = 0.505A$$

$$\text{At } 0.4 \text{ Sec} = 0.8(1 - e^{-0.4 \div 0.2}) = 0.691A$$

$$\text{At } 0.6 \text{ Sec} = 0.8(1 - e^{-0.6 \div 0.2}) = 0.760A$$

$$\text{At } 0.8 \text{ Sec} = 0.8(1 - e^{-0.8 \div 0.2}) = 0.785A$$

$$\text{At } 1 \text{ Sec} = 0.8(1 - e^{-1 \div 0.2}) = 0.794A$$

Equation 15 - Charging Current Calculation

6.3. MANUALLY PLOTTED CHARGING RESULTS

Times taken every 0.05 seconds to create chart and plotted.

Using the IC calculation, the current at any given time by altering the time constant in the equation. The values have been used to create a chart on excel, as shown in figure 18. The RL transient current growth results for these times have been included in the appendix [table 10](#).

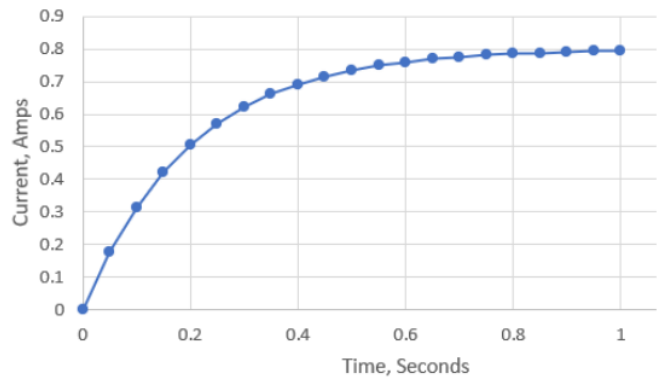


Figure 18 – Calculated Chart

6.4. RL CHARGING ANALYSIS

The results in the table below were taken from simulated and calculated experiments.

Inductive IC Charging		
Time	Calculated	Simulated
0.2	0.505	0.505
0.4	0.691	0.691
0.6	0.76	0.76
0.8	0.785	0.785
1	0.794	0.794

Table 9 - Calculated and Simulated Inductive Times

Inductive IC charging simulated and calculated results are identical at 1T and 5T, current will be expected to reach the I_{max} of 0.8A.

6.5. RL CURRENT DISCHARGING CALCULATION AND SIMULATION

The decaying current is determined by the following mathematical formula

$$IL = I_{max} \left(e^{-\frac{t}{T}} \right)$$

Equation 16 - IL Discharging Current

This formula must be transposed in order for time to be the subject

$$\left(\frac{IL}{I_{max}} \right) = \left(e^{-\frac{t}{T}} \right)$$

$$\ln \left(\frac{IL}{I_{max}} \right) = \left(-\frac{t}{T} \right)$$

$$\ln \left(\frac{IL}{I_{max}} \right) (T) = t = \text{time}$$

Equation 17 - Transposed to Subject of Time

The elapsed time when the current in the circuit was discharging at a rate of 100mA

$$t = \ln \left(\frac{100 \times 10^{-3}}{0.8} \right) \times (0.2) = 0.415 \text{ sec}$$

The elapsed time when the current in the circuit was discharging at a rate of 10mA

$$t = \ln \left(\frac{10 \times 10^{-3}}{0.8} \right) \times (0.2) = 0.876 \text{ sec}$$

Below the simulated results discharging at 10mA and 100mA have been plotted. In the simulation the times start at 1 second as the discharging begins in the second transient time period so will be subtracted by 1 to get the final value.

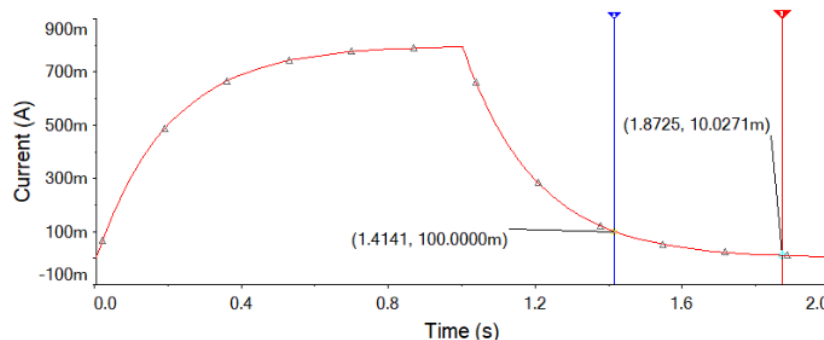


Figure 19 - Discharging RL Current

6.6. RL DISCHARGING ANALYSIS

In the table below the calculated and simulated times discharging at 10mA and 100mA have been recorded. Discrepancies in the values can be attributed to the rounding of figures.

