

Signal Conditioning

by Aaron Stewart Hillam

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Signal Conditioning

BEng Electrical & Electronic Engineering
ACDA5006 – Transducers and Signal Conditioning

Prepared by:

Mr Aaron Hillam

P141233

Submitted to:

Dr Steve Mosey

School of Computing

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Abstract

This report focuses on the design of signal conditioning circuit for a temperature sensor which can produce 0V signal at a temperature of -20°C and 5V for 100°C . The circuit must aid in the removal of 120mVpk-pk 50Hz mains frequency.

It has been determined that an attenuation of 60dB at 50Hz will be required to remove the interference. Through the evaluation of various band filters, a design of a 4th order Butterworth filter has been identified to meet the requirements and has been implemented.

The results shows that the signal conditioning circuit indeed meet the criteria, whilst removing the mains frequency noise. The addition of an over voltage protection circuit has been added to prevent any potential interference or damage.

Declaration

'This report is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.'

Signed: Mr A. Hillam

Date: 26/01/2021

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1.0 Introduction

This report focuses on the design of signal conditioning circuit for a temperature sensor which can produce 0V signal at a temperature of -20°C and 5V for 100°C . The circuit must aid in the removal of 120mVpk-pk 50Hz mains frequency. In addition, over voltage protection and gain and level shift circuits must be added.

1.1 Temperature Sensors

Temperature sensing is the measurement and translation of reactance's between two points. A thermometer functions by adding liquids such as alcohol or mercury to a sealed container. As the temperature of the liquid increases, it starts to expand, forcing it to raise to a specific point and lowers when the temperature drops. Thus, the measurement of expansion from a known start point, such as 0°C , to another determined position. This is then translated for the user. [1] [2] [3]

Unfortunately, the rate of expansion of a thermometer is too slow and inaccurate for digital temperature readings. There are many methods of temperature sensing. However, the principle is the same, measure a change between two points.

As an example, a thermocouple consists of two different materials of equal length, which have different thermal properties. As the materials are heated up the voltage of each material will change but at different rates. Using a voltmeter, it is possible to determine the voltage difference between the two. Again, the sensor is calibrated by placing it in known temperatures, such as ice water at 0°C or boiling water at 100°C . The rate of difference is logged and used for calculating the any value on a gradient. This is then translated to readings that the user can understand. [2] [1] [3]

A more accurate method, is a resistance temperature detector, it is similar to the thermocouple, but rather than assuming ice water or boiling water is definitely 0°C or 100°C respectively, as this can cause inaccurate readings; instead by using Ohms Law of $V=IR$, as long as the current remains the same, the change in resistance of each material will change the voltage, again these are used to compare a voltage difference, and create a temperature gradient. [2] [1] [3]

1.2 Signal Conditioning

Signal conditioning is the process of taking an analogue signal, which is processed and converted into a compatible digital signal which can be used in monitoring and control devices. During the conversion process, the conditioning circuit filters; potential hazards which could come through the signal path and cause damage to the sensor; unwanted noise; and electrostatic interference from ground loops. Signal amplification consists of increasing the input strength/amplitude, this has the effect of increasing the resolution of many measurement devices. Linearization is the signal process of converting non-linear signals into a linear signal. There are many filters types, which can be used for signal conditioning. There are three characteristics to consider, which include the optimization for maximum flatness of the passband response; the steepness of the transition from passband to stopband; the rate of distorted waveforms as a result of phase shifts. Each of the criterion considered, has a filter design specifically for optimising, that characteristic. These include the 'Butterworth', which aims at maximising the flatness of the passband; the 'Chebyshev' which is focused on improving the steepness of transition from passband to stopband; the 'Bessel' which focuses on flat time delay (see appendix A for characteristics diagram). Each of these can be implemented for 'bandpass', 'band-stop', 'highpass' and lowpass filters. [1] [2]

1.3 Over voltage protection

Over voltage is the condition, where the voltage supply reaches higher levels than a load can handle. This could occur when the properties of components change as a result to the environment; the result of miscalculations; and the use of adjustable components such as voltage regulators, this can occur when making adjustments passed the limits of the loads.

