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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.

August 16, 2020

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Nomenclature

Variables and functions

V^+	Operational amplifier non-inverting input
V^-	Operational amplifier inverting input

Acronyms and abbreviations

Op Amp	Operational Amplifier
LPF	Low-pass Filter

Chapter 1

System design

1.1. System overview

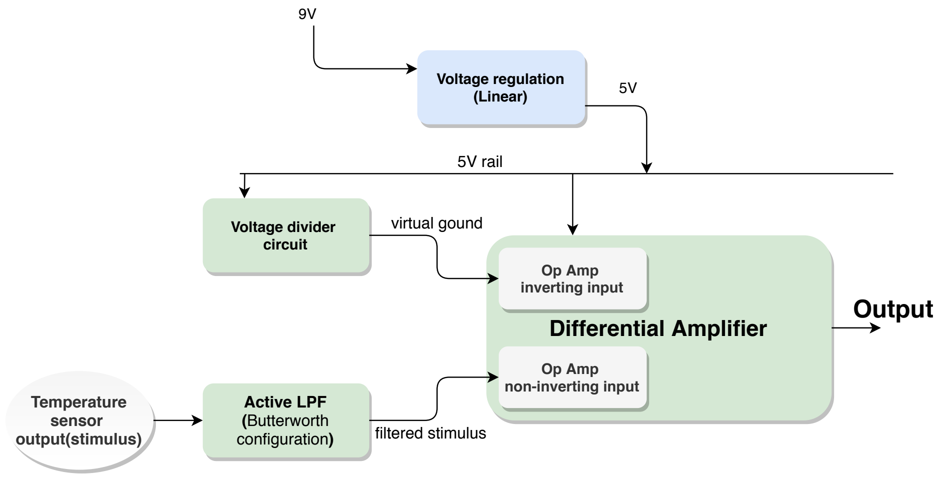


Figure 1.1: System diagram

The purpose of this design is to implement a signal conditioning circuit for an analogue temperature sensor. The **voltage regulator** shall provide a regulated 5V supply to the circuit from a nominal 9V power. An Op Amp circuit in a **differential amplifier** configuration is used: It provides a gain and removes a dc offset from the sensor output(stimulus) and thus, amplifies it from millivolts to volts while staying within the recommended output voltage range. In order to remove the dc offset from the stimulus and establish a virtual ground -given that only a positive voltage rail shall be used to power the Op Amp- a **voltage divider**(a resistors circuit) is used. Before feeding the stimulus to the amplifier, it is first filtered using an **active low-pass filter** in the Butterworth configuration. The filter shall suppress noise from the stimulus by attenuating components at 50Hz and above.

1.2. Rationale

A linear regulator was chosen over a switching mode regulator due to the low noise levels on its output despite the switching regulator being more power efficient.
A second order Butterworth low-pass filter has low noise levels, relatively short settling time and a sharp drop-off gradient after the cut-off frequency(approximately 40db/dec): these characteristics make it an ideal choice for a filter given that noise need to be suppressed from the stimulus at 50Hz without attenuating the dc components.

Chapter 2

Voltage regulation

2.1. Introduction

This section deals with the power conditioning of the circuit. Two alternatives were available; namely a linear voltage regulator, the LM7805 or a switching mode regulator, the LM2595. The linear regulator's resistance varies according to the load and results in a constant output voltage. Conversely, switching regulators rapidly switch a series element(FETs) on and off. These devices store the input energy temporarily and then release that energy to the output at a different voltage level. [1]
The following subsection documents the rationale followed in the choice of the regulator.

2.2. Design

In order to pick which one of the regulators in the design, both the linear and switching mode regulators were implemented with additional circuitry and their respective performances were compared.

- **Linear regulation**
  The circuit diagram is illustrated in figure 2.1 bellow. Capacitors C1 and C2 are used to smooth out noise on the 9V input supply and the 5V regulated output, respectively.

