EEE 313
Thermocouple Instrumentation Amplifier Controlled Heater
Project Design Phase Report

"I affirm that I have not given or received any unauthorized help on this report and that this work is my own."

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Section: 1

Date:14.11.2024

Sign:

1)Introduction

This experiment focuses on designing and simulating a single-supply thermocouple instrumentation amplifier to control a heater temperature using a type-K thermocouple. The design aims to maintain a specified target temperature above room temperature for the heater resistance by employing an ON/OFF controller circuit, which turns the heater on when the temperature falls below the target which is room temperature + 34° in my case and off when it rises above it. A type-K thermocouple provides the temperature input to the amplifier, generating a small voltage proportional to the temperature difference. This signal requires significant amplification due to its low sensitivity, approximately 39.2 μV/°C. The design also integrates a comparator with hysteresis to ensure stable switching, and an LED indicator for visual feedback, signaling when the heater is active. Components used include the LM324 operational amplifier, a BJT for switching, and standard passive components. The LTSpice simulation demonstrates the circuit's performance, verifying it meets the specifications for output voltage levels at different temperature conditions. Following specifications will be considered:

1. The output voltage at 2V±0.5V when the thermocouple is at room temperature (thermocouple output voltage is zero).

2. The output voltage is 9V±1V when the temperature is at the required temperature (thermocouple voltage is 39.2×TS μV)

3. LED turns ON when the heater resistance is being heated. It should turn OFF when the heater is OFF.

2) Measuring OPAMP Specs

Although we assume ideally that no current flows into the OPAMP inputs, real OPAMPs have a small input bias current. This current can introduce voltage drops across input resistances, leading to errors at the output, especially problematic in our design since we are amplifying the signal thousands of times. Measuring and compensating for input bias current helps to minimize these errors, ensuring that the amplified signal reflects true temperature. Similarly, input offset voltage causes a small in the output. Since this offset can drift with temperature, measuring and accounting for it is essential for maintaining consistent results.

Measuring the input bias current and offset voltage is essential in precise instrumentation amplifier design, especially when dealing with small signals like those from a thermocouple. The input bias current, a small current flowing into the OPAMP's inputs, can cause voltage drops across input resistances, leading to output errors. Minimizing this effect is crucial for accurate signal amplification, particularly in high-gain configurations. The input offset voltage, a small DC voltage needed to make the output zero when inputs are equal, impacts the amplifier’s baseline accuracy. As it varies with temperature, accurately measuring and compensating for this offset helps maintain consistent performance, ensuring that the amplifier reliably translates thermocouple signals into temperature-proportional voltages.

