

Final Draft

by Gomer Morgan-Gray

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L5 - Transducers and Signal Conditioning (ACDA5006)

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2316794

03/12/2024

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Abstract

This report details specification, design, and testing of a signal conditioning system to be used with a thermocouple, the main objective of the circuit is to reduce a 50Hz noise signal from nearby mains equipment to an acceptable level, the circuit also includes level shifting, amplification, and overvoltage protection.

The proposed circuit consists of a diode clamping circuit to protect from Misplaced apos. up to 34V, for reducing the noise a 4th order Sallen & Key low pass filter was used, making use of a custom filter response to achieve an attenuation of 64.1dB at 50Hz, this was then able to surpass the design requirement of keeping the noise below 16.67mV p-p, this ensures a temperature accuracy of $\pm 0.25^{\circ}\text{C}$.

Signal amplification was then achieved via a non-inverting op amp, with a calculated gain of 218.91, amplifying the transducers signal of -3.4mV to 6.8mV to the correct 5V range, however due to the transducer outputting a negative voltage below 0°C a difference amplifier is used to offset the signal by a fixed amount, adjusting the voltage to 0-5v, the offset voltage is derived from resistive divider.

Several alternative circuits were considered for use, such as multiple feedback filters, crowbar over voltage protection and instrumentation amplifiers, however, were not implemented due to complexity or cost considerations.

The design takes cost efficiency into account by utilizing E24 preferred resistor and capacitor values, and general-purpose components. Trimmer potentiometers have been included for fine adjustments of both the circuit gain and offset allowing for compensation of manufacturing tolerances and for making up for errors introduced by using E24 resistors.

Testing was conducted via simulations and showed a linear response of the circuits output to temperature change, little ripple, and a response time of 78ms comparable to commercially available products.

proposed design offers a standard 24v power supply input for use within industrial control systems.

Introduction

The problem covered in this report is that an input signal from an external temperature transducer is affected by electrical interference from nearby mains equipment, in this case 50hz 120mV peak to peak has been added to the temperature signal, the circuit proposed will be required to attenuate this noise to an appropriate level then scale and level shift the signal to the required 0-5V range, over voltage protection should be added to ensure the system is capable of withstanding unintended inputs.

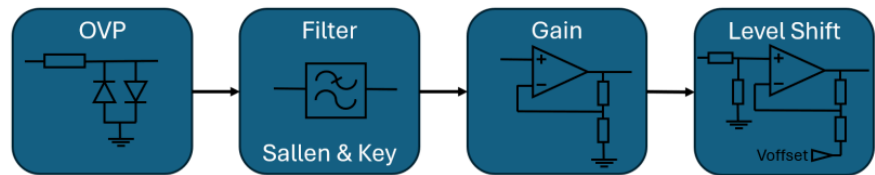


Figure 1 – Circuit Block Diagram.

As shown in figure 1 the first section of the circuit will be over voltage protection. This will be used to limit the maximum voltage allowed further into the circuit preventing distortion due to the op-amps clipping, or in extreme conditions damage to them.

The second section will be filtering. For this role, a Sallen & Key Filter was chosen, this will be in a low pass configuration, it has been decided that an accuracy of $\pm 0.25^{\circ}\text{C}$ should be targeted meaning the noise at the output should be below 0.0167V p-p.

Temperature Range ($^{\circ}\text{C}$)	ouput Range (V)	desierd maximum influence ($\pm^{\circ}\text{C}$)	V/ $^{\circ}\text{C}$	maximum output noise p-p (V)
150	5	0.25	0.033333333	0.016666667

Table. 1 – Noise target/c calculations.

The third section will be amplification. The expected input signal from the temperature transducer is approximately 68uV/ $^{\circ}\text{C}$ and from the specified temperature range of -50 to 100 $^{\circ}\text{C}$ this gives an expected voltage of -3.4mV to 6.8mV the chosen filter will provide some amplification; however further amplification will be required to reach the necessary 0-5V range this will be done using a non-inverting op-amp.

The fourth and final section will be to add the offset voltage. The used temperature transducer produces negative voltages for temperatures below 0 $^{\circ}\text{C}$ and the desired output is 0-5V a fixed offset voltage will be added, this will be done using a difference amplifier and feeding one of the inputs with a fixed negative reference voltage.