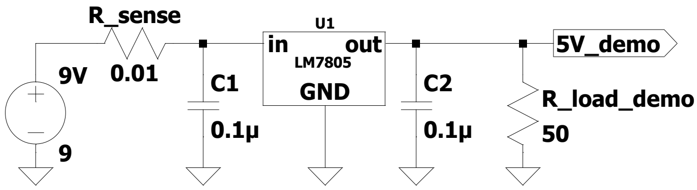


Figure 2.1: Linear regulator circuit diagram

  Capacitors C1 and C2 values, 0.1 µF each, were selected as suggested in the LM7805 data sheet specifications for typical applications circuits for a minimal noise linear regulation. [2]

- **Switch mode regulation**
  The circuit diagram as derived from the LM2595 data sheet [3], is illustrated in figure 2.2 bellow.

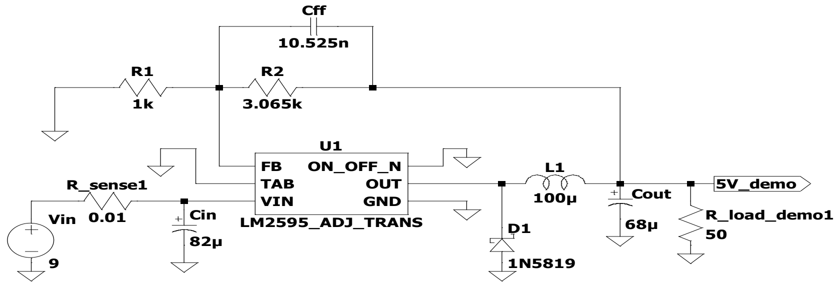


Figure 2.2: Switchmode regulator circuit diagram

The configuration is for an adjustable output voltage and it was preferred to a fixed output voltage for more flexibility.
In both the linear and switching regulator evaluations, a resistive load, $\mathrm{R}_{\mathrm{load\_demo}}$ was used to draw 100mA from the 5VDC side. Hence, $\mathrm{R}_{\mathrm{load\_demo}} = \frac{5V}{100mA} = 50\,\Omega$
• R_1 and R_2:
$R_1 = 1\,\mathrm{k}\Omega$, $R_2 = R_1\left(\frac{V_{\mathrm{OUT}}}{V_{\mathrm{REF}}} - 1\right)$, where $V_{\mathrm{REF}} = 1.23\,\mathrm{V}$.
$\therefore R_2 = 3,065k\Omega$
These two resistors set the output voltage value to the required 5V.

• Catch Diode D1: A Schottky diode, the 1N5819 was picked due to its fast switching speed and low forward voltage drop.

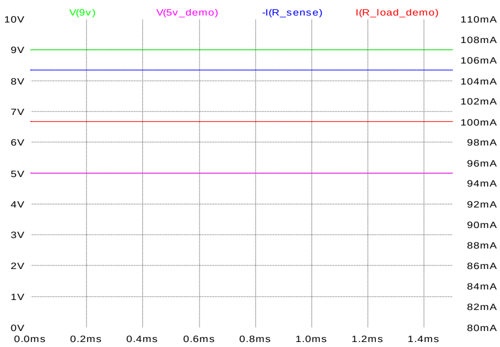
• Capacitors C_{in} and $\mathrm{C}_{\mathrm{out}}$ values were selected following the quick design table for a 5VDC output [3].

• FeedFoward Capacitor C_{ff}: Although this capacitor is only required for an output voltage greater than 10V, adding it substantially reduces noise levels at the regulator output, hence it was retained in the design. $\mathrm{C}_{\mathrm{ff}} = \frac{1}{31\times10^3\times\mathrm{R}_2}$
$\therefore \mathrm{C}_{\mathrm{ff}} = 10.5\,\mathrm{nF}$

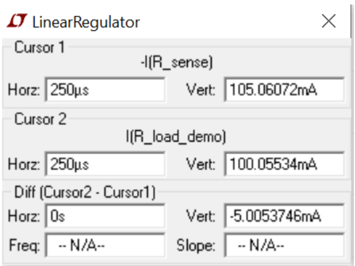
• L1: from the given formula $\mathrm{E}\cdot\mathrm{T} = (\mathrm{V}_{\mathrm{IN}} - \mathrm{V}_{\mathrm{OUT}} - \mathrm{V}_{\mathrm{SAT}})\cdot\frac{\mathrm{V}_{\mathrm{OUT}}+\mathrm{V}_{\mathrm{D}}}{\mathrm{V}_{\mathrm{IN}}-\mathrm{V}_{\mathrm{SAT}}+\mathrm{V}_{\mathrm{D}}}\cdot\frac{1000}{150\mathrm{kHz}}(\mathrm{V}\bullet\mu\mathrm{s})$, where $\mathrm{V}_{\mathrm{SAT}} = 1\mathrm{V}$ and table 30 in the data sheet [3], L1 value was chosen to be $100\,\mu\mathrm{F}$.
With the linear and switchmode regulators designed as above, a 5VDC regulated output was expected through simulations. The following subsection documents the obtained results.