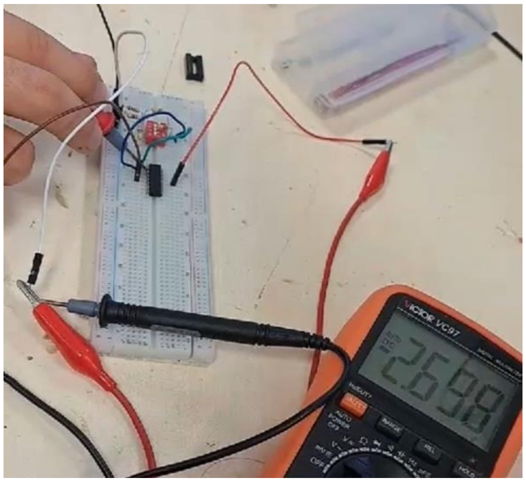


Fig.1

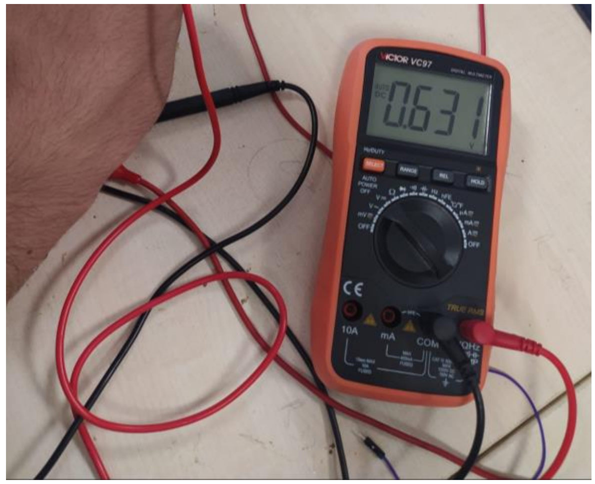


Fig.2

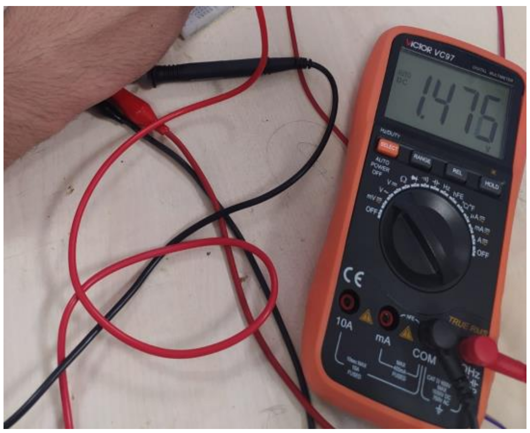


Fig.3

Fig.4

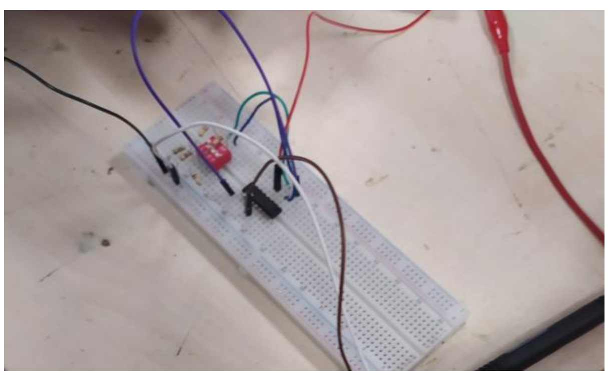


Fig.5: OPAMP offset measuring Circuit

Measured offset voltages can be seen in Fig.1-Fig.4 . After measuring the voltages I inputted the voltages to the offset calculator(Fig.6) provided by Mr. Atalar. Using the equations provided instructions in instrumentation amplifier

- $VIO = -Vout1 * \text{R1/R3}$ with both S1 and S2 closed
- $IIB2 = VIO/\text{R2} + Vout2\ \text{R1/(R3R2)}$ with S1 closed and S2 open
- $IIB1 = -\ VIO\ /\text{R2} - Vout3\ \text{R1/(R3R2)}$ with S1 open and S2 closed
- $IIO = -VIO/\text{R2}\ -Vout4\ \text{R1/(R3R2)}$ with both S1 and S2 open

1	R1	100			
2	R2	1.00E+05			
3	R3	1.00E+05			
4				S1	S2
5	vout1	-0.631		ON	ON
6	vout2	-2.69		ON	OFF
7	vout3	0.241		OFF	ON
8	vout4	-1.47		OFF	OFF
9					
10	VIO	6.31E-04	0.63	mV	
11	IB2	-2.06E-08	-20.59	nA	
12	IB1	-8.72E-09	-8.72	nA	
13	IIO	8.39E-09	8.39	nA	
14	IB1-IB2	1.19E-08	11.87	nA	

