

Resonance

by Alexander Dand

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This report studies the effects of frequency on an RLC Circuit in both simulated and real world environments. It will investigate and analyse the phenomena of Resonance and Q-Factor, some practical applications of these effects, and the differences between 'real' and 'perfect' components.

Resonance

E&E Principles Year 1
Assignment

Martin Dand - 1810440

Resonance

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1 Introduction

1.1 Task Description

In this assignment, we were tasked with building a circuit consisting of a resistor, an inductor and a capacitor all supplied by a fixed amplitude AC current through a signal generator (commonly referred to as an RLC Circuit, due to these being the letters most commonly used to denote Resistance (R), Inductance (L) and Capacitance (C)). The initial work was conducted within a simulated environment. Voltage measurements were taken at a point to obtain readings of voltage over the Inductor (V_L) and voltage over the Capacitor (V_C) whilst varying the frequency of the AC current. Once a suitable suite of readings had been taken, the experiment was transferred to a lab, where a similar circuit was constructed using real components, and measurements were taken using an oscilloscope. The aim of the experiment was to investigate and analyse the effects of AC frequency on V_L and V_C and furthermore investigate the phenomena of Resonance and Q-Factor within an RLC Circuit.

1.2 What is Resonance within an RLC Circuit?

Reactance (the opposition of change of flow of current within an AC circuit, denoted as X) can be capacitive or inductive, and can be defined by the following formulae: [1]

Inductive reactance: $X_L = 2 \cdot \pi \cdot f \cdot L$

Capacitive reactance: $X_C = \frac{1}{2 \cdot \pi \cdot f \cdot C}$

The total reactance in a circuit can be calculated by: $X_T = X_L - X_C$

Resonance is defined as a frequency point in a circuit where the inductive reactance of the inductor becomes equal in value to the capacitive reactance of the capacitor [2]. At this point, they are equal in magnitude but cancel each other out because they are 180 degrees out of phase. The inductive reactance of an inductor (opposition to the flow of alternating current in an inductive circuit, commonly denoted as X_L) is proportional to the frequency of a circuit and the capacitive reactance of a capacitor (opposition to the flow of AC in a capacitive circuit, commonly denoted as X_C) is inversely proportional to the frequency. [3]

In short, there is a magnification of voltage seen at the resonant frequency within a circuit as the impedance (total of resistance and reactance, denoted as Z) drops sharply due to X_L equalling X_C , but due to the cancellation effect the net effect is zero. Therefore, at Resonance, $Z = R$.

Resonance is incredibly useful within electronics as it allows for many tuning applications to function (AM radio, oscillator circuits, television signals, and other filtered signal applications). It can be used to increase or decrease impedance along certain frequencies. It also allows for wireless power systems such as laptops, wireless mobile phone charging, vehicles such as electric cars or maglev trains and implanted medical devices through Resonant Inductive Coupling. [4]

1.3 What is Q-Factor within an RLC Circuit?

Q-Factor, or Quality Factor is a term used throughout many Physics and Engineering disciplines. It is defined as 'a dimensionless parameter that indicates energy losses within a resonant element' [5]. Specifically, regarding Electronics and RLC Circuits this is seen as 'the voltage magnification factor achieved across the coil and capacitor compared with the supply voltage' [6]. This can be defined by the formulae:

$$Q = \frac{X_L}{R} = \frac{2 \cdot \pi \cdot f \cdot L}{R}$$

Or:

$$Q = \frac{X_C}{R} = \frac{1}{2 \cdot \pi \cdot f \cdot C \cdot R}$$

Or:

$$Q = \frac{f_r}{BW}$$

Terms not already referenced:

BW = Bandwidth of the response.

f_r = resonant frequency of the circuit

Note that $(2 \cdot \pi \cdot f)$ is equal to one full cycle of the sinusoidal wave, and can be substituted with ω .

Q-Factor can also be defined by:

$$Q = \frac{1}{R} \sqrt{L/C}$$

Essentially, Q-Factor is the measure of the quality of a circuit as a tuning device. [3] A circuit with a narrower bandwidth and therefore higher Q-Factor, is capable of more efficiently rejecting frequencies outside of this bandwidth. This means that the signal it allows through is clearer, with less interference. The converse is true of a circuit with a wider bandwidth. The reason a resistor is placed within the circuit is to act as a 'dampener', allowing for greater control of the allowed signals due to manipulation of the Q-Factor.

2 Method

2.1 Simulated Circuit

The initial work was done in a simulated environment in the classroom. Using a circuit design program (Proteus 8), we set up a simple circuit as below, with values of $R = 3.3\Omega$, $L = 1 \times 10^{-3}$ Henrys, $C = 1 \times 10^{-6}$ Farads. A Voltage probe was attached to obtain the combined values of V_L and V_C throughout the experiment.