The result of over voltage is the potential to cause damage to the circuit, load and supply. However, over-voltage protection can be implemented. These have the responsibility of diverting voltage spikes. Within circuitry, the protection can include the use of diodes. A single diode has the effect of preventing reverse voltage, which can occur if the voltage source is connected incorrect. The diode only allows the voltage to flow one way, but if it tries to flow in reverse, it functions by resisting the reverse voltage by converting it into heat. By connecting two diodes in anti-parallel, it provides protection by sinking any voltage spikes back to ground. [4]

1.4 Gain and Level Shift

Throughout the process of signal conditioning, sometimes it is not possible to reach the range of voltage signal range. The level shifting amplifier is designed to adjust the range by increasing or decreasing the gain. [2] [4] [1] [3]

1.5 Voltage Noise / Interference

When transmitting signals, there is a potential to gain mains noise / interference. This is due to a range of different sources of transmission and receiving. As an example, for wireless communication. Bluetooth runs at 1mW, mobile phones around 100mW and a base station around 40W. As the signal transmit to a new receiver, it may pick up a much higher signal than needed. Equally, in terms of isotropic antenna, where the transmission is attenuates in a spherical manner from the transmitter. The receiver is then required to receive the now heavily attenuated signal. However, this received signal could have lost too much potential to read thoroughly. [4] [1] [5]

Mains interference is the result of picking up other transmitted signals, as an example, the wiring within the plug socket could be acting as an antenna, picking up general radio waves, these can cause distortion to any unfiltered device connected to the mains supply. Additional causes of interference can be the result of component quality. Such as, the tolerances of each component used, any material degradation such as bent / crushed wires, rust, water damage. These sources of interference can be detected through methods, such as using a wireless radio to pick up interference, then by switching an electrical device off, such as a TV, if the interference stops then the TV is the source of interference. This can be repeated to track down all sources of interference within the household. In addition, noise can be picked up from powerlines, which is typically a result of faulty power junction, which has a weakened connection, resulting in arcing. The gap causes a broadband RFI generation. [4] [1] [5]

2.0 Method

It is assumed that the signal frequency changes at a rate of 5Hz. This would provide an acceptable change in reading.

The following conditions for the given scenario are:

0V signal at -20°C

5V signal at 100°C

Attenuation of at least 60dB at 50Hz

Frequency Cut-off = 10Hz, 4th order.

Selected capacitor value = 100nF.

Maximum deviation of +/-0.5°C

The voltage gain equation will be used to identify the interference noise.

Voltage Gain (dB)

$$A_v = 20 \log \frac{V_{out}}{V_{in}}$$

The cut off frequency formula, is transposed and calculated to determine an acceptable resistor value.

Cut-Off Frequency

$$R = \frac{1}{2\pi fC}$$

Upon determining the required rate of attenuation, a suitable circuit design will be determined. The data in figure 1 will be used to calculate acceptable feedback resistor values.

Poles	Butterworth	Bessel		Chebyshev (0.5dB)		Chebyshev (2dB)	
	K	c _n	K	c _n	K	c _n	K
2	1.586	1.272	1.268	1.231	1.842	0.907	2.114
4	1.152	1.432	1.084	0.597	1.582	0.471	1.924
	2.235	1.606	1.759	1.031	2.660	0.964	2.782
6	1.068	1.607	1.040	0.396	1.537	0.316	1.891
	1.586	1.692	1.364	0.768	2.448	0.730	2.648
	2.483	1.908	2.023	1.011	2.846	0.983	2.904
8	1.038	1.781	1.024	0.297	1.522	0.238	1.879
	1.337	1.835	1.213	0.599	2.379	0.572	2.605
	1.889	1.956	1.593	0.861	2.711	0.842	2.821
	2.610	2.192	2.184	1.006	2.913	0.990	2.946

Figure 1: Filter Design Values [1]

$$k = 1 + \frac{R2}{R1}$$

$$\frac{R2}{R1} = k - 1$$

Once a suitable resistance for R1 has been selected, R2 is then calculated using the following formula.

$$R2 = R1(k - 1)$$

The filter circuit will then be set up, using the values identified. The scenario of the interference noise and the temperature sensor will be emulated through the use of Proteus software package, by connected sine generators.