Fig.6

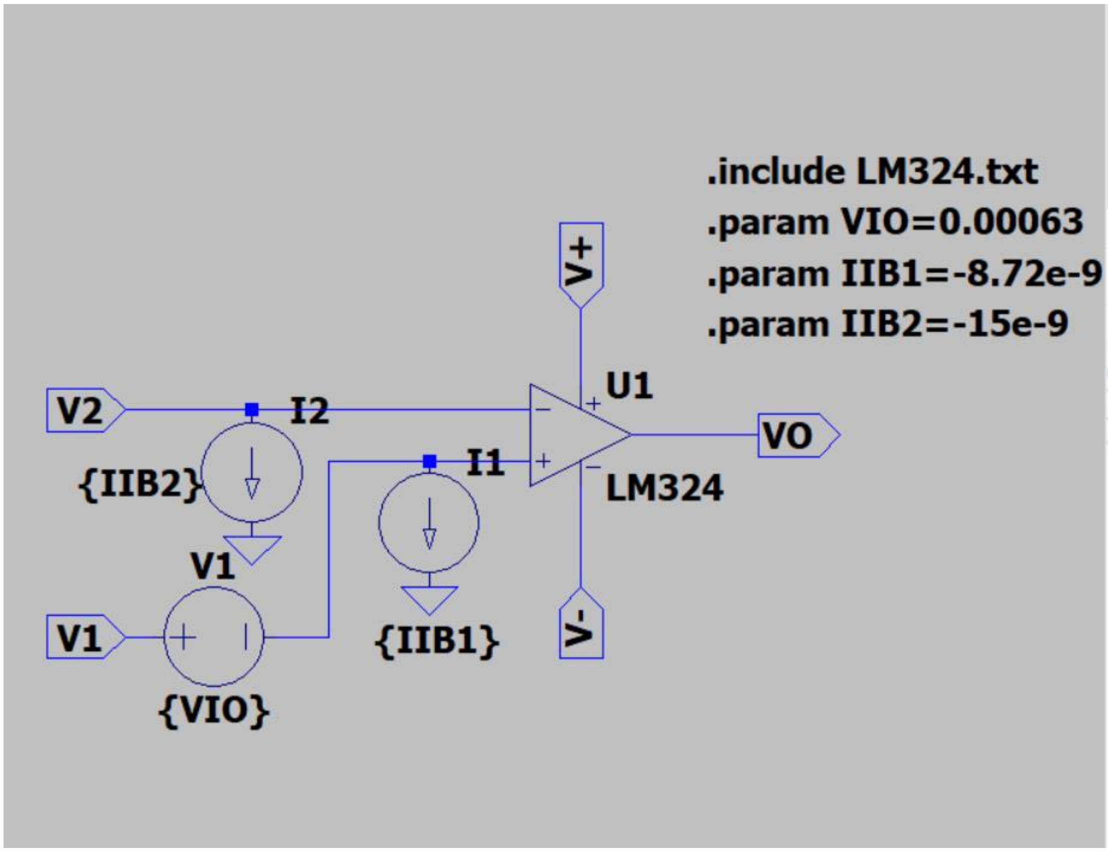


Fig.7

After inserting the calculated values into the OPAMP model created, OPAMP is ready to simulate the real life OPAMP we have so we can start designing our circuit.

3) Design

We can divide the design into 4 parts: Amplification and differential part (instrumentation amplifier), comparison part and BJT part. Their functions can be summarized as:

Amplification Part:

This section is responsible for amplifying the small voltage from the type-K thermocouple, which has a low sensitivity (39.2 μV/°C). The thermocouple output needs great amplification to produce a usable voltage range for temperature monitoring. By using a high-gain configuration, this stage ensures that even minor temperature changes produce detectable output variations, which are then processed by the remaining stages.

Differential Op-Amp Part:

Here, a differential amplifier processes the amplified signal, effectively canceling out any common-mode noise that might have been introduced in the previous stage. This section also incorporates offset compensation to counteract the input offset voltage, which is particularly important in single-supply systems like this. By rejecting noise and adjusting for offset voltage, this stage provides a clean, reliable voltage that accurately represents the temperature at the thermocouple.

Comparator Op-Amp Part:

The comparator stage functions as an ON/OFF controller. It compares the thermocouple's processed voltage to a reference voltage representing the set temperature. When the thermocouple voltage falls below the reference, the comparator output goes high, turning on the heater. The comparator includes a small hysteresis (0.1V) to prevent rapid switching around the setpoint, ensuring smooth operation without fluctuations when the temperature is near the target.

BJT Part:

This final section consists of a BJT switch connected to the heater and an LED. When activated by the comparator, the BJT enters saturation, allowing current to flow through the heater. The LED also lights up to indicate that the heater is active, providing visual feedback on the system's status. Ensuring the BJT is in saturation prevents excessive power loss and allows it to switch efficiently, prolonging the device's lifespan and ensuring reliable operation. BJT should never get into ACT state, it should go between SAT an$_d$ OFF .

The most crucial part of this design is the amplification part where we amplify the signal from thermocouple. Referring the instrumentation amplifier we have given the equation :

$$vo \approx vR + (v1 - v2)(R2/R1)(2R + Ra)/Ra$$

Since we don't want any gain in the difference amplifier, we should keep R1 and R2 same. After choosing R_1 and R_2 equal equation turns into :

$$vo \approx vR + (v1 - v2)(2R + Ra)/Ra$$

We have 3 unknowns. V_R should be chosen such that we have 2V when the thermocouple is at room temperature. So, V_R is found as 2V. We are left with the resistor values R and R_a. We should choose these values such that we get 9V when (V1-V2)= (39.2 μV/°C)X 34C°. After doing calculations and keeping in mind that we should use resistor values in Lab, we are left with multiple resistance options. The ratio of $(2R + Ra)/Ra$ should be around 5300. Closest result is obtained when R_a is chosen as 1KΩ and R as 2.7MΩ which gives the ratio 5400.