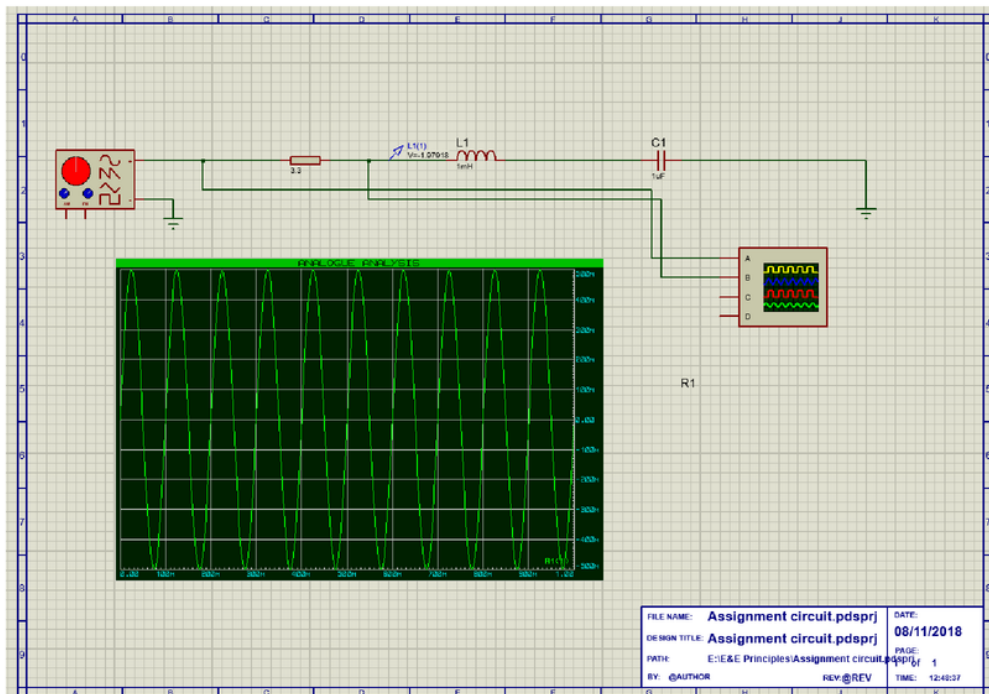


Figure 1 - RLC Circuit setup

A Signal Generator and Oscilloscope were also attached to the circuit, to modify the frequency and monitor the $V_L + V_C$ values respectively. The signal generator output was set to 12Vpk-pk at a frequency of 100Hz, and the value of $V_L + V_C$ was logged. The frequency was modified to a range of values up to a value of 20kHz (see Figures 3 and 4), and the same data was taken each time. We were instructed to take several closely spaced measurements around the peak of the response in order to determine the peak more accurately. Once all the data had been obtained, a graph was generated to display the data points.

2.2 Lab Circuit

Once we had the required simulated data, we needed a real-world comparison. In a lab environment, we constructed the same circuit on a breadboard using the following components:

Resistor:	Inductor:	Capacitor: [7]
Stated Value – 3.3Ω	Stated Value: 1mH	Stated Value: $1\mu\text{F}$
Measured Resistance – 2.89Ω	Series Resistance: 2.89Ω	ESR* @ 1kHz – 5.09189×10^{-5}
		ESR @ 10kHz – 7.63784×10^{-4}
Measured inductance – $13.7\mu\text{H}$	Measured Inductance – 0.977mH	Measured Capacitance: $1.013\mu\text{F}$

*ESR – Equivalent Series Resistance – intrinsic resistance present within ‘real’ components

Table 1 - Component Values

*ESR – Equivalent Series Resistance – intrinsic resistance present within ‘real’ component

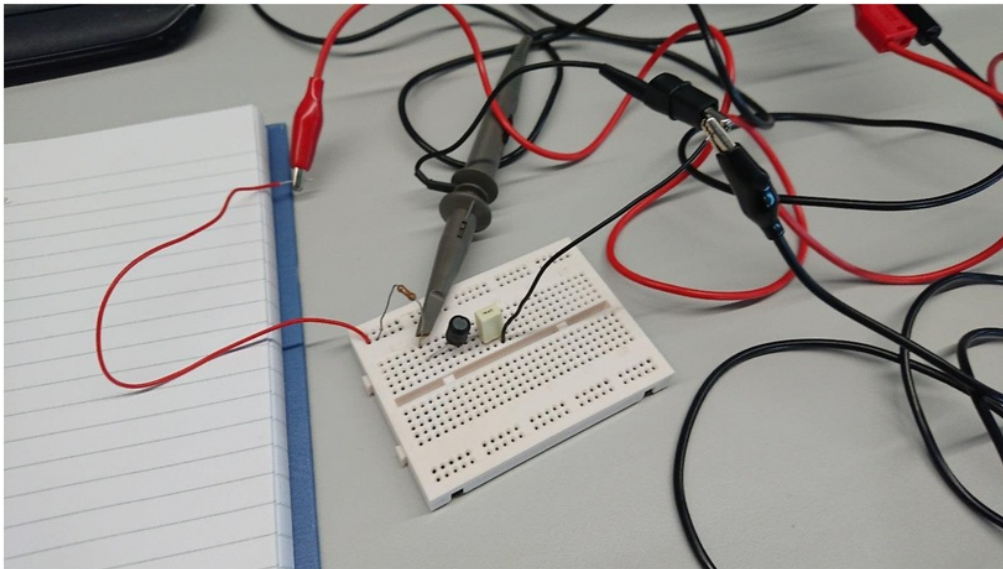


Figure 2 - RLC Circuit lab setup

As shown in Figure 2, the probe was connected between the Resistor and the Inductor in order to capture the value of $V_L + V_C$. In this instance, it was suggested that 12Vpk-pk may be too high for the real-world components, and that 4Vpk-pk would be more suitable as the numbers generated were of less importance than the circuit behaviour to be analysed. The Signal Generator was set accordingly, and a suite of results were generated using the same frequencies as used in the simulated experiment.