2.3. Results

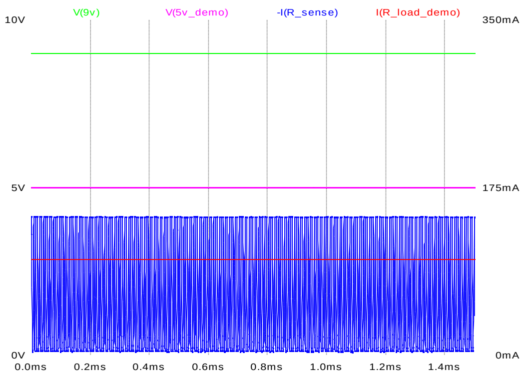
To select the adequate regulator(linear or switchmode), simulations were performed on the above two designs in order to asses their conformity to the expected results as well as the output noise levels and power efficiencies. Figure 2.3 bellow illustrates the simulation results:



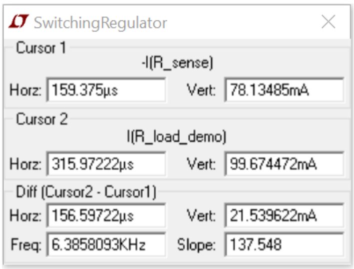
(a) Linear regulator input and output voltages and currents



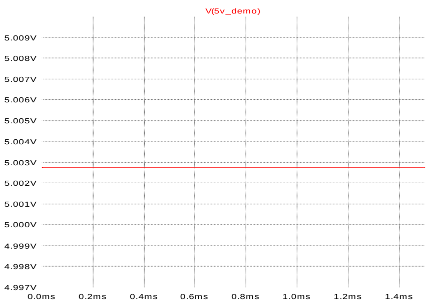
(b) cursor currents values



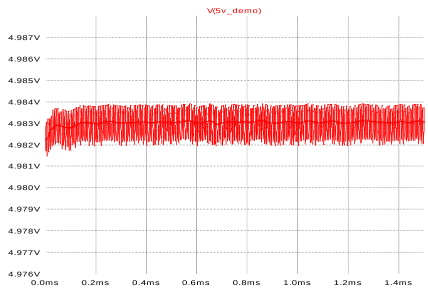
(c) Switchmode regulator input and output voltages and currents



(d) cursor currents values



(e) Linear regulator output noise level



(f) Switchmode regulator output noise level

Figure 2.3: Voltage regulation, comparing the linear and Switchmode regulators

In addition, the difference between the input and output currents vary between the two regulator, which causes their power efficiency to differ.
Efficiency and power calculations as well as dropout voltages comparison are illustrated in table 2.1 bellow.

Regulator	Input Voltage	Input Current	Input Power	Output Voltage	Output Current	Output Power	**Efficiency**	**Dropout Voltage**
Linear	9VDC	105.06mA	945.547mW	5.003VDC	100mA	500.3mW	**52.91%**	**2V**
Switchmode	9VDC	60.23mA(rms)	560.03mW	5.00VDC	100.01mA	501.5mW	**89.55%**	**0.1V**

Table 2.1: Efficiency and power calculation

2.4. Summary

As expected, both the liner and switching mode regulators output 5VDC with 100 mA into the 50 Ω demo load. However, the switching mechanism in the switchmode regulator introduces lots of noise(approximately 1.61 mVpp) on its output despite the regulator's high efficiency(89.55%) and very low dropout voltage (0.1 V). Inversely, the linear regulator has very low output noise levels (practically none) but with low efficiency (52.91%) and relatively high dropout voltage (2 V), meaning the input voltage needs to be at least 7 V for the regulation to occur. Given its low output noise levels, the liner regulator was preferred to the switchmode one. In addition, despite the linear regulator low efficiency, the power loss is approximately 445.25 mW for the 100 mA output current. A thermal analysis in the above condition resulted in a junction temperature of 53.94°C which is way smaller than the the 125°C maximum rated. Keeping in mind that the circuit will operate at less than 50 mA output current, we can thus expect less power loss in the linear regulator.