The amplification part is almost finished but we should also prevent OPAMPS from saturating. The part, or DC shift voltage, is essential in single-supply designs to keep all op-amps within their linear operating range, preventing them from reaching saturation. Since the thermocouple signal and amplified output need to vary above and below the baseline for accurate temperature sensing, acts as a reference voltage that centers the signal within the allowable input and output range of the op-amps. If the choose Vsh as 8.25 V we can ensure that OPAMPS are not SAT. Creating a Voltage divider with 12K and 10K should be proper. After picking up the other resistor from the suggested range from the document we complete the Instrumentation amplifier part. Which can be seen in Fig.1

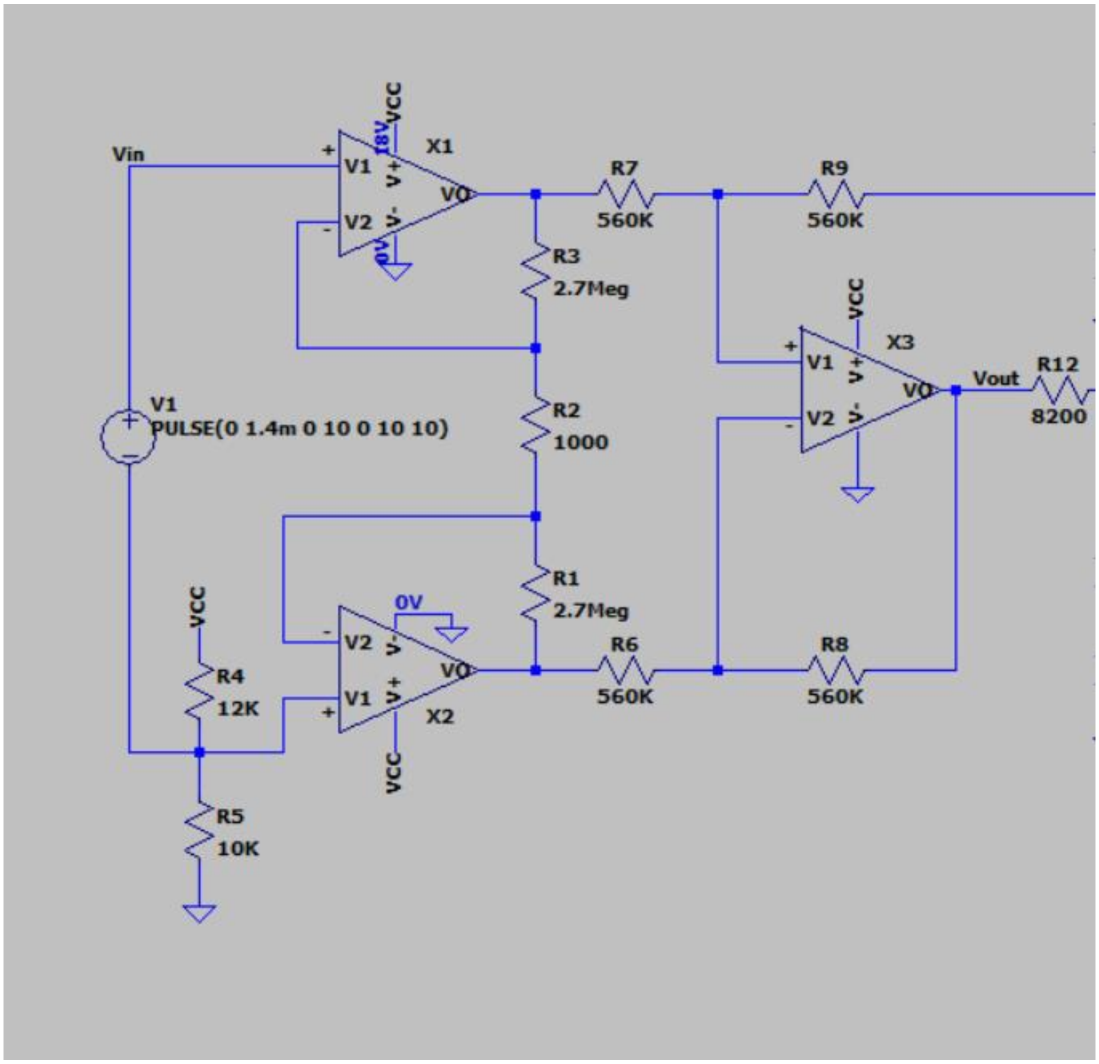


Fig.8

Since LtSpice don’t have the simulated version of the thermocouple we can simply use a voltage source as the representation of the voltage created by thermocouple. In Fig.1 It is already seen that when thermocouple voltage is 1.37 mV which represents the scenario that temperature is above 34.6C°. Output voltage is 9V.