The amplification and offset voltage should also be slightly adjustable to allow for correction of errors in differences between manufactured circuits, this will be done by adding trimmer potentiometers.

Background information

Need for signal conditioning

The circuit discussed in this report is an example of signal conditioning. Signal conditioning is the process of preparing a signal for further processing [1] specifically in this case filtering, amplification and level shifting will be used to prepare the signal.

The need from filtering is due to a large noise signal compared to the transducers output signal, any further circuitry will be unable to discern the intended signal from noise.

Passive sensors such as the thermocouple used in this application produce very small outputs which later circuitry will be unable to use. As an example, a common ADC such as the one used within the Atmega 328p has a resolution of ~20mV [2], meaning the unconditioned signal would be unusable and amplification will be required.

Other technologies available

During the design of the proposed circuit there were several technologies that I considered for use, such as:

- Multiple feedback filter, this has better high frequency response than the used Sallen & key filter however the filter is more complicated [3] and due to this the Sallen and key filter was chosen.
- Over voltage protection, an alternative to the used diode clamping circuit would be a crowbar circuit, this makes use of a Zener diode and thyristor to provide a low impedance path to ground, protecting the circuit [4, P. 690-691]
- An alternative for the used differential op-amp for adding the offset voltage would be an instrumentation amplifier, the benefits of which are that it is configured with a single resistor and provides a high input impedance and a low output impedance, however these benefits are outweighed by the additional cost as the benefits are unnecessary in this application [5].

Method

There were several factors considered whilst designing this circuit such as cutoff frequency (F_c), number of filter stages, filter response, gain required to reach desired output voltage, voltage offset and OVP Level.

Cutoff Frequency

The first parameter to be chosen was cutoff frequency. The cutoff frequency of a circuit is the point at which it attenuates the input signal by 3dB [6], as the intended input signal will be a slow changing temperature a safe value for cutoff frequency will be 5Hz, this will ensure a high level of attenuation of the 50Hz noise signal.

Filter

Determining the number of filter orders was done by experimentation, from testing 2nd, 4th and 6th, it was identified that the 4th order would provide the necessary amount of attention whilst keeping components to a minimum, which is desirable if the circuit was to be produced at scale.

Deciding on the filter response was next in the design process, there are several typical filter responses such as Butterworth, Bessel and Chebyshev [4, P. 407-409], simulations were performed and attenuation recorded for all 3 (figure 2) to determine which was most suitable for this application.

Filter response	Attenuation at 50Hz (dB)
Chebyshev	75
Butterworth	71.6
Custom	64
Bessel	59.9

Table 2 – Filter response testing results.

The custom values were decided upon to ensure no oscillations, which were introduced from the Chebyshev and Butterworth, whilst keeping the attenuation to the required level, this was the response ultimately chosen for this application.

Custom Response values	Stage 1	Stage 2
Cn	1.216	1.303
K	1.118	1.997

Table 3 – Custom filter response values.

Amplification

At this stage in the circuit the noise signal has been greatly attenuated and the transducer signal has been partially amplified from the filtering stage, however further amplification is still required to reach the desired 5v output range.

Taking measurements of the voltage after the filtering stage, the amount of gain required can be calculated.

	Input (V)	Desired Output (V)	Required Gain
High	1.60E-02	5	218.91
Low	-6.84E-03	0	Not In Text
Range	2.28E-02	5	

Table 4 – Gain calculations.

The lowest voltage measured was -6.84mV and the highest was 16mV. This gave a voltage range of 28.8mV dividing this by the intended output range the required gain of 218.91 can be calculated.

Level shifting

Having achieved the correct voltage range for the output signal, the only alterations required to the signal are level shifting so the voltage begins from 0V, measuring the signal from the amplification range the amount of offset voltage can be determined.

	Measured Output (V)	Desired Output (V)	Required Offset (V)
High	3.745	5	1.245
Low	-1.245	0	Range Error (V)
Range	4.99	5	0.01

Table 5 – Offset voltage calculations.