The simulation will then be used to analyse the noise and temperature sensing range. Upon the successful implementation of a filter circuit, a gain and level shifter circuit will be used to increase the gain and the rate of attenuation. Resulting in the removal of the interference noise. An over voltage protection circuit will then be added, to prevent high voltages entering and damaging the sensor and/or signal conditioning circuit.

3.0 Design

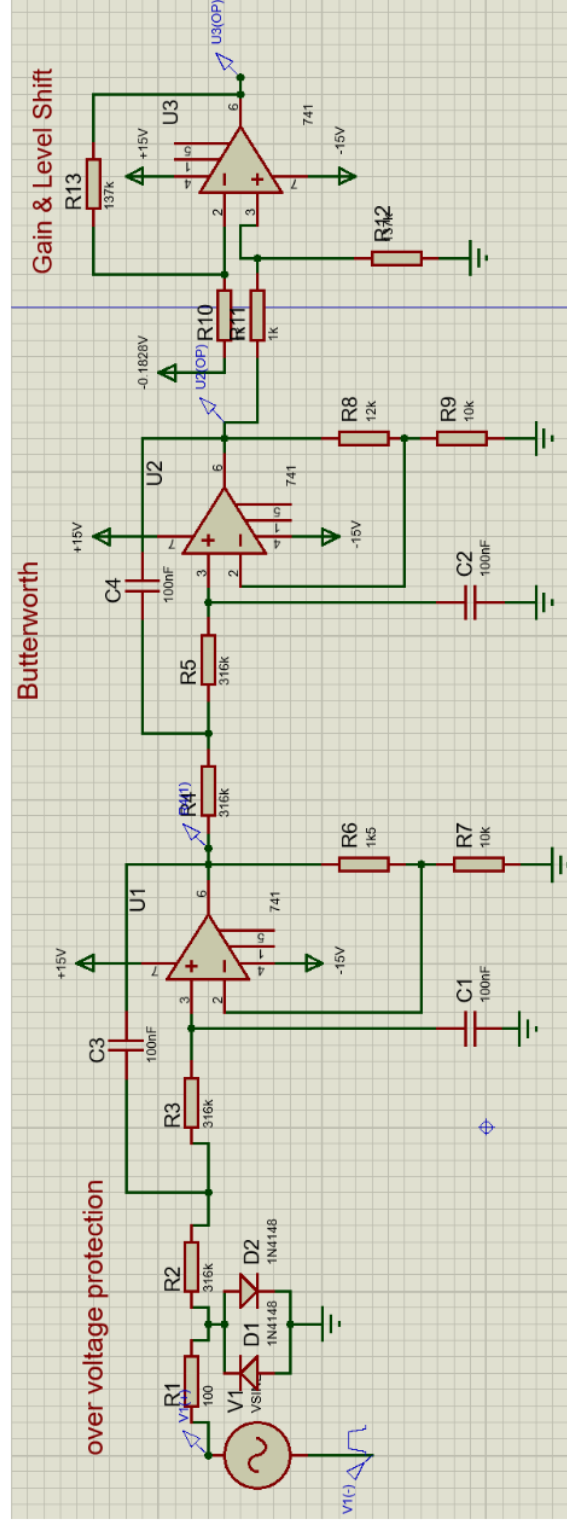


Figure 2: Circuit Design

Figure 2 shows the design of the signal conditioning circuit, which includes: the over voltage protection; the 4th order Butterworth and the gain & level shift.