Since we don’t need any amplification after the first part, we should keep the R_1 and R_2 values same as we assumed in the V_{out} equation (Equation 1). In order to ensure stability, we should choose from big resistors such as 560KΩ 1MΩ. In my circuit 560KΩ gave the best result so I have kept the 560KΩ. I should make a remark about the R1 value since R11 and R12 also contribute to the Rth. The upper branch of OPAMP 3 (x3) Sees the Thevenin resistance of R9//(R10+R11). Not to disturb the stability, we should keep R10 and R11 values considerably smaller than R9 so other resistors are not so effective.

Completing the amplifier section we can proceed with the comparator. The comparator should watch whether the output voltage is 9 or below. Therefore, we should feed the OPAMP with 9V in one input and with the V_{out} at the other. We can implement a simple voltage divider to get 9V from 18V source.

To ensure that the output signal does not flicker around the 9V we put a large feedback resistor. Complete circuit can be observed from Fig. 2.

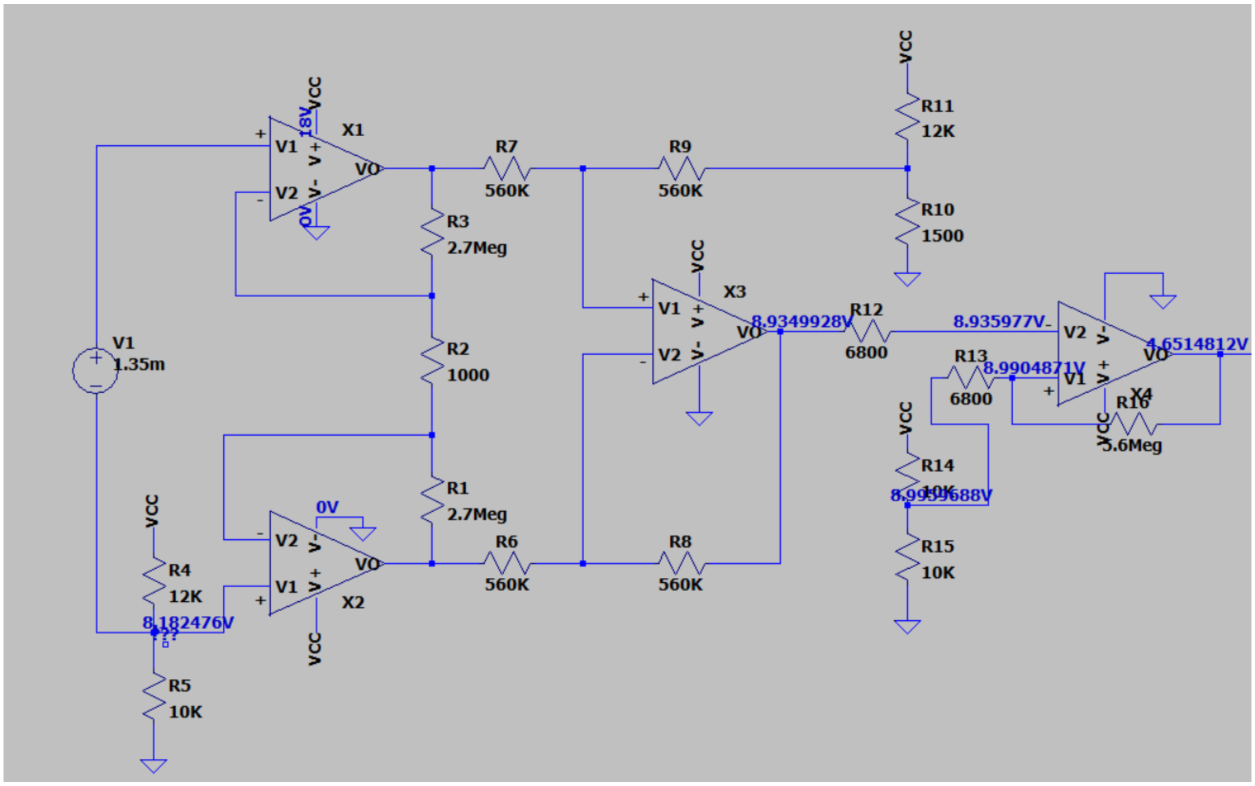


Fig.9

While choosing the R_{13} and R_{16} resistor values. We should be careful about the concept,hysteresis. Hysteresis is a characteristic seen in OPAMPS, where the output relies not only on the current input but also on the history of inputs. In order to get a good hysteresis value Mr. Atalar has recommended that R_{16} should be at least 1000 times larger than R_{13}. So, 8.2MΩ is suitable for our circuit.

