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# E344 Assignment 1

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Report submitted in partial fulfilment of the requirements of the module Design (E) 344 for the degree Baccalaureus in Engineering in the Department of Electrical and Electronic Engineering at Stellenbosch University.

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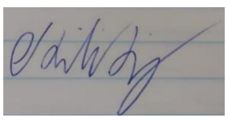
| 21739064<br>Studentenommer / *Student number* | <br>Handtekening / *Signature* |
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# Nomenclature

### Variables and functions

| | |
|---|---|
| $R$ | Resistance |
| $i$ | Current |
| $P$ | Power |
| $A$ | Amperes |
| $V$ | Voltage |
| $\Omega$ | Ohms |
| $s$ | Seconds |
| $F$ | Farad |
| $H$ | Henri |
| $W$ | Watt |
| $C$ | Celsius |

## Acronyms and abbreviations

| | |
|---|---|
| op-amp | Operational amplifier |
| ADC | Analog to digital converter |
| Vpp | Voltage peak to peak |
| DC | Direct current |
| AC | Alternating current |
| LPF | Low-pass filter |
| Av | Gain |

# Chapter 1

# Introduction

A temperature sensor is used in the design of a health device. The analog output of the sensor is to be interpreted by a micro-controller. However, the voltage range of the temperature sensor is too small to be accurately interpreted by an ADC. The micro-controller has an input range from 0-5 V. Therefore, an operational amplifier circuit is to be built to manipulate the signal from the temperature sensor to be easily processed by the micro-controller. This report will show the design and results of the circuit shown in figure 1.1 that achieves this goal.

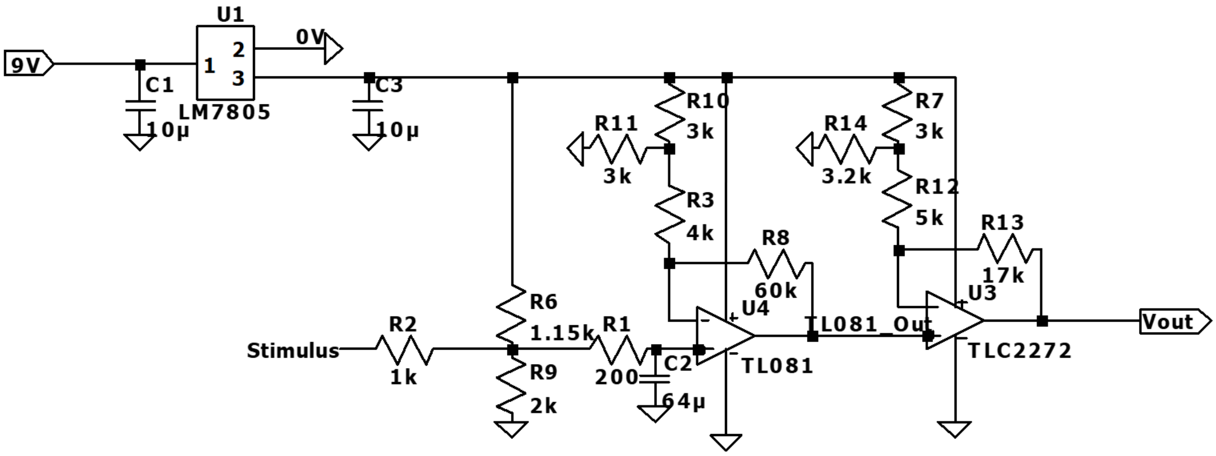


**Figure 1.1:** Circuit Diagram

The requirements for the temperature sensor is to have an output voltage range of $3.2V$ but optimally $3.5V$. The circuit must not draw more than $25mA$ but ideally less than $15mA$ from a 9V battery. The output must have a step response of under $100ms$. The output must cancel noise from the input such that there is no more than 80mVpp of noise, however less than 50mVpp is ideal.