Chapter 3

Temperature sensor conditioning circuit

3.1. Intro

This section documents the design of the of the temperature sensor conditioning circuitry. It includes a differential amplifier and an active low pass filter.

3.2. Design

3.2.1. Low Pass Filter design

An active low pass filter in the Butterworth configuration was selected. It has a fast step response as well a steep amplitude drop-of gradient after the corner (3dB) frequency. The circuit digram is illustrated in figure 3.1 bellow.

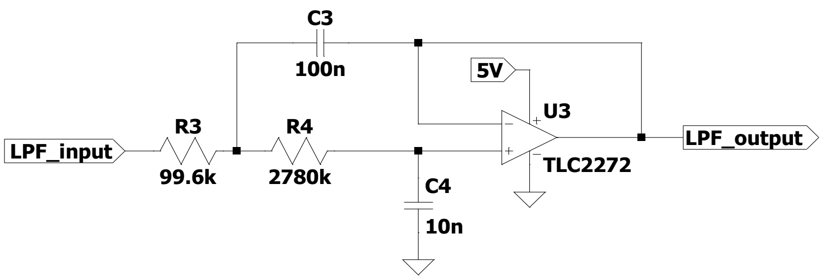


Figure 3.1: Low Pass Filter circuit diagram

Designing the above circuit involved selecting values for capacitors C3 and C4 and resistors R3 and R4 for a corner frequency of 5Hz. Given that it's a second order low pass filter we can thus expect the signal at 50Hz (10 times the corner frequency) to be attenuated by -30 to -40dB. With a -30dB attenuation, the 15mV amplitude (corresponding to 1°C as per specifications) noise signal will be attenuated to 0.5mV amplitude. Given that the differential amplifier has a gain of 41, this will ensure that the gain at the final output is at most $41 \times 0.5\text{mV} = 20.5\,\text{mVp}$ which is smaller than the required $80\,\text{mVp}$.

•Select $C4 = 10\,\text{nF}$; then choose $C3 = 10 \times C4 = 100\,\text{nF}$ for a faster step response.

•Select $R4 = 2780\,\text{k}\Omega$; With C4, C3 and R4 fixed, the only degree of freedom left is on R3, which is computed below for a 5Hz cut-off frequency:

$\mathrm{f}_c = \frac{1}{2\pi\cdot\sqrt{c_3 R_3 c_4 R_4}}$

$R_4 = \frac{1}{\mathrm{f}_c^2\cdot(2\pi)^2 c_3 R_3 c_4} = \frac{1}{5^2(2\pi)^2\cdot 100.10^{-9}\cdot 10\cdot 10^{-9}\cdot 2780.10^3}$

$\therefore \quad R_4 = 99,6k_\Omega$, resulting Bandwidth: 5Hz and rise time of approximately 83.91 ms.

3.2.2. Differential Amplifier design

A non inverting differential amplifier configuration was used. The circuit features a reference voltage or virtual ground, used given that only a positive supply was used to power the amplifier. The circuit diagram is illustrated in figure 3.2 bellow:

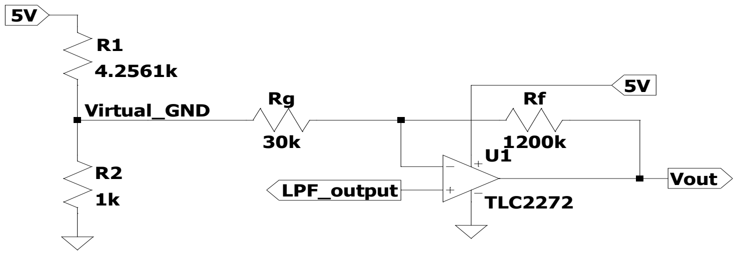


Figure 3.2: Differential Amplifier circuit diagram

•Rf and Rg: for amplifier gain

Input range: 930mV(34°C) to 1050mV(42°C) or 120mV swing. Targeted output range: 0.1 to 4.9V or a 4.8V swing. Hence gain $\alpha = \frac{4{,}8\mathrm{V}}{120\mathrm{mV}} = 40 = \frac{\mathrm{R}_f}{\mathrm{R}_G}$