Discharging Time (Sec)		
mA	Simulated	Calculated
10	0.872	0.876
100	0.414	0.415

Table 10 - RL Discharging Current Times

The lower value of current indicates that the time will be higher as the discharging inductor releases its stored energy is exponentially consumed by the resistor and is converted to heat.

7. CONCLUSION AND RECOMMENDATIONS

Initially the capacitor is uncharged in the RC circuit, the switch is then closed causing the transient response. At first the growth rises rapidly and then stabilises as it begins to reach its steady state. The time it takes for the capacitor to charge is determined by the RC, the capacitor charges slower with a larger RC value than with a lower value. The maximum voltage or V_{max} has been achieved at $5T$ (99.3%), which is known as the steady state and at this point the capacitor is considered fully charged and will stay charged as long as there is a supply voltage. As the transient charging curve is exponential, it will never reach a full 100% charge. As seen in the charts, whilst charging the current will start at the I_{max} as a large current will flow, the speed of the charging process decreases over time as the capacitor is losing its charge until eventually the potential difference across the capacitor is equal to the potential difference and current can no longer flow.

When the fully charged capacitor is disconnected from its DC voltage, just like a battery it maintains a steady voltage across the terminals, when fully discharged it will be $0V$. The capacitor starts to discharge but it does not lose its charge at a constant rate, the RC discharging curve shows a steeper initial decay rate that subsequently falls exponentially as the capacitor loses charge the slower and the value of the VC decreases, resulting in a lower discharging current. The capacitors' stored energy is released when current is discharged through the series resistor, resulting in the I_c across the capacitor increasing from the $-I_{max}$ to $0A$ at $5T$ as seen in the charts.

Now an inductor has been added in place of a capacitor, the energy is stored similarly to a capacitor, except it does as a magnetic field. When the dc source is disconnected the inductors current will not go straight to the I_{max} , instead the voltage of the inductor will cause the current to lower slowly is to avoid unplanned changes in the circuits current.

Although the project's objectives were met, it would be advantageous to look into and examine the circuits more thoroughly by repeating the experiments to gather more data that can be compared.

8. APPENDIX

Table 11 - Practical Charging Times

	Time in S	Vc	Ic
	5	0.54	0.92
	10	1.04	0.84
	15	1.49	0.71
	20	1.86	0.7
	25	2.21	0.64
	30	2.55	0.59
	35	2.84	0.54
	40	3.13	0.49
	45	3.37	0.45
	50	3.61	0.41
	55	3.81	0.38
	60	4	0.35
	70	4.34	0.29
	80	4.64	0.24
	90	4.85	0.21
	100	5.05	0.17
	110	5.21	0.15
	120	5.35	0.12
	130	5.47	0.1
	140	5.56	0.09
	150	5.65	0.07
	160	5.71	0.06
	170	5.77	0.05
	180	5.82	0.04
	190	5.86	0.04
	200	5.9	0.03
	210	5.93	0.03
	220	5.95	0.02
	230	5.98	0.02
	240	5.99	0.02
	250	6.01	0.01
	260	6.02	0.01
	270	6.03	0.01
	280	6.04	0.01
	290	6.05	0.01
	300	6.06	0.01

Table 12 - Practical Discharging Times

	Time in S	Voltage	Current
	0	6.03	-1
	5	5.52	-0.92
	10	5.07	-0.84
	15	4.62	-0.77
	20	4.24	-0.7
	25	3.87	-0.64
	30	3.56	-0.59
	35	3.24	-0.53
	40	2.98	-0.49
	45	2.72	-0.45
	50	2.5	-0.41
	56	2.25	-0.38
	60	2.1	-0.37
	70	1.76	-0.34
	80	1.48	-0.29
	90	1.24	-0.24
	100	1.05	-0.2
	110	0.88	-0.17
	120	0.74	-0.14
	130	0.62	-0.12
	140	0.53	-0.1
	150	0.44	-0.08
	160	0.37	-0.07
	170	0.32	-0.06
	180	0.27	-0.05
	190	0.23	-0.05
	200	0.19	-0.03
	210	0.16	-0.03
	220	0.14	-0.02
	230	0.12	-0.02
	240	0.1	-0.02
	250	0.08	-0.01
	260	0.07	-0.01
	270	0.06	-0.01
	280	0.05	-0.01
	290	0.04	-0.01

Table 13 – RL Manually Plotted Times

Time	Current
0	0
0.05	0.176959
0.1	0.314775
0.15	0.422107
0.2	0.505696
0.25	0.570796
0.3	0.621496
0.35	0.660981
0.4	0.691732
0.45	0.715681
0.5	0.734332
0.55	0.748858
0.6	0.76017
0.65	0.768981
0.7	0.775842
0.75	0.781186
0.8	0.785347
0.85	0.788589
0.9	0.791113
0.95	0.793079
1	0.79461