# Chapter 2

# Voltage regulation

To achieve the 0-5V range we will use a 0V and a 5V rail for the op-amp circuit. To do this we need to regulate the voltage from 9V to 5V. There are two main options to consider; the switchmode regulator and the linear regulator (see figure 2). The switch mode regulator has a great power efficiency and a low current draw, as it will only draw as much current that is needed to supply the output current. This comes with two major drawbacks. Firstly, it is far more complex and will increase the cost of the circuit and the area required. Secondly, the switch-mode regulator creates significant noise. The linear regulator on the other hand has a significantly worse power efficiency and higher current draw. However, the linear regulator has a lower cost of complexity, simpler to use and creates no noise. This is extremely important with temperature measurements, since the false reading of temperature of even 1 $^{\circ}$C on a person is a significant problem. The linear regulator has a larger power usage which is not ideal for portable devices. The maximum input voltage range for the linear regulator before breaking or dropping out is 6.3V - 30V. For the switch mode regulator it is 5-45V. The maximum power rating for the linear regulator is $750mW$.

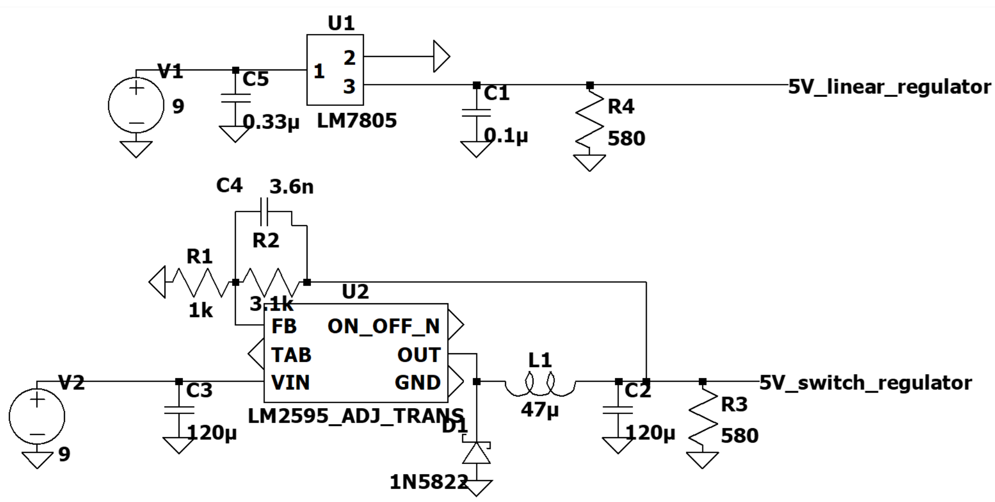


**Figure 2.1:** Linear and switch-mode voltage regulation circuits

Designing a linear voltage regulator is rather simple. A LM7805 voltage regulator is used to regulate down to 5V [1]. Then adding the standard input capacitor of 0.33u and output capacitor of 0.1u [1]. The switch-mode regulator is more complex to design. Firstly the variable output configuration is used to ensure a stable output of 5V. To design for 5V, the equation $R2 = R1(Vo/Vref - 1)$ is used to design for the bias resistors, where R1 is $1k\Omega$ and $Vref = 1.23V$ [2]. Therefore, $R2 \approx 3.1k\Omega$. For the voltage drop of 4V from 9V to

5V two 120uF capacitors are used at the input and output [2]. A 3.6nF capacitor is used corresponding to the 5V output voltage [2]. With the assumption of a maximum input voltage of 10V a 47uH inductor is chosen [2]. The linear regulator has a current draw of 13.8$mA$ to power the amplification circuit, where as the switch mode has a draw of only 5.8$mA$. The switch-mode regulator has significantly less current draw. The circuit draws 8.6mA and the output power is then $8.6mA * 5 = 43mW$. The power efficiency can be calculated with the equation $Peff = Pout/Pin$. The efficiency of the linear regulator is then 35% and the swtichmode regulator is 82% efficient. This shows that the switch-mode regulator is far more power efficient than the linear regulator. The switchmode regulator creates noticeable noise due to its use of a internal oscillator. When a perfect 9V DC supply is connected to the regulator it creates a sinusoidal noise output. Figure 2.2 shows the output difference between the switch mode and linear voltage regulation. A low noise output is very important as small variation will be amplified through the circuit along with the wanted DC component and will decrease the reliability of the device.