OVP

Over voltage protection will be done using a diode clamping circuit, this consists of a resistor and diode pair used for clamping both positive and negative voltages, Silicone diodes will be used for this role as the higher voltages of Zener diodes is unnecessary.

Design

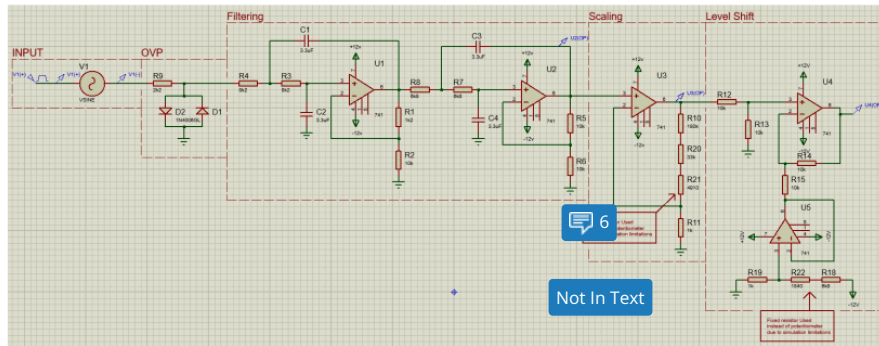


Figure 3 – Complete circuit overview.

To reduce manufacturing cost, it was decided to make use of the E24 preferred resistor & capacitor values laid out in IEC 60063 [7], these values are not always exact to what is needed from the calculations however upon testing with the closest values the circuit still performs to an acceptable level and where exact values are needed trimmer pots will be added.

Section 1:

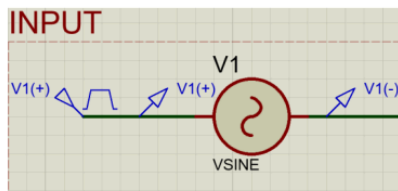


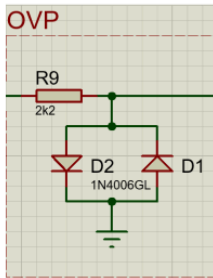
Figure 4 – Input circuit

This section simulates the specified input parameters, the pulse generator is used as the thermocouple providing a square wave signal of -3.4mV to 6.8mV (-50 to 100°C), the "VSINE" generator which adds the 120mV, 50Hz noise signal.

In reality the specified input signal would be from a temperature transducer and a length of cable placed near mains powered equipment causing the unintended EMF on the cable [4, P. 478].

The specific temperature transducer is a type E thermocouple, there are several types e.g. J, K, E, N, etc.... the type specifies the combination of materials used, the type E consists of chromel–constantan [8] and outputs the specified 68uV/°C

Section 2:



As previously discussed, this part of the circuit will be used to ensure that excess voltages are stopped from traveling further into the circuitry. R9 was chosen to not introduce too large of an impedance into the circuit path whilst still reducing the current flow to protect the circuit. D1 and D2 are standard silicone diodes with a forward voltage of 1.1v [9]. These components allow for OVP of up to 34V. (Figure - 5 OVP Calculations)

Figure 6 – Over voltage protection circuitry

Section 3:

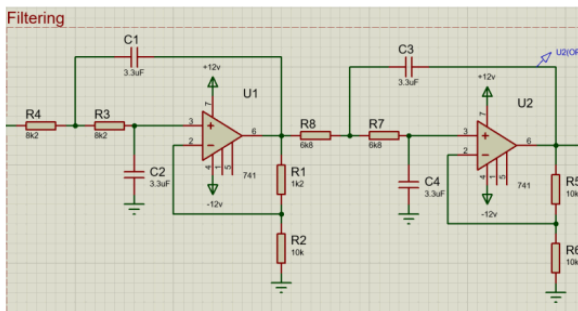


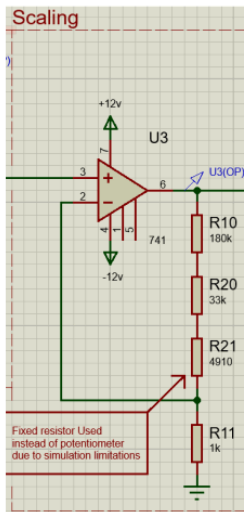
Figure 7 – Filtering

The value of C was first to be determined this was done by using the formula $C = \frac{1}{2\pi f X_c}$, Ideally it is desirable for X_c to equal $\sim 10,000$ at our cutoff frequency, this calculation gave 3.1 nF and the nearest preferred capacitor value is 3.3nF [3].