Select $\mathrm{R}_f = 1200\,\mathrm{k}\Omega$ (large enough to limit current consumption), hence, $\mathrm{R}_g = \frac{1200\,\mathrm{k}\Omega}{40}$

$\therefore \quad \mathrm{R}_g = 30\,\mathrm{k}\Omega$

•R1 and R2: for virtual ground design

V^+ and V^- symbols used bellow correspond to the inverting and non-inverting inputs of the Op Amp respectively.

KCL at V^-: $\frac{\mathrm{V}^- - \mathrm{V}_{\mathrm{virtual\_GND}}}{R_G} + \frac{\mathrm{V}^- - \mathrm{V}_{\mathrm{out}}}{R_f} = 0$

$\therefore \mathrm{V}_{\mathrm{out}} = \left(\frac{\mathrm{R_f}}{\mathrm{R_G}} + 1\right)\mathrm{V} - \frac{\mathrm{R_f}}{\mathrm{R_G}} \cdot \mathrm{V}_{\mathrm{virtual\_GND}}$

$\mathrm{V}^- = \mathrm{V}^+ = \mathrm{V}_{\mathrm{LPF\_out}}$ (Ideal Op Amp)

$\therefore \mathrm{V}_{\mathrm{out}} = \left(\frac{\mathrm{R_f}}{\mathrm{R_G}} + 1\right) V_{\mathrm{LPF\_out}} - \frac{\mathrm{R_f}}{\mathrm{R_G}} \cdot \mathrm{V}_{\mathrm{virtual\_GND}}$

The goal is to remove the DC component from the amplifier input $V_{\mathrm{LPF\_out}}$, 990mV corresponding to 38°C and introduce a 2.5VDC offset at the output for an optimal output swing.

$\therefore \left(\frac{\mathrm{R_f}}{\mathrm{R_G}} + 1\right) \cdot \mathrm{V_{DC}} - \frac{\mathrm{R_f}}{\mathrm{R_G}} \cdot \mathrm{V}_{\mathrm{virtual\_GND}} = 2,5$

$\therefore \left(\frac{1200}{30} + 1\right) \cdot 0,990 - \frac{1200}{30} \cdot \mathrm{V}_{\mathrm{virual\_GND}} = 2,5$

$\therefore \mathrm{V}_{\mathrm{virual\_GND}} = 0.9525\,\mathrm{V}$

Select $\mathrm{R}_1 = 1\,\mathrm{kV}$

$\mathrm{V}_{\mathrm{virtual\_GND}} \quad = \frac{\mathrm{R}_1}{\mathrm{R}_1 + \mathrm{R}_2} \cdot 5$

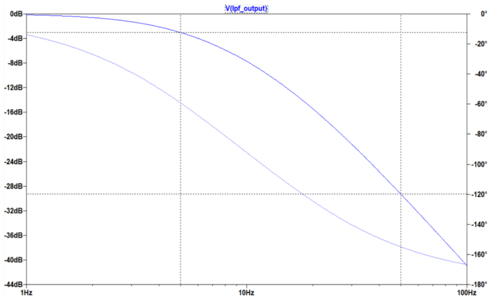
$\therefore \quad 0,95225 = \frac{1000}{1000 + R_2} \cdot 5$

$\therefore \quad \mathrm{R}_2 = 4,2561\mathrm{k}\Omega$

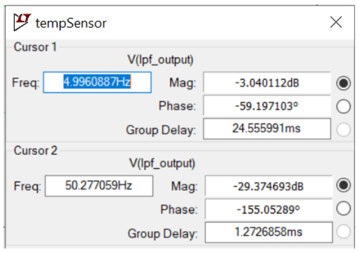
In addition, with $\mathrm{V}_{\mathrm{virtual\_GND}} = 0.9525\,\mathrm{V}$, the voltage at V^- will be at most be $0.9525\,\mathrm{V}$ and the voltage at V^+ will vary between $930\,\mathrm{mV}$ and $1052\,\mathrm{mV}$ -corresponding respectively to 34°C and 48°C plus noise- Hence, VIN_min $= 930\,\mathrm{mV}$ and VIN_max $= 1052\,\mathrm{mV}$; This falls well within the TLC2272 common-mode input voltage range of -0.3 to 4V [4].