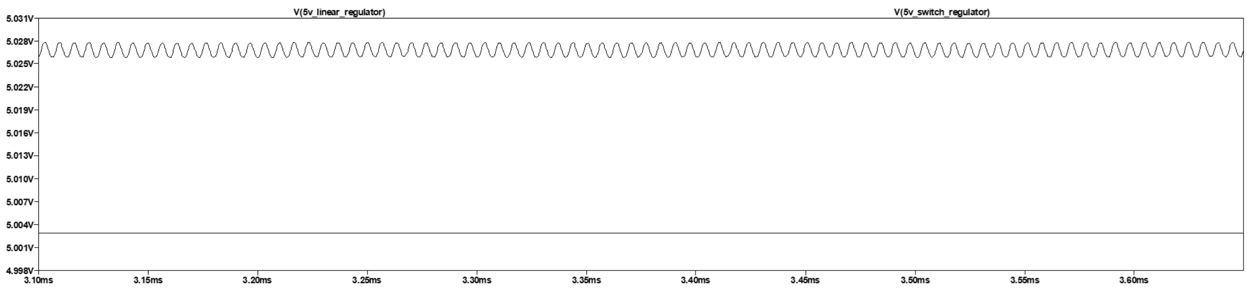


**Figure 2.2:** noise response : switch-mode vs linear regulation

The final choice is made to use the linear voltage regulator. This is due to its stable nature and it is significantly cheaper and less complex to use. Even though it has a higher current draw of 13.8$mA$, it is within the advanced requirements and, therefore, it is worth sacrificing a bit of power for simplicity of design, cost and lack of noise.

## 2.1. Summary

The two voltage regulators work as expected and meet the requirements of this project, even though there are substantial differences in power usage and usability. If the total current draw of the device is too large for the battery specifications when combining the temperature sensor with the rest of the system, the switch regulator will be used. If this is the case, the circuit will have to be partially redesigned to compensate for the introduced noise.

# Chapter 3

# Operational amplifier circuit design

The goal of the operation amplifier is to have the largest voltage range possible and to remove the noise that the heat sensor creates. The analog output specifications are given as 0 $^{\circ}$C the output is 660mV and for every $^{\circ}$C increase the voltage increases by 25mV. The range we are interested in is the temperature range of human skin - 34 to 42 $^{\circ}$C will suffice. The voltage range can then be calculated as $660 + 25 * 34 = 1.51V$ and $660 + 25 * 42 = 1.71V$. The range is then from 1.51V to 1.71V. We can expect noise to come from the temperature sensor and we can model it as a 50Hz 1$^{\circ}$C variation. The signal can be modelled as shown in figure 3.1.

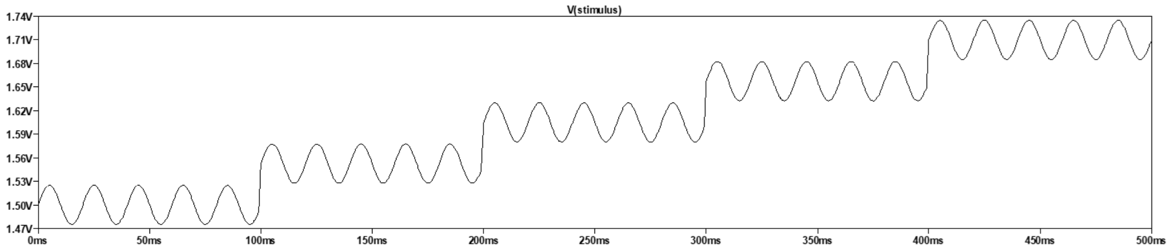


**Figure 3.1:** Temperature sensor output: Stimulus

## 3.1. Design

The input voltage range has to be manipulated to the full range of 0 - 5V for the micro-controller. First, we must shift the input range to the middle of our required output voltage range. This can be done using the JFET-Input operational amplifier TL081. It is low cost and accurate, but it does not have a large voltage range and so we cannot amplify to the required range using only this op-amp [3]. Figure 3.2 shows the full voltage range of 1.57V - 3.47V of the TL081 op-amp.