The filter resistor values were determined by $R = \frac{1}{2\pi \cdot f_c \cdot C \cdot C_n}$
Where C_n is from the previously determined filter response values.

R1 and R5 were then calculated using $R = (K - 1) \cdot R_2$, K is the previously determined gain value for the filter stage and R2 is 10000 to give reasonable values for R1.

Section 4:



As previously calculated the required gain to reach a 5V range is 218.91, making use of the non-inverting gain formula ($R1 = (Gain-1) * R2$), taking $R2$ to be $1k$ the required value for $R1$ is 217.9k. (figure 8 – Scaling Calculations)

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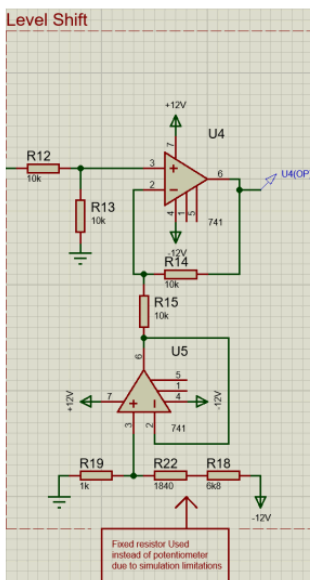
Using preferred values this can be approximated with a 180k, 33k and 10k potentiometer.

The potentiometer will allow for fine adjustments over the gain to compensate for component tolerance [10].

* $R2$ chosen to be $1K$ to produce reasonable values for $R1$

Figure 9– Scaling Circuitry

Section 5:



The difference in amp will be configured with no gain, this is done by using the same value resistors.

To produce the offset voltage a resistive divider was used, values for which were calculated using $R1 = (R2 / Vout) * Vin - R2$ where $R2$ is again $1k$

(Figure 10 – Offset Calculations)

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Vin for this will be the negative supply rail ($-12V$), this is because the difference amp will subtract the voltage on its negative terminal, thus a negative reference is necessary.

$R2$ can be approximated by a $6.8k$ and a $5k$ potentiometer, which is again used to fine adjust the offset voltage.

Figure 11 – Scaling Circuitry

Results

Time domain Results:

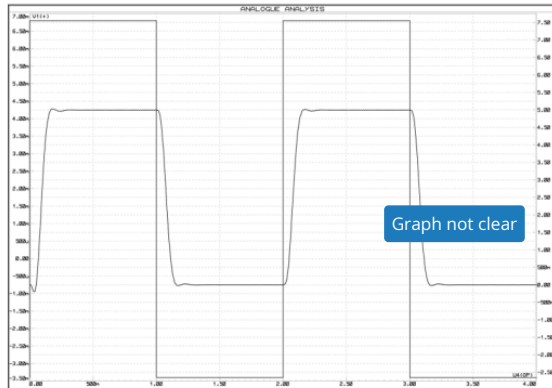


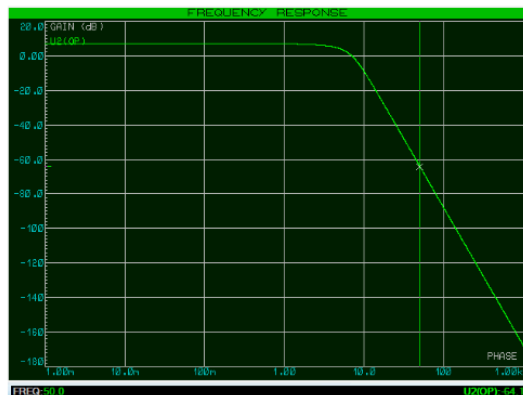
Figure 12 – Time Domain Result graph

Figure 15 is the simulated signal from the transducer, which shows the correct - 3.4mV to 6.8mV, also shown is the filtered, scaled, and amplified signal, using the scale on the right-hand side, a 0 - 5v range is shown.

The interference is also seen to be significantly reduced.