4.0 Results

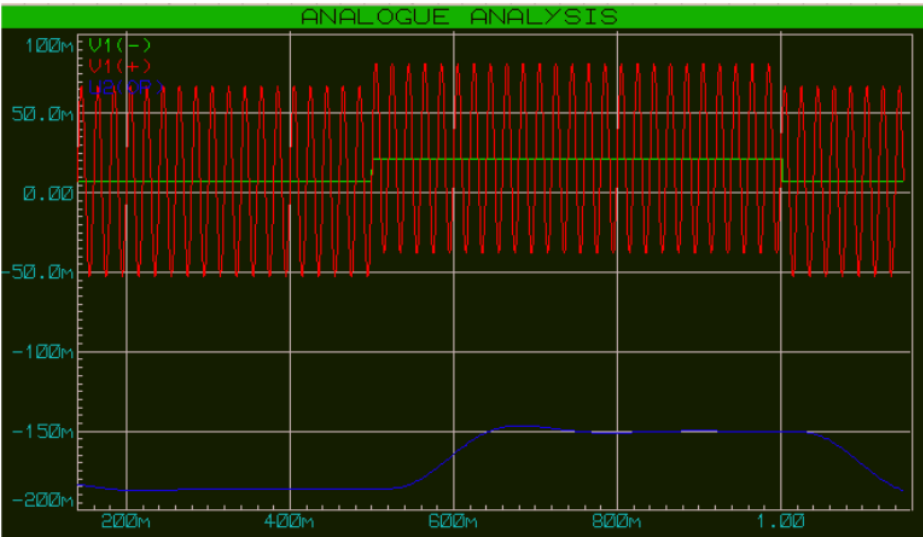


Figure 3: Noise Analysis

Figure 3 shows the noise in red in comparison to the unfiltered signal reading highlighted in green. The blue line indicates the signal reading after being filtered through the Butterworth.

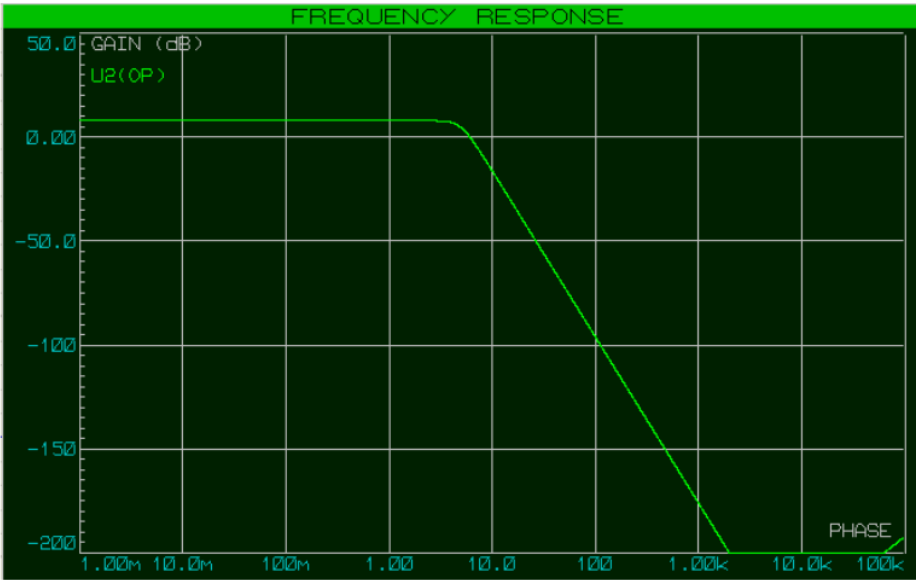


Figure 4: Passband Efficiency

Figure 4 shows the characteristics of the low band filter.