3 Results

3.1 Response Graphs

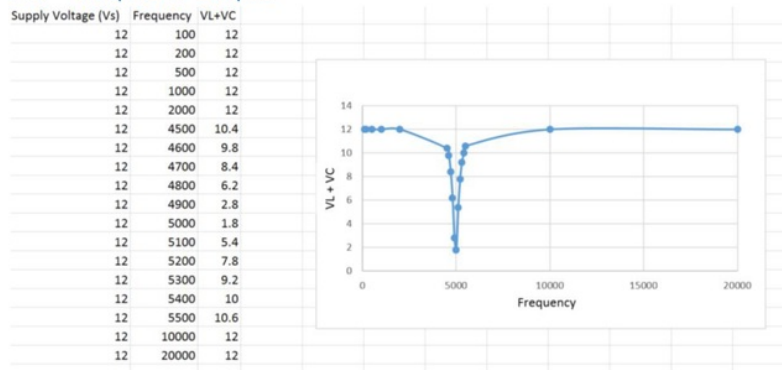


Figure 3 - Simulated Circuit Results

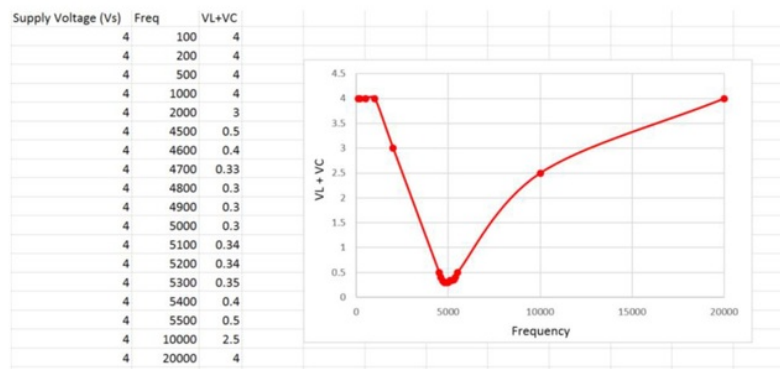


Figure 4 - Lab Circuit Results

From a brief review of the results, we can assume that the Resonant Frequency, f_r , is around 5kHz as it is at this frequency value that the voltage drop is the greatest. This is further supported by observation of the Oscilloscope during the experiment. The following phenomena was observed (please note, the blue wave denotes the AC current 'I' and the yellow wave denotes voltage measured across the inductor and the capacitor ' V_L+V_C ')