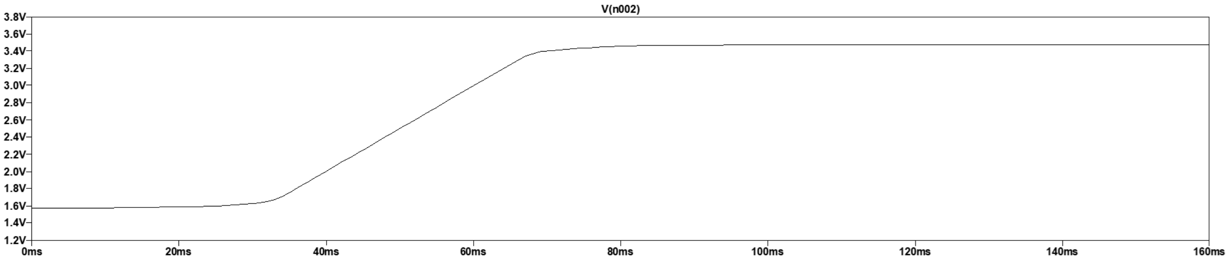


**Figure 3.2:** TL081 output range

The input signal needs to be centralized in the middle of the op-amp's output voltage range. However, the input voltage is found to be around 1.6V. The op amp will be designed using a virtual ground. If the signal is assumed to be received at 0V and we have a -2.5V and 2.5V rail for the op-amp, then the op-amp can be designed accordingly. Now the ground reference is shifted up by 2.5V. Ground connections are replaced by 2.5V sources that are created by using voltage division from the 5V source. The 1.6V input is shifted to 2.5V by using bias resistors as shown at the input of the circuit - where the ratio of the resistors is $2.5/1.5 = (R6/R9) = 1.66$. If R9 is chosen as a $2k\Omega$ resistor, then R6 is equal to $1.2K\Omega$. This is adjusted slightly to $1.15K\Omega$. The TL081 amp is used to amplify the input as much as possible within its voltage range. If The maximum output range of the op-amp is $3.47 - 1.57 = 1.9V$, then the maximum gain is $1.9V/(1.71 - 1.51) = Av \approx 10$. Av can be calculated as R3/R8. If R3 is $4k\Omega$, then R8 will be $40k\Omega$. However, R8 can be increased to $60k\Omega$ before coming close to the rail. The output of this stage is a amplified version of the input centred around 2.5V. Now the signal range is increased further through the use of the more expensive rail to rail op-amp TLC2272, which has a very large output range of 9.1mV - 4.4V as shown in figure 3.3 [4]. The design of this op-amp is the same as the precision op-amp except the input is already centred around 2.5V. A gain of 3.5 is required to achieve the maximum voltage range possible without risk of clipping. R12 is chosen as $5k\Omega$ and R13 is calculated as $5k * 3.5 \approx 17k\Omega$.