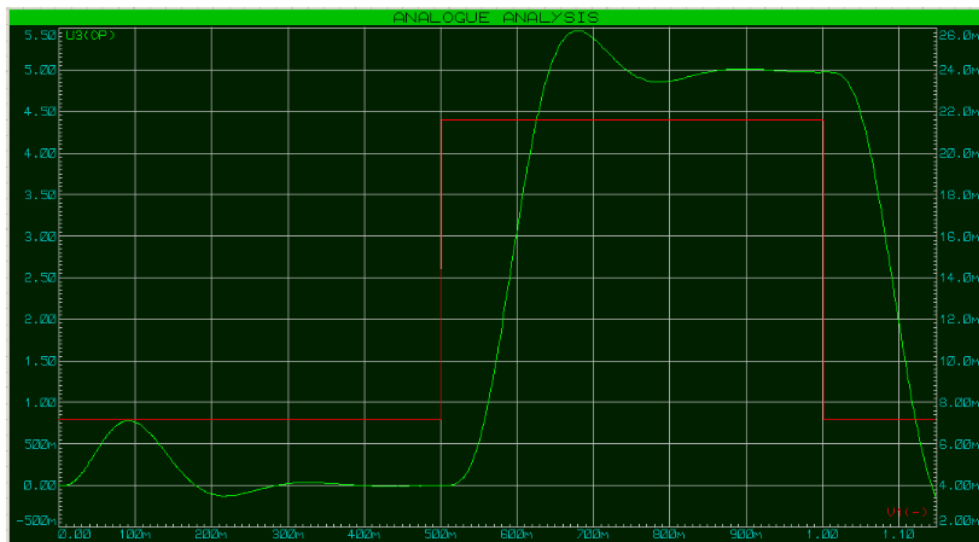


Figure 5: Gain and Level Shift

Figure 5 shows the noise marked in red compared to the filtered signal after the gain and level shift circuit has been implemented.



Figure 6: Characteristic Comparison

Figure 6 shows the comparison of the Butterworth characteristics before the gain and level shift (marked in green) and after the gain and level shift (marked in red).

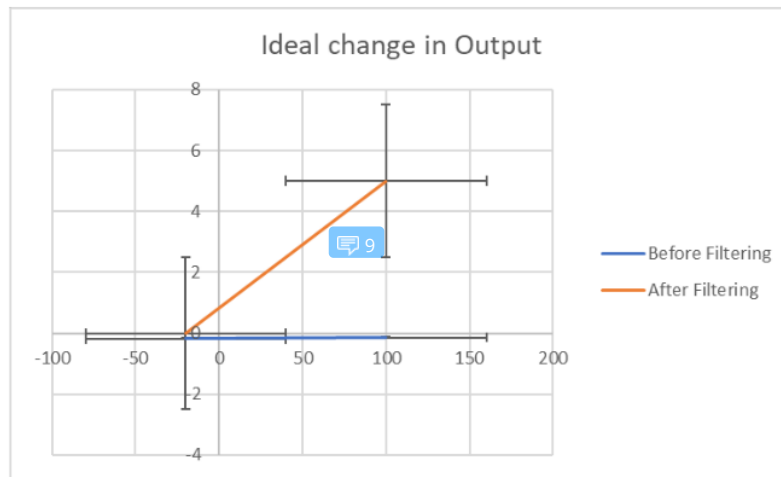


Figure 7: Change in Output

Figure 7 shows the change in output by comparing the change in temperature against voltage.

5.0 Discussion

Informed literature regarding signal conditioning, focuses on the comparison of characteristics of common signal filtering circuits. For the given scenario, a Butterworth filter has been selected as a suitable design. The Butterworth filter provides a middle ground of characteristics compared to the Bessel and Chebyshev. This makes it a good starting point for understanding filters. In addition, the Butterworth is a simple circuit to build.

The range of noise has been calculated using the following voltage gain equation.

$$A_V = 20 \log \frac{120\mu V}{120m} = -60dB$$

The equation shows that the voltage gain of the unwanted noise is -60dB. An attenuation value of at least -60dB at 50Hz is required to ensure the noise is rejected. According to the arts of electronics [1] the rate of attenuation is -20dB/decade per order. As a result, a 4th order Butterworth filter has been selected, which amounts to a total attenuation of -80dB, dependant on the accuracy and tolerance of the circuit components.