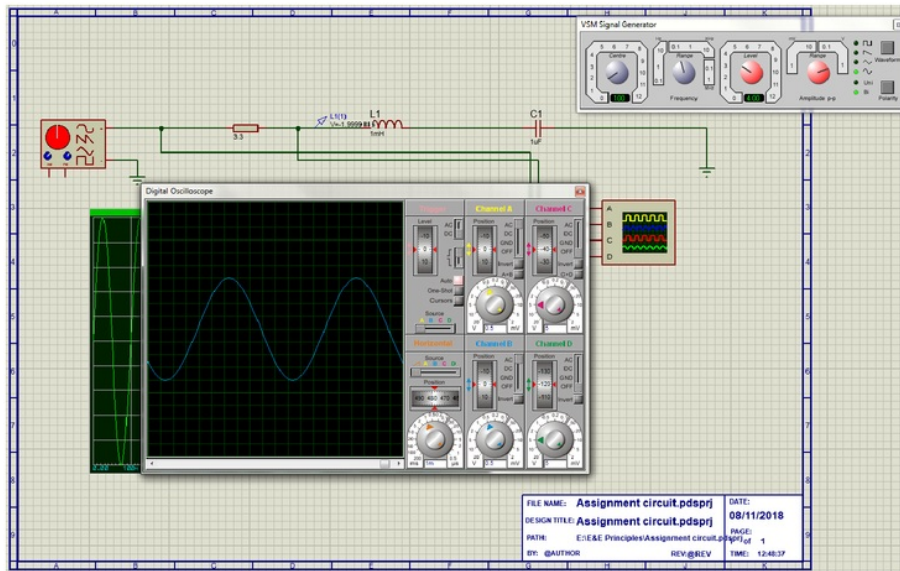


Figure 5 - Supply Voltage against VL+VC - 100Hz

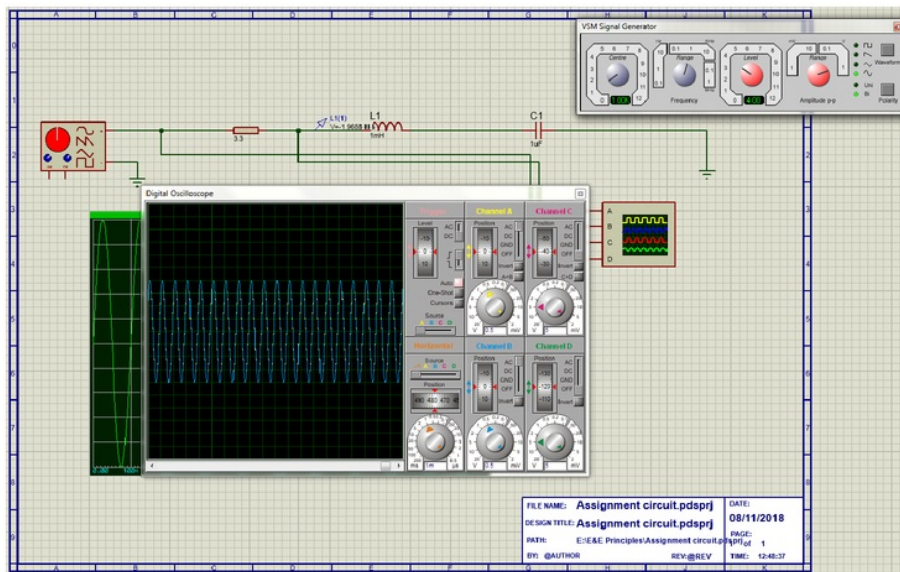


Figure 6 - Supply Voltage against VL+VC - 1kHz

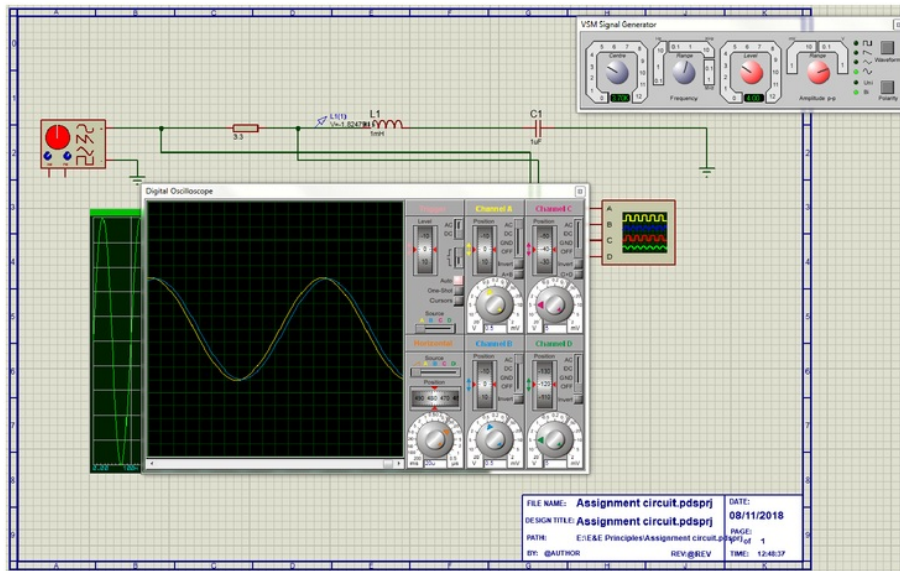


Figure 7 - Supply Voltage against VL+VC - 3.7kHz

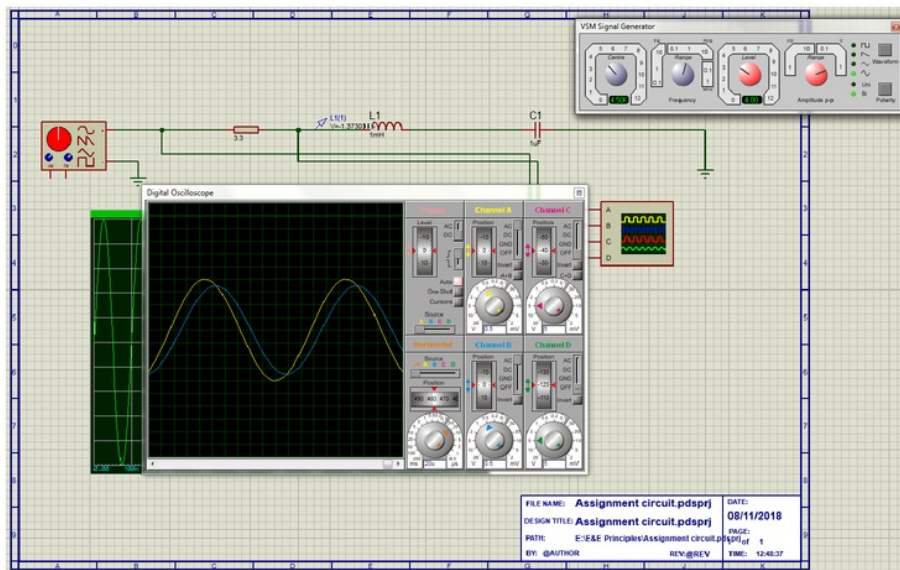


Figure 8 - Supply Voltage against VL+VC - 4.5kHz

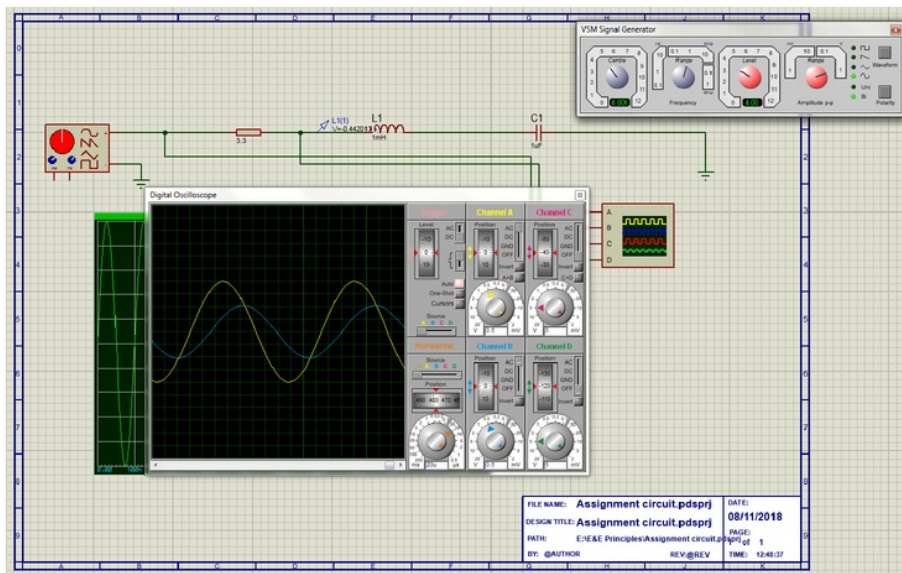


Figure 9 - Supply Voltage against VL+VC - 4.8kHz

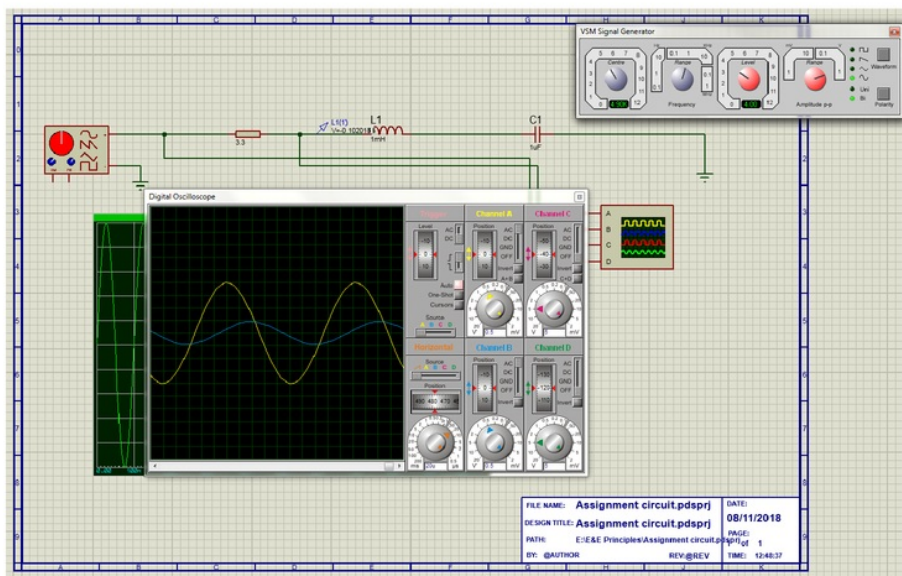


Figure 10 - Supply Voltage against VL+VC - 4.9kHz

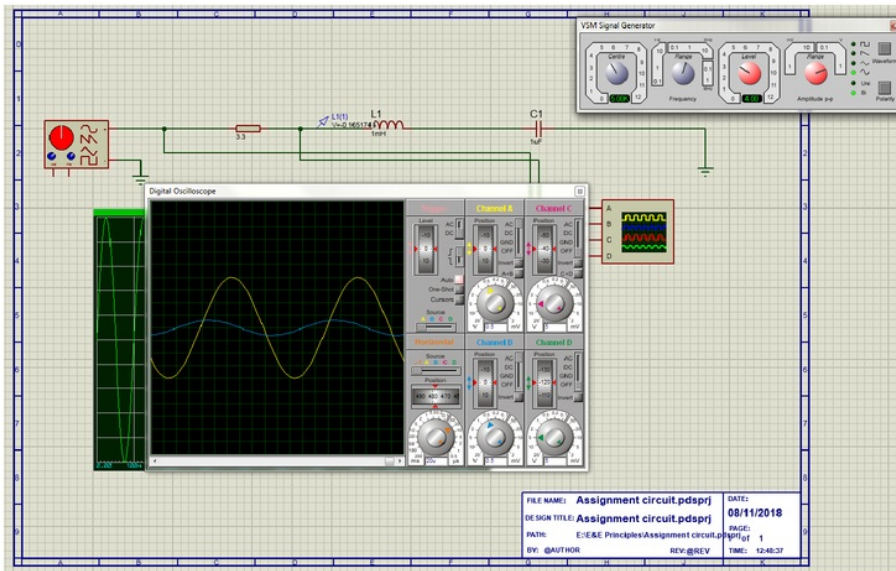


Figure 11 - Supply Voltage against VL+VC - 5kHz

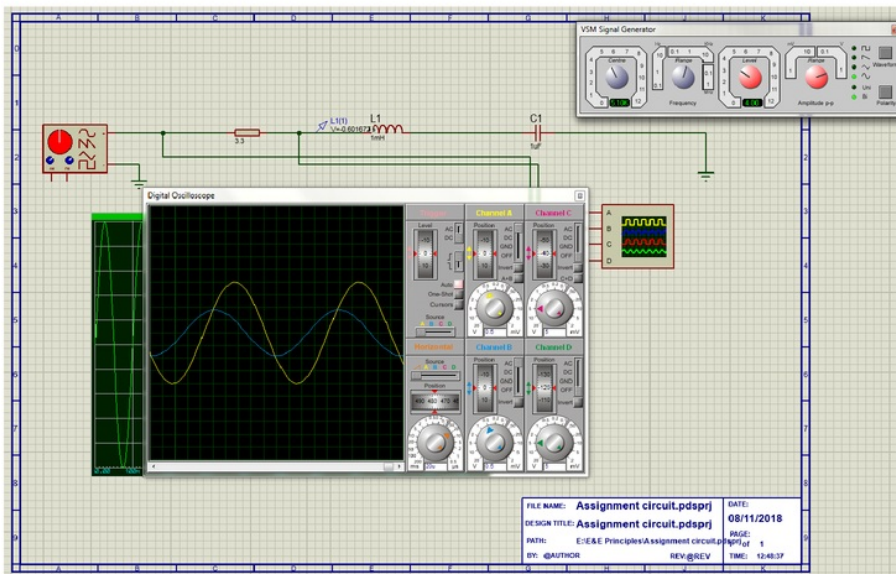


Figure 12 - Supply Voltage against VL+VC - 5.1kHz

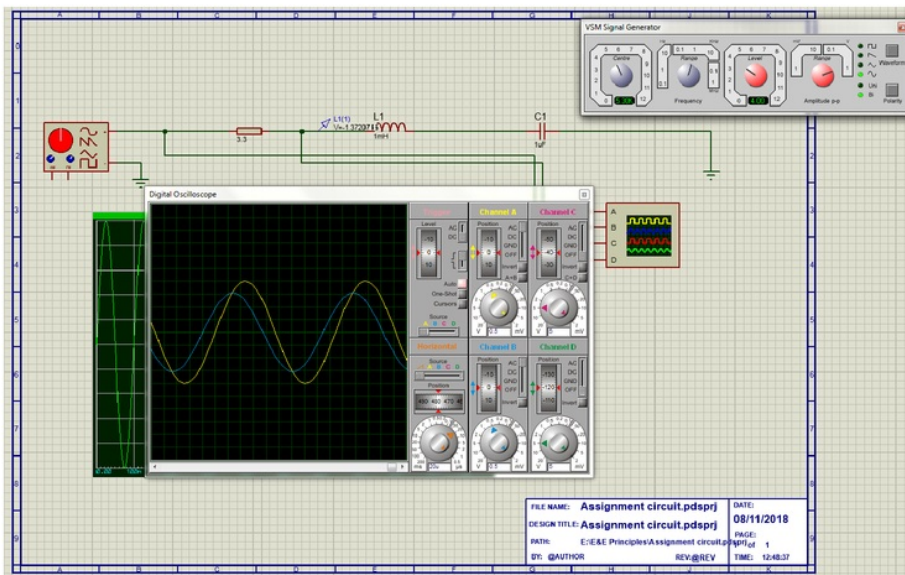