The input delay of the circuit has been measured as 78mS.

Frequency domain Results:



Shown in figure 13 is the filter response of the Sallen & key active filter using custom gain values determined earlier.

At 50Hz an attenuation of 64.1 dB is observed

Figure 13 – Frequency domain Results Graph

Discussion

Output:

Reviewing the output from the circuit the correct voltage range is present, measured to be 0 – 5 V.

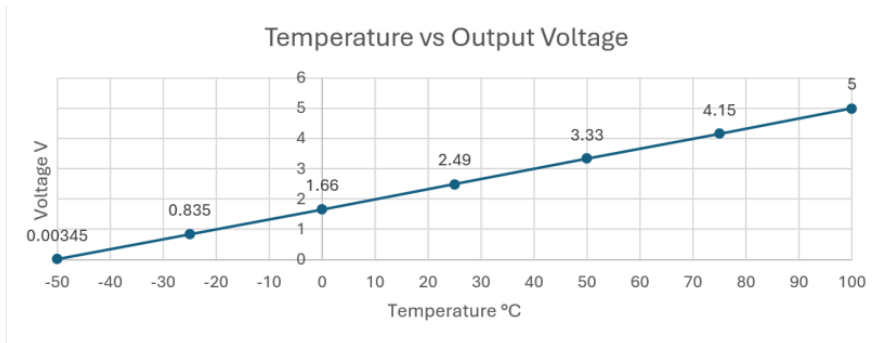


Figure 14 – Circuit output over complete temperature range

The circuit responds linearly to the increase in temperature from the simulated thermocouple, this is beneficial as any non-linearity introduced will directly affect any later circuitry and cause deviations from the correct value.

From Analyzing the circuits output, it can also be noted that there is little to no ripple introduced by the filtering stage, this is as expected as it was a key consideration whilst designing the filter.

Filtering:

Taking several readings of the output voltage with the thermocouple input steady, the variation caused by the noise at the output was measured on average as 12.67mV p-p this is better than the required 16.67mV p-p meaning the system can exceed the desired $\pm 0.25^{\circ}\text{C}$ accuracy. Depending on the exact application this will likely be ok, however, some systems may have the requirement for better accuracy, a 6th order Sallen & key filter would help improve this, but more components would be necessary and would also increase the systems response time.

Delay:

As previously mentioned, the response delay of the circuit is 78mS. This is adequate for the intended use case of the circuit as temperature is a slow-moving property and a control system will be able to deal with this level of input delay.

This circuit has comparable response delays to commercially available products such as the “PR Electronics 5437 Temperature Transmitter” which claims a 70mS response time [11]

OVP:

The OVP circuit proposed is capable of up to 34V, however any event greater than this will cause the current limiting resistor to exceed its power limit and ultimately fail. A possible solution to this could be to replace it with a PTCC (Poly Fuse), which will allow for a low impedance path under normal conditions, and an extremely high impedance under fault conditions [12].

Power Supply:

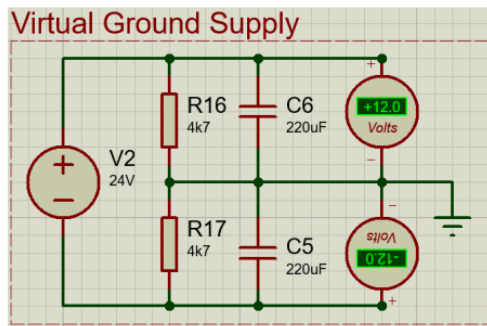


Figure 15 – Power supply

For the correct operation of this circuit a dual rail supply is necessary, $\pm 12V$ will be more than adequate to power the op-amps. These supply rails can be created easily from a 24V supply as this is a commonly available voltage in industrial control system [13] to create these voltages a split rail supply circuit will be used.

Adjustability:

As previously mentioned, it was desired to be able to adjust both the offset voltage and the gain, this was done by adding trimmer potentiometer.

In the gain stage this allowed for a range of 214 – 224, this allows for compensating for component tolerances.

However, in the offset stage introducing the resistive divider as the offset reference source caused issues as the differential amp loaded the output of the divider. The fix to this was to add a unity gain follower, which provided a lower impedance source of the reference voltage and fixed the issue introduced [4, P. 407].