The frequency of 5Hz has been assumed, as this would provide a fast temperature. Allowing more accurate readings to be taken. A 1nF capacitor value has also been selected for the purpose of calculating the cut-off frequency, as resulted in the following formula.

$$R = \frac{1}{2\pi \times 100nf} = 318.31E3 = 3.16k\Omega \text{ closest}$$

From figure 1, the gain values for the 4 pole Butterworth are shown as 1.152 and 2.235. These are inserted into the formula:

$$R2 = R1(k - 1)$$

For the two stages of the Butterworth design, the feedback resistors are as follows:

Stage 1 $R2 = 10k \times (1.152 - 1) = 1520 = 1.5k$ closest commercially available

Stage 2 $R2 = 10k \times (2.235 - 1) = 12350 = 12k$ closest commercially available

Figure 2 depicts the completion of the signal processing circuit. It includes the two stages of the Butterworth, with a sine generator shown as v1(-) connected to produce an input value, which crosses through a noise generator shown as VSINE. This simulates the 50 Hz, 120mVpk-pk interference.

An over-voltage protection circuit, consisting of 2 anti-parallel diodes and a reference resistor, has been added. The circuit significantly reduces the potential of high voltages entering and damaging the circuit.

An initial analysis of the noise in relation to the temperature readings was conducted as depicted in figure 3. The green signal indicates the frequencies range available for reading temperature. However, the red signal demonstrates the significant increase of interference. Thus, rendering the temperature sensor unreliable. The blue signal shows how much the signal has shifted away from the interference after the implementation of the 4th order Butterworth filter. It is clear that the filter has helped to isolate and improve the required temperature signal range.

Figure 4 shows and confirms the characteristics of a Butterworth filter. As such, the passband is relatively straight, there is a moderate transition phase, until it flattens out at the bottom.

A gain and level shifter circuit has been added to the end of the circuit, as highlighted. The purpose of this is to increase the overall gain, thus improving the rate of attenuation. The result as shown in figure 6, demonstrates that the circuit without the gain and level shifter, as marked in green, still does not adequately attenuate to remove the noise. The signal marked in red, shows a significant increase in gain, thus a higher rate of attenuation.

Figure 5 demonstrates and compares the rate of attenuation, after the implementation and adjustment of the gain and level shift circuit. As shown, the desired signal range surpasses the interference range. Thus, rejecting the noise. The figure does show a delay between the noise and the filter taking place. However, this can be reduced by selecting more accurate capacitor values.

Figure 7 demonstrates the change in output readings. Identified in blue, this reading output was before the implementation of filtering / signal conditioning. As indicated, the readings are negligible. Thus, rendering the sensor unusable. The orange line indicates the reading output after the implementation of the signal conditioning circuits. As shown, the temperature reading range functions from -20°C at 0V up to 100°C at 5V. Thus, meeting the requirements.

6.0 Conclusion

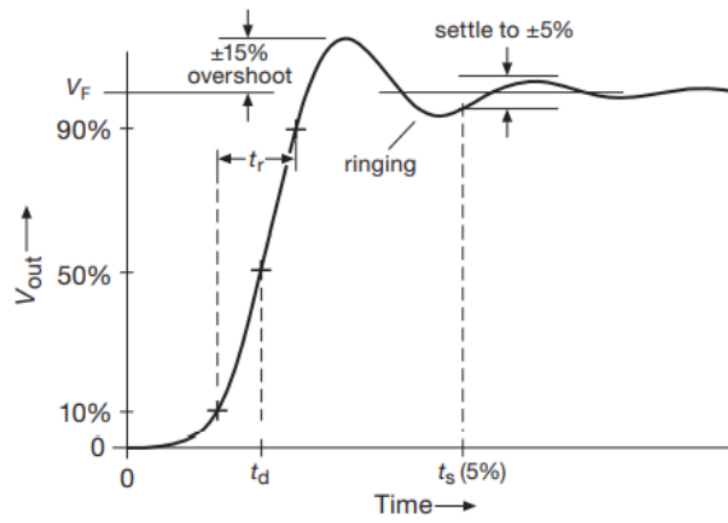
Through the implementation of the circuit simulations, an emulation of the given scenario and the desired end result, were successful. However, there are many ways to improve and optimise the circuits, through the use of different filter types; the accuracy of the resistor and capacitor values; and implementing and adjusting a gain and level shift circuit. The following conclusions can be made:

- All digital signals have the potential of harbouring unwanted frequencies / noise.
- Signal conditioning is essential for allowing a signal to meet its use.
- Almost all noise can be removed.
- The standard circuit designs are not 100% accurate. Thus, considerations of the type of circuit and number of poles must be calculated.
- The change in circuit design has the effect of:
 - Increasing / decreasing the overall cost.
 - Increasing / decreasing the filtering of noise.
 - Increasing / decreasing the complexity of the design
 - Increasing / decreasing the overall tolerances.