Figure 13 - Supply Voltage against VL+VC - 5.3kHz

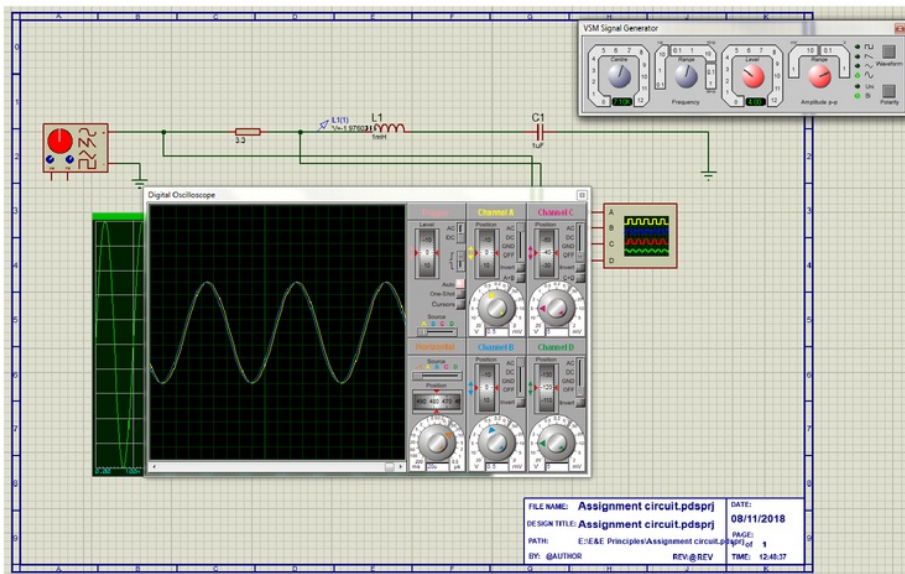


Figure 14 - Supply Voltage against VL+VC - 7.1kHz

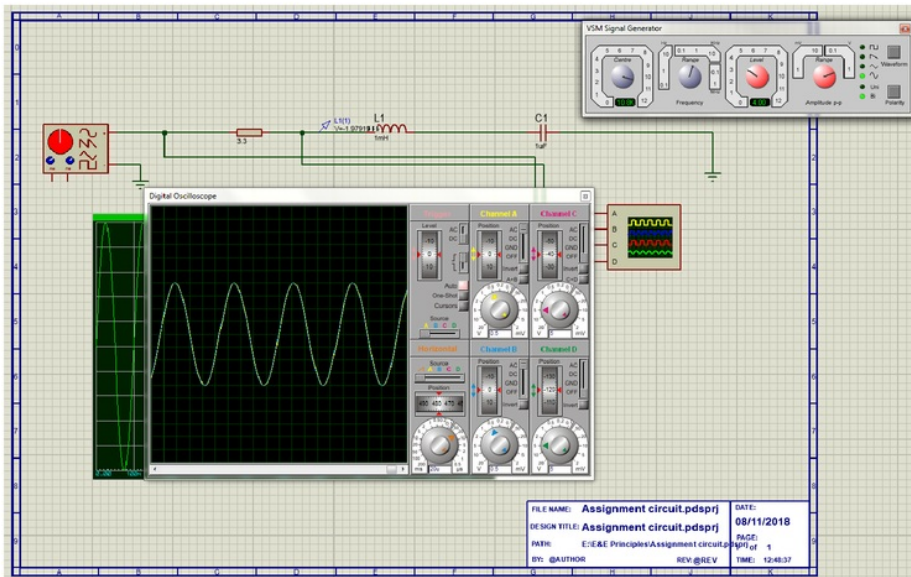


Figure 15 - Supply Voltage against $V_L + V_C$ - 10.8kHz

As can clearly be seen from these images, ' $V_L + V_C$ ' is leading 'I' initially, showing that the circuit is capacitive. After 5kHz however, the circuit becomes inductive, shown by the fact that 'I' leads $V_L + V_C$. This further indicates that f_r can be taken to be a value of around 5kHz.

3.2 Calculations – Simulated Circuit

From these results, we can work out the Bandwidth of each circuit (and therefore the Q-Factor), using the following calculations:

Bandwidth is calculated at the 70.7% amplitude points of the circuit [6]. In our experiment, the following calculations apply:

To find the 70.7% amplitude points in the Simulated Circuit:

$$((V_L + V_C)_{\max} - (V_L + V_C)_{\min}) \times 0.293$$

Or:

$$(12 - 1.8) \times 0.293 = 2.9886$$

Therefore, these points on the graph can be plotted here, and the bandwidth is calculated as the frequency range between the 70.7% points (please note I have enlarged the relevant section of the graph for greater accuracy):

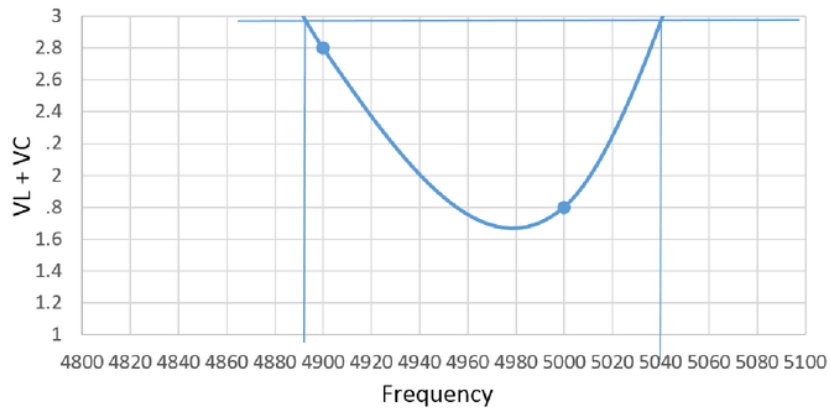


Figure 16 - Bandwidth, Simulated Circuit

As you can see on the graph, the simulated circuit exhibits a very narrow bandwidth, which we can work out using the following formulae [6]:

$$BW = \Delta f = f_h - f_l$$

f_l can be seen to be 4893Hz, and f_h can be seen to be 5040Hz.