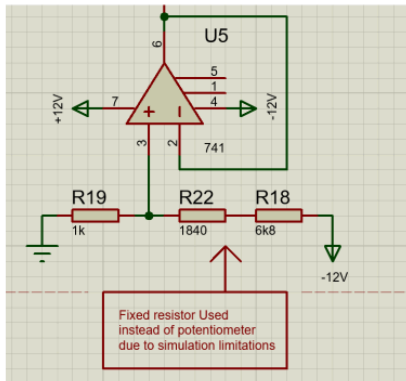


Figure 16 - Offset reference generator circuit.

Thermocouple Issues:

As previously disused the circuit is intended to work with a transducer input of -3.4mV to 6.8mV calculated using the specified $68\mu\text{V}/^\circ\text{C}$, however due to the non-linearity of thermocouples, the real input voltage would be -2.7mV to 6.3mV. The proposed circuit can be made to work with range by adjusting the gain potentiometer.

Conclusion

The circuit designed in this report successfully demonstrates a signal conditioning system for use with a thermocouple temperature transducer. The key features of the circuit are overvoltage protection (OVP), filtering, amplification, and level shifting. The circuits and components were decided upon through calculating required values and considerations of circuit cost and complexity.

The used 4th order Sallen & key filter provided an effective attenuation of 64.1dB reducing the influence of the 50Hz noise signal to below the desired maximum of 16.67mV p-p and allowed for an accuracy $\pm 0.25^{\circ}\text{C}$.

The filter made use of a custom response which was determined through testing Bessel, Chebyshev, and Butterworth to ensure maximum attenuation without introducing ripple into the output signal.

Further stages then amplified the signal to the correct 0 - 5 v range from the original - 3.4mV to 6.8mV transducer signal making uses of a non-inverting op amp, level shifting was then provided by a differential amp with adjustability from a trimmer potentiometer.

Over voltage protection was implemented with a simple diode clamping circuit which ensured protection for fault conditions up to 34V.

Alternative circuits for OVP, filtering and level shifting were reviewed and considered for use, such as making use of a PPTC resistor in the OVP circuit to allow for greater fault tolerance.

The circuit also showed good linearity with low ripple and a response time of 78mS, comparable to commercially available products, the circuit has also been designed to work with 24v for easy use with industrial automation systems where 24v is common.

References

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[13] V. Vaidya, "The Industrial Automation Power Dilemma: Part 1 - Industrial Control Architecture," Analog.com, Mar. 21, 2014. (accessed Nov. 25, 2024) <https://www.analog.com/en/resources/technical-articles/the-industrial-automation-power-dilemma-part-1--industrial-control-architecture.html>

Appendix

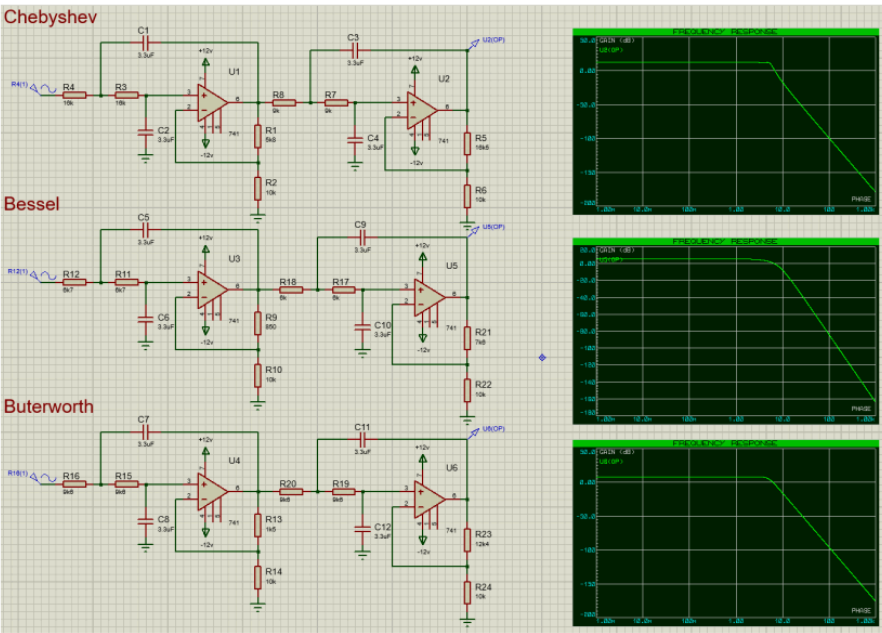


Figure 2 – filter response testing.