7.0 References

- [1] P. Horowitz and W. Hill, The Art of Electronics Third Edition, Cambridge: Cambridge University Press, 2015.
- [2] S. Gibilisco and . Monk, Teach Yourself Electricity and Electronics, Sixth Edition, New York: McGraw-Hill, 2016.
- [3] A. Malvino and D. Bates, Electronic Principles Eighth Edition, New York: McGrawHill Education, 2016.
- [4] P. Hasse, Overvoltage Protection of Low Voltage Systems, The Institution of Engineering and Technology (IET), 2000.
- [5] . T. Justinian Anatory, Broadband Power-Line Communication Systems, Southampton: WIT Press, 2010.
- [6] Microsoft, "IMARGUMENT function," Microsoft, 2019. [Online]. Available: <https://support.microsoft.com/en-us/office/imargument-function-eed37ec1-23b3-4f59-b9f3-d340358a034a>. [Accessed 08 01 2021].
- [7] Microsoft, "IMABS function," Microsoft, 2019. [Online]. Available: <https://support.microsoft.com/en-us/office/imabs-function-b31e73c6-d90c-4062-90bc-8eb351d765a1>. [Accessed 08 01 2021].

8.0 Appendix-A Filter Characteristics



[1]

Signal Conditioning

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

68/100

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5

PAGE 6



Comment 1

Thermocouples rely on the Seebeck effect whereby a temperature gradient causes the migration of electrons from the hot side to the cold side of the material. This movement of electrons creates a potential difference across the material which can be measured.

PAGE 7



Comment 2

Does not have to be a digital signal. The circuit in this assignment doesn't end with a digital signal.

PAGE 8



Comment 3

attenuated



Comment 4

Generally, the interference would run the opposite direction. Large currents flowing in the mains wiring would create large AC electromagnetic fields which have the potential to induce AC current flow into nearby conductors (which could be wiring to a temperature sensor)



Comment 5

arcing

PAGE 9



Comment 6

How did you decide these? How did you know a 4th order filter with a cutoff at 10 Hz would give enough attenuation at 50Hz?



Comment 7

Why 100nF? Why not any other capacitor value?

PAGE 10

PAGE 11

PAGE 12

PAGE 13



Comment 8

The red signal isn't the noise, it's a simulated change in temperature across the full range - the input signal.

PAGE 14



Comment 9

What do the error bars represent?

axis labels and units missing.

PAGE 15



Comment 10

How did you decide this number?

PAGE 16



Comment 11

How long is the delay? You were asked to measure it.

"Determine the response time for your design."



Comment 12

Due to the time constant of the resistors and capacitors (R2&C3 etc) used in the filter circuits. If the capacitor value was changed this would mean either you would need to change the resistor value to compensate, in which case the time constant stays same - same delay; or leave the resistor value meaning the cut off frequency changes - time constant changes giving a different delay.

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PAGE 18

PAGE 19



Comment 13

Very good selection of references.

PAGE 20

GRADING FORM: SMU GENERIC_SMOSEY

AARON STEWART HILLAM

68.25

ENGAGEMENT WITH LITERATURE

including reading, referencing, academic conventions and academic honesty



Outstanding knowledge of research-informed literature embedded in the work. Outstanding selection of relevant and credible sources. High-level referencing skills consistently and professionally applied.

4.1

KNOWLEDGE & UNDERSTANDING

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



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

20.4

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 communicate ideas and evidence accurately and convincingly. Sound conclusions

19.5

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



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

19.5

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 with an exceptionally high level of professionalism. Work is exceptionally coherent, very fluent and is presented professionally.

4.75