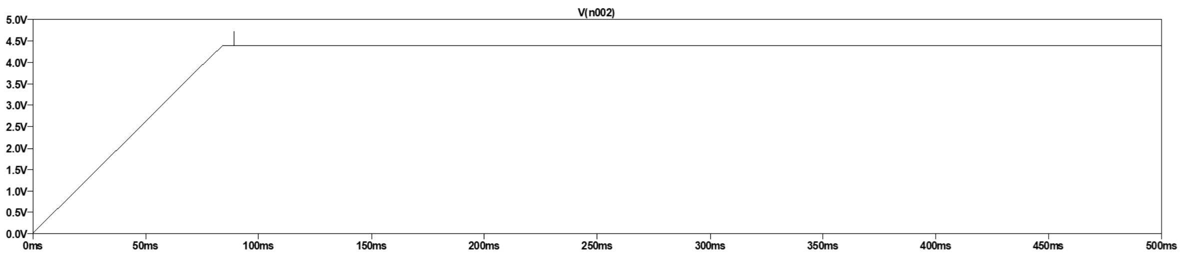


**Figure 3.3:** TLC2272 output range

## 3.2. Noise cancellation and rise time

Now noise cancellation has to be inter grated into the circuit. The goal is to achieve less than 80mV of noise while maintaining a step response under $100ms$. The initial choice would be to create a LPF using multiple op-amps which would be able to obtain this. However, a simpler solution can be used while obtaining similar results which will keep the complexity low. This is done by using a simple RC low-pass filter. The LPF is placed at the input of the first op amp. It is placed at the input and not at the output for two reasons. Firstly, if the noise is canceled before the amplification process it is easier to ensure a maximum voltage range without worrying about clipping due to noise. Secondly, The filtration will happen at a lower voltage range. This means that a smaller capacitor can be used to save space, which is important for a portable device. The step response of this system is shown in figure 3.4a. The step response can be calculated as the time it takes to reach 90% of its final value. For a step input of 1.5-1.5525V the step response is shown in figure 3.4. The rise time is therefore at the voltage $90\% * 1.91 = 1.82V$ which corresponds to a rise time of

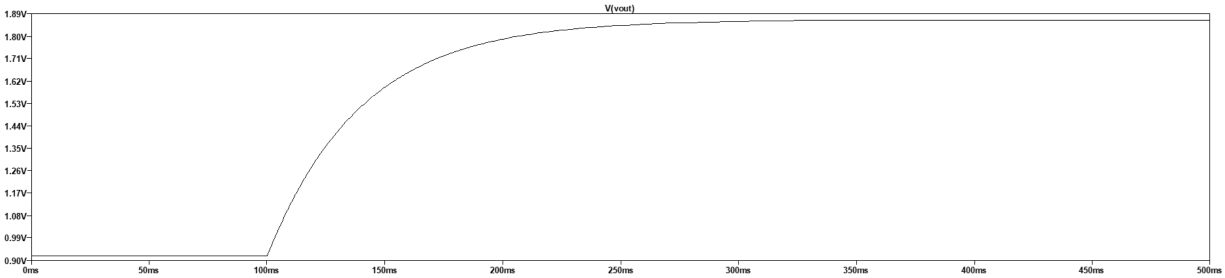


**Figure 3.4:** Rise time

The noise output of the system is shown in figure 4.5. The sinusoidal peak to peak voltage is 70mV which meets the standard requirements.

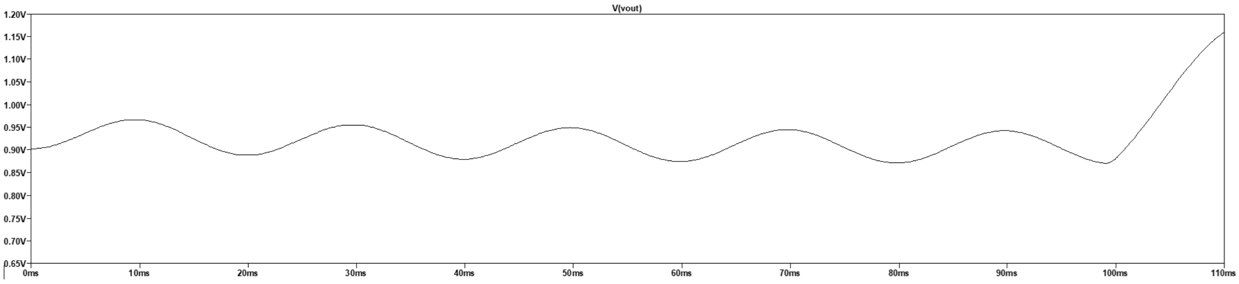


**Figure 3.5:** Noise output

## 3.3. Final output

The final output of the amplification circuit powered by a 9V source is shown below in figure 3.6. The full voltage range is from 880mV to 4.5V. This corresponds to a voltage range of 3.62V which satisfies the advanced requirements.