3.3. Results

Figures 3.3, 3.4, 3.5, 3.6 and 3.7 bellow documents the simulation results for both the Low-pass filter and the differential amplifier.



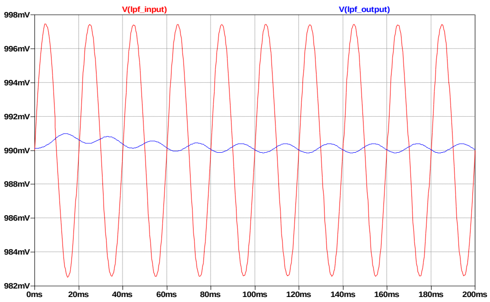
(a) LPF bode plot



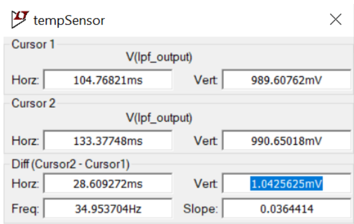
(b) corner frequency

Figure 3.3: Bode plot: corner frequency and amplitude response at 50Hz

As designed for, the bandwidth(corresponding to the corner frequency) is 5Hz and the attenuation at 50Hz is -29.37dB(close to the expected -30dB).



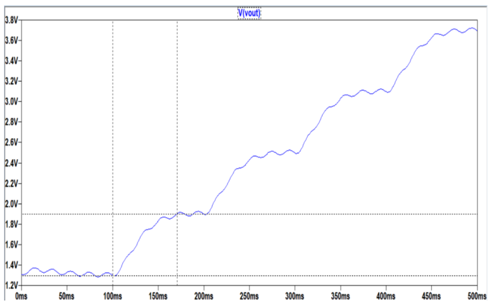
(a) LPF input and output



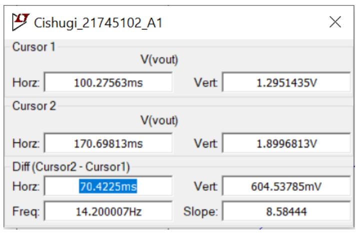
(b) output amplitude

Figure 3.4: Low-pass filter noise suppression simulation results

As illustrated in figure 3.4 above, a 15 mV amplitude noise signal (corresponding to 1°C) is attenuated to 1 mVpp. After amplification, with a gain of 41, the noise will thus be only 41 mVpp or 20.5 mVp, meeting the ”bellow 80 mVp requirement”.



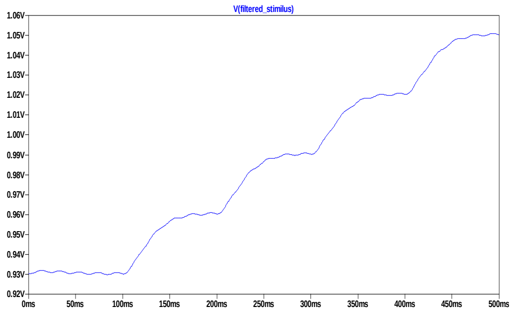
(a) final output volatge



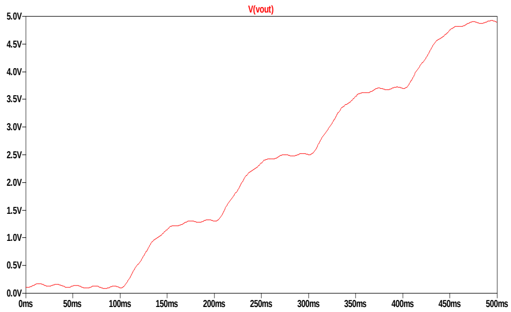
(b) settling time

Figure 3.5: Low-pass filter rise time simulation results with the differential amplifier included

As illustrated in figure 3.5 above, the LPF rise time is 70.42 ms which is even better than the 83.91 ms designed for. The plot illustrates a 1°C step in temperature from 36°C to 40°C(not full range, just for demonstration) and after each step, the rise time is 70.42 ms which meets the "bellow 100 ms settling time".