Therefore:

$$\begin{aligned} BW &= 5040 - 4893 \\ &= 147\text{Hz} \end{aligned}$$

We also know that $f_l = f_r - \frac{\Delta f}{2}$, which we can rework to $f_r = f_l + \frac{\Delta f}{2}$

This means we can precisely calculate the resonant frequency as:

$$\begin{aligned} f_r &= 4893 + \frac{147}{2} \\ &= 4966.5\text{Hz} \end{aligned}$$

From our previous definitions, we know that $Q = \frac{f_r}{BW}$

Therefore:

$$\begin{aligned} Q &= \frac{4966.5}{147} \\ Q &= 33.79 \end{aligned}$$

3.3 Calculations – Lab Circuit

Using the same calculations for the Lab Circuit:

$$((V_L + V_C)_{\max} - (V_L + V_C)_{\min}) \times 0.293$$

Or:

$$(4 - 0.3) \times 0.293 = 1.0841$$

And the bandwidth for this circuit can be seen below:

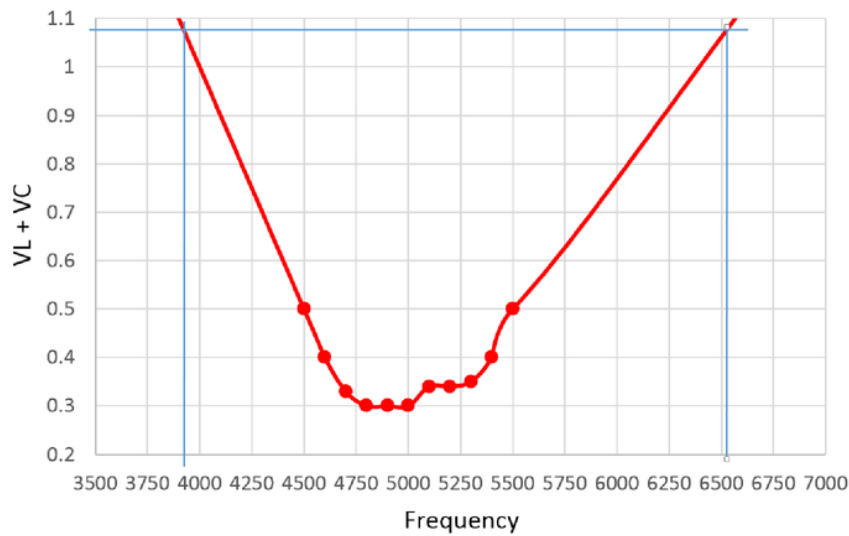


Figure 17 – Bandwidth, Lab Circuit

The bandwidth in the Lab circuit is much wider, approximately 2600Hz.

From this:

f_l can be seen to be 3925Hz, and f_h can be seen to be 6525Hz.

$$\begin{aligned} BW &= 6525 - 3925 \\ &= 2600\text{Hz} \end{aligned}$$

Also:

$$\begin{aligned} f_r &= 3925 + \frac{2600}{2} \\ &= 5225 \end{aligned}$$

Therefore:

$$\begin{aligned} Q &= \frac{f_r}{BW} \\ Q &= \frac{5225}{2600} \\ Q &= 2.0096 \end{aligned}$$

4 Discussion

The first discussion point is driven by the results obtained from the experiments. Given the results shown in the graphs for both simulated and lab experiments, it is shown that as suggested in the lab

experiment that the actual supply voltage is somewhat irrelevant when it comes to the analysis of Q-Factor and Resonance. Looking at the shape of both series of results, both graphs show a similar voltage drop at a similar frequency, around 5kHz. This supports the formulae provided that Q is a function of X_C and X_L , as the same values of components were used in both experiments.

Another discussion point to address is the difference in Q-Factor between the two circuits. As shown within the Results section, there is a dramatic difference in bandwidth and therefore Q-Factor. There are several reasons behind this.

From the theory, we can see that Q is inversely proportional to the resistance of a circuit. The higher the resistance, the lower the Q-Factor. Within a primitive simulated circuit, each component is only granted the attributes associated with it (resistors have only resistance, inductors only have inductance, capacitors only have capacitance). The problem with this is that each 'real' component has its own intrinsic resistance, or ESR (see Table 1). Whereas in a simulated environment each component is simply what is stated, each 'real' component can be seen as a miniature circuit comprised of several imaginary components.

For example, a capacitor can be seen as:

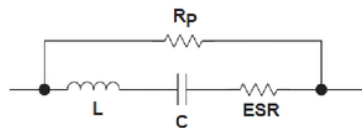


Figure 18 - Equivalent Circuit for a Capacitor [8]

As seen in Table 1, the capacitance 'C' is accompanied by an inductance (L, dominant at high frequencies), an ESR value in series, and a parallel resistance (R_p). The inductance is due to capacitive reactance being a function of frequency. At low frequencies, the capacitive impedance is high and blocks signals. As the circuit frequency approaches resonance, X_C decreases to a minimum figure at f_r after which X_L takes over, and the circuit becomes inductive.