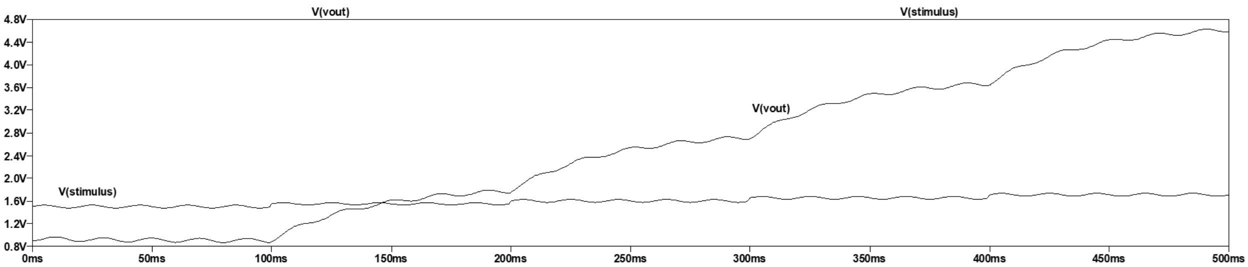


**Figure 3.6:** Input vs output

## 3.4. Summary

The design works to my expectations and have met all requirements. However, the noise reduction was not able to be reduced below the advanced requirement of 50mVpp without the rise time of over 100ms. If an input outside of the range of 34 - 42 $^{\circ}$C is measured, the circuit will hit the rails and the output will be completely unreliable.

# Chapter 4

# System and conclusion

## 4.1. System

The linear voltage regulator will regulate the 9V source to 5V for the op-amp circuit. The analog output of the sensor will be manipulated such that it will be easily received by the micro-controller. The output range is large enough to achieve this. If the noise reduction is not sufficient, the problem can be solved in software by using a mathematical LPF which will not impede on the rise time as much.

## 4.2. Lessons learnt

The benefits of being able to link mathematical expressions and theory directly to LTspice, and see real time results, are very useful in the design process. The importance of a low simulation time, and the benefit this gives in saving time during design, was learnt. The basics of how to use LaTeXwas obtained and the capacity will be further explored.

# Bibliography


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[2] T. instruments, “Lm2595 simple switcher® power converter 150-khz 1-a step-down voltage regulator,” 2016.

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# Appendix A

# Social contract

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E-design 344 Social Contract

2020

The purpose of this document is to establish commitment between the student and the organisers of E344. Beyond the commitment made here, it is not binding.

In the months preceeding the term, the lecturer (Thinus Booysen) and the Teaching Assistant (Michael Ritchie) spent countless hours to prepare for E344 to ensure that you get your money's worth and that you are enabled to learn from the module and demonstrate and be assessed on your skills. We commit to prepare for the module, to set the tests and assessments fairly, to be reasonably available, and to provide feedback and support as best and fast we can. We will work hard to give you the best opportunity to learn from and pass analogue electronic design E344.

Signature: .............................. Date: 13 July 2020

I, Philip Kirby have registered for E344 of my own volition with the intention to learn of and be assessed on the principals of analogue electronic design. Despite the potential publication of supplementary videos on specific topics, I acknowledge that I am expected to attend the lectures and lab sessions to make the most of these appointments and learning opportunities. Moreover, I realise I am expected to spend the additional requisite number of hours on E344 as specified in the yearbook.

I acknowledge that E344 is an important part of my journey to becoming a professional engineer, and that my conduct should be reflective thereof. This includes doing and submitting my own work, working hard, starting on time, and assimilating as much information as possible. It also includes showing respect towards the University's equipment, staff, and their time.

Signature: .............................. Date: 15/08/2020

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# Appendix B

# GitHub Activity Heatmap