(a) Op Amp input range



(b) Op Amp output range

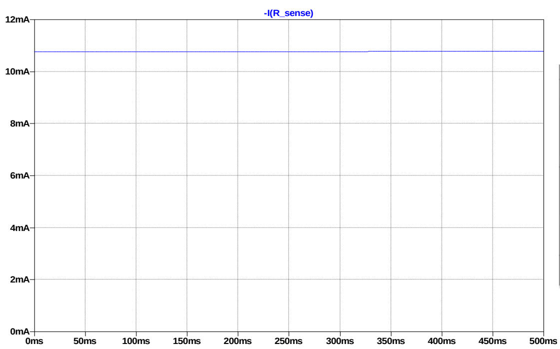
Figure 3.6: Full Op amp input and output range simulation results

Table 3.1 bellow records the measured full input and output ranges as well as the measured output voltages corresponding to temperatures between 34°C and 42°C.

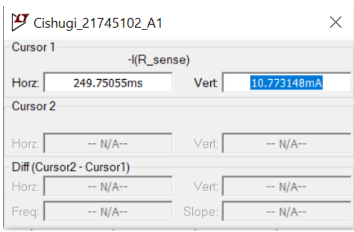
T °C	34	35	36	37	38	39	40	41	42	**Full range**
Stimulus (mV)	930	945	960	975	990	1005	1020	1035	1050	**120 mV**
Vout (V)	0.1	0.7	1.3	1.9	2.5	3.1	3.7	4.3	4.9	**4.8V**

Table 3.1: measured full Op Amp input and output ranges

Hence, as designed for, VIN_max is 1050 mV and VIN_min is 930 mV.
Figure 3.7 bellow illustrates the total average current used by the temperature sensor circuit.



(a) Total current



(b) Total current value

Figure 3.7: Total average current of temperature sensor circuit

Hence, the total average current used by the circuit is 10.77 mA, which is smaller than the 25 mA required threshold.

3.4. Summary

The Low pass filter successfully suppressed the noise and the differential amplifier produced a 4.8V range as designed for while the total current consumption stayed bellow 11mA.

Chapter 4

System and conclusion

4.1. System

Overall, the full circuit works as designed considering the simulation results in the previous sections. The liner regulator outputs a 5VDC with very little to no noise and supplies it to the active low pass filter and the differential amplifier circuit. These together form a temperature sensor, the first building block of the health monitor system. This part alone of the system draws an average of 10.77mA from the 9V supply, leaving (100mA - 10.77mA) = 89.23mA for the rest of the system. Using table 4.1 below, the calibration constant for the temperature sensor can be derived:

T °C	34	35	36	37	38	39	40	41	42
Stimulus (mV)	930	945	960	975	990	1005	1020	1035	1050
Vout (V)	0.1	0.7	1.3	1.9	2.5	3.1	3.7	4.3	4.9

Table 4.1: Temperatures and corresponding output voltages

$\therefore \mathrm{T}\ {}^{\circ}\mathrm{C} = \frac{5}{3} \cdot \mathrm{V_{out}} + \frac{203}{6}$

After calibration, the temperature value will be rounded to the nearest integer using quantisation.

4.2. Lessons learnt

•The theory behind a switchingmode regulator as well as design procedures to include it in a certain application.

•How to select a certain filter configuration and design it given a bandwidth and rise time specifications.

•The full design of a differential amplifier with a virtual ground given specific requirements.

Bibliography

[1] Renesas Electronics Corporation, "Linear vs. switching regulators," 2021. [Online]. Available: https://www.renesas.com/cn/en/products/power-management/linear-vs-switching-regulators.html

[2] *LM78XX, LM78XXA 3-Terminal 1 A Positive Voltage Regulator*, LM7805 datasheet, Fairchild, September 2014.

[3] *LM2595 SIMPLE SWITCHER® Power Converter 150-kHz 1-A Step-Down Voltage Regulator*, LM2595 datasheet, Texas Instruments, May 2016.

[4] *TLC227x, TLC227xA: Advanced LinCMOS Rail-to-Rail Operational Amplifiers*, TLC2272 datasheet, Texas Instruments, March 2016.

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, Elijah Seth Cishugi 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: 16th / August / 2020

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Appendix B

GitHub Activity Heatmap