	Input resistor		Maximum Fault Voltage (V)
Resistance (Ohm)	2200		34.27
power Rating (W)	0.5		
	Clamping Diode		Maximum Fault Current (A)
Current Rating (A)	0.8		0.015
Forward Voltage (V)	1.1		

Figure 5 – OVP Calculations.

Scaling			
	Input (V)	Desierd Output (V)	Requierd Gain
High	1.60E-02	5	218.91
Low	-6.84E-03	0	
Range	2.28E-02	5	
Resistor	Resistor Values (Ohm)	E24 Fixed Resistor Values	Additional Resistor
R1	217914	180k + 33K = 213k	+ 10k Pot
R2	1000	1000	
	Potentiometer (10K)	Gain Range	
High	213000	214.00	
Low	223000	224.00	

(Figure 8 – Scaling Calculations)

Offset			
	Measured Output (V)	Desierd Output (V)	Requierd Offset (V)
High	3.745	5	1.245
Low	-1.245	0	Range Error (V)
range	4.99	5	0.01
	Resistor Values (Ohm)	E24 Fixed Resistor Values	Additional Resistor
R1	8639	6800	+ 5k Pot
R2	1000	1000	
Supply Voltage			
		-12	
	Potentiometer (5k)	Offset Voltage Range (V)	
High	11800	-0.94	
Low	6800	-1.54	

(Figure 10 – Offset Calculations)

Final Draft

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

87 /100

PAGE 1

PAGE 2

PAGE 3

QM

Misplaced apos.

Misplaced apostrophe:

An apostrophe can function to indicate a possessive when accompanied by an -s ("the book that belongs to Roy" = "Roy's book"). For words that already have an -s at the end, just adding the apostrophe will do ("the team belonging to the boys" = "the boys' team"). Certain exceptions to this rule apply, and possessive personal pronouns ("like ours," "yours," "hers," "his," "its") are possessive already and therefore do not take an apostrophe. It is always wrong to use a possessive apostrophe to simply make a word plural.



Comment 1

Excellent



Comment 2

Excellent



Comment 3

Excellent abstract

PAGE 4

QM

Not In Text

You have included a figure without mentioning it in the text. You should refer to the figure in the text, otherwise it is not worth including as the reader will not know what it relates to.

PAGE 5

PAGE 6



Comment 4

table 2?

QM

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PAGE 7

QM

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Comment 5

Good

QM

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PAGE 8



Comment 6

Too small to see the details.

QM

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Comment 7

Excellent

PAGE 9



Comment 8

How was this determined?



Comment 9

This seems a bit small. I was expecting a μF value here.

Your design has 3.3 μF capacitors in it, is this a typo?

**Comment 10**

Should there be an image for this caption? You would not usually use a caption for text in your report.

**Comment 11**

Should there be an image for this caption? You would not usually use a caption for text in your report.

**Graph not clear**

Graph is not clear.

Tip: make graphs smaller on screen before copying them, this will make the text larger and the information on them clearer.

**Comment 12**

Excellent work. Ensuring a linear response is key.

**Comment 13**

Well spotted.

GRADING FORM: SMU GENERIC_SMOSEY

GOMER MORGAN-GRAY

86.75

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.

4.5

KNOWLEDGE & UNDERSTANDING

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

-  Highly detailed knowledge and understanding of the main theories/concepts, and a critical awareness of the ambiguities and limitations of knowledge.

24

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.

-  "Exceptional work; judiciously selected and evaluated evidence. Very high quality analysis, developed independently or through effective collaboration.
Ability to investigate contradictory information and identify reasons for contradictions.
Highly persuasive conclusions

27

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



Outstanding levels of application and deployment skills. Assimilation and development of cutting edge processes and techniques.

27

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.

4.25