Similarly for an inductor:

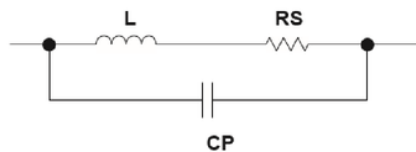


Figure 19 - Equivalent Circuit for an Inductor [8]

In an Inductor, the inductance 'L' runs in series with an inherent resistance (R_S), and with an equivalent parallel capacitor. As an inductor is made up of a wire wrapped round a core, the wire itself holds a resistance. This innate resistance lowers the Q-Factor. This is denoted in Table 1, where it shows a series resistance for the Inductor used in the experiment of nearly 3Ω . This is almost the same value as the Resistor, effectively doubling the resistance instantly.

When considering 'real' circuits vs simulated ones, the simulation program as a baseline will consider primitive components and connecting cables to have no resistance (unless these parameters are programmed in when building the circuit), as the ESR is almost negligible and for artificial purposes

can be disregarded. However the reality is that there is no such thing as a perfect conductor, and all material has some value of Resistivity (measured in Ω/m). Resistance itself is given by the formula $R = \frac{\rho l}{A}$ where ρ is the resistivity of the material, l is the length of the material and A is the cross-sectional area that the current is travelling through [3]. This means that the longer a material is, or the smaller the cross sectional area of the material, the greater the resistance opposing the flow of current. These are not considered in a simulated circuit, and the resistance of each part of the circuit is taken to be zero. Unless the attributes of any component (including connecting wires) are changed to take this into account, this effect is seen throughout.

Another thing that could contribute to the increase in resistance is again shown in Table 1 with the disparity between the 'Stated Value' and 'Measured Value' of the components. Whilst simulated components are assigned a value, components in real life are rarely the precise figure given as their value. Where historically components have had tolerances applied to them (some up to 10% of their value, which could cause some concerns when designing precision circuits) however due to modern manufacturing methods, these tolerances have been reduced to around 1%.

Other factors relating to the components used could be due to use. These components are used in a public lab and have possibly been used many times by other students. Incorrect handling of the components could cause loose connections which could affect the readings. Oxidation and subsequent corrosion, or residue on the terminals of the component would increase resistance. Exposure to excess voltage or current (common in a teaching environment) would also cause damage to the devices. Excess temperature due to said excess voltage or current can also cause a component to fail. The breadboards supplied are also a potential point of failure due to all the previously mentioned issues.

We also must consider the human factor. Readings taken by eye are intrinsically less accurate than those taken automatically. Also the fact that the oscilloscope was set manually for each reading would bring in a further margin for error (this can be seen on Figure 17 where there is less of a smooth curve at the peak response point).

All of these effects added together show the differences between the simulated circuit and the lab circuit. The difference in the sharpness of the response, and therefore the quality of the circuit are affected by each of these factors. Whilst individually each effect may be minor, the net effect is an easily discernible difference in the series of results.

5 Conclusions

The task set was to investigate and analyse the phenomena of Q-Factor and Resonance in an AC Circuit. These effects were initially described, the theory behind each was discussed and some applications for Resonance were listed.

A simulated circuit was built, a series of readings were obtained and basic theory was applied to these results. A similar circuit was built in a lab and the results were taken using a similar data set as the simulated experiment. These results were compared against each other and the main difference in the results was found to be due to the fact that there is no such thing as a perfect device outside of a simulated environment.

For future experiments, there are several avenues which could be taken. The first recommendation would be to standardise the voltage to 4Vpk-pk across both experiments. Whilst it has been discussed that the voltage doesn't play much of a role in this type of research, for continuity purposes, this should be addressed. Other variations to this could be investigating the effect each

component has on resonance and Q-Factor by substituting differing values of component, even down to differing lengths of wire in the lab environment. This could be done using a series of fixed value components, or by substituting in variable resistors, inductors and capacitors. From a personal point of view, if we were to be reconstructing the experiment I feel the fixed options would be better as variable components are generally less precise and have greater tolerances granted them due to this. Further investigation could also be made into the precise effects of putting each component into a parallel circuit, rather than in series. During my research I have discovered there is a substantial amount of further information regarding the behaviour of RLC components in parallel and I feel that this would be another interesting comparison to investigate.

If the scope of the experiment were to evolve, an application that was touched upon earlier, that of tuning circuits, I feel would be a natural progression of this experiment. This would be a variation on the experiment where variable components would be a better fit, as it would be more efficient than repeatedly constructing a different circuit each time a different bandwidth was required.

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Resonance

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

68/100

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GRADING FORM: SMU GENERIC_SMOSEY

ALEXANDER DAND**67.50****ENGAGEMENT WITH LITERATURE**

including reading, referencing, academic conventions and academic honesty



Inclusion of a wide range of research-informed literature, including sources retrieved independently. Selection of relevant and credible sources. Very good use of referencing conventions, consistently applied.

3.4**KNOWLEDGE & UNDERSTANDING**

Knowledge of the basic underlying concepts and principles of a subject.



Knowledge is extensive. Exhibits understanding of the concepts explored and the breadth and depth of established views.

19.5**COGNITIVE & INTELLECTUAL**

Evaluate underlying concepts and principles of a subject and interpret qualitative and quantitative data in order to develop lines of argument

and make sound judgements.



Sound, logical, analytical thinking; synthesis and evaluation. Ability to devise and sustain persuasive arguments, and to review the reliability, validity & significance of evidence. Ability to communicate ideas and evidence accurately and convincingly. Sound, convincing conclusions.

20.4

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



A very good application of a range of methods, tools and techniques. Very good consideration of the context of the application, with perceptive use of examples, where relevant. Evidence of some innovation and creativity.

20.7

TRANSFERABLE SKILLS

Communicate the results of their study/work accurately and reliably, and with structured and coherent arguments; the qualities needed for employment requiring the exercise of some personal responsibility within a structured and managed environment.



Can communicate professionally and, confidently in a suitable format. Work is coherent, very fluent and is presented professionally.

3.5