As a last step we should include a BJT basically acting as a switch. BJT only works in SAT mode since we do not need any amplification in this part. If BJT is in SAT mode there is current passing through the resistor, so it gets heated up and there is a LED connected to BJT to indicate whether the resistor is getting heated or not. The resistors R_{18} and R_{19} are chosen according to lecture notes and I also R_{17} is inserted to limit the current and keep the LED safe.

Although it is not included in these schematics it is useful to mention that we can also use resistor at the emitter of the BJT. The reason behind the usage of emitter resistor is related to power rating of load resistor. Sine the resistor in the labs are not power resistors their power ratings are low. If we the resistors starts to degrade before we turn off the BJT circuit may get damaged. In order to prevent the load resistor from burning we may add an emitter resistance. However, this is only a remark for the hardware part of this project.

I included a shunt capacitor when taking the input voltage. This step is not important in the software phase since DC source don't have any AC noise in LTspice but in reality, there is always noise, so just to be sure shunt capacitor is added to circuit. The final circuit can be observed in Fig.10 .

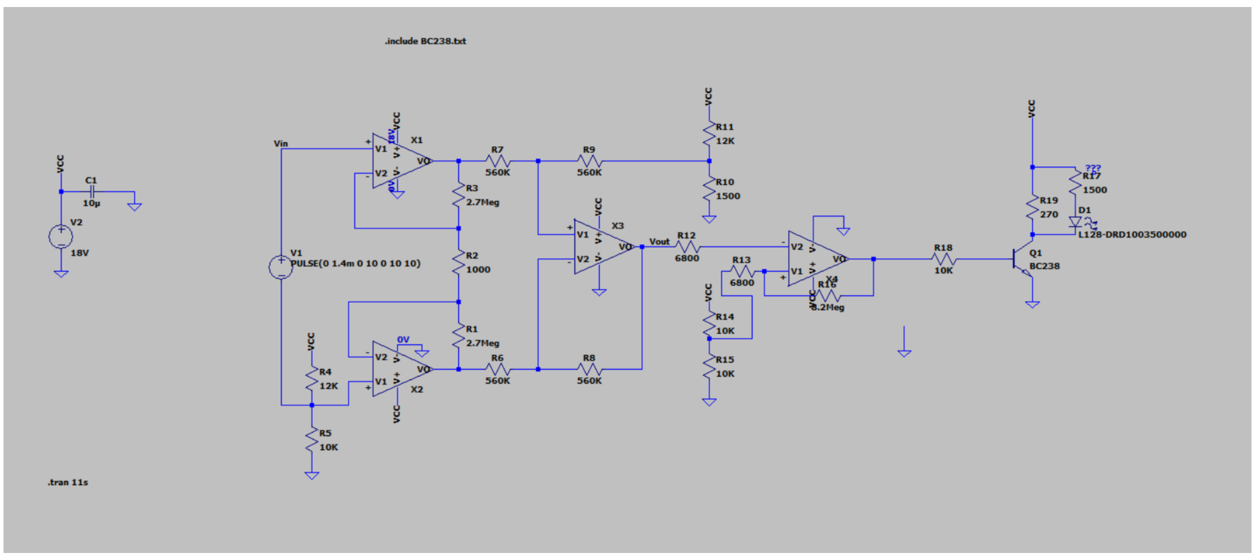


Fig.10

4)Testing and Satisfactions of The Criteria

4.1) Transient Analysis

In order to test the design, we must create a voltage source that represents the temperature increase over the time. To accomplish that we can use the code : PULSE(0 1.4m 0 10 0 10 10). This creates a voltage source that starts from 0V and goes to 1.4mV in

10 seconds which will represent the temperature measured by thermocouple from room temperature to 35 C° (1.4mV/39.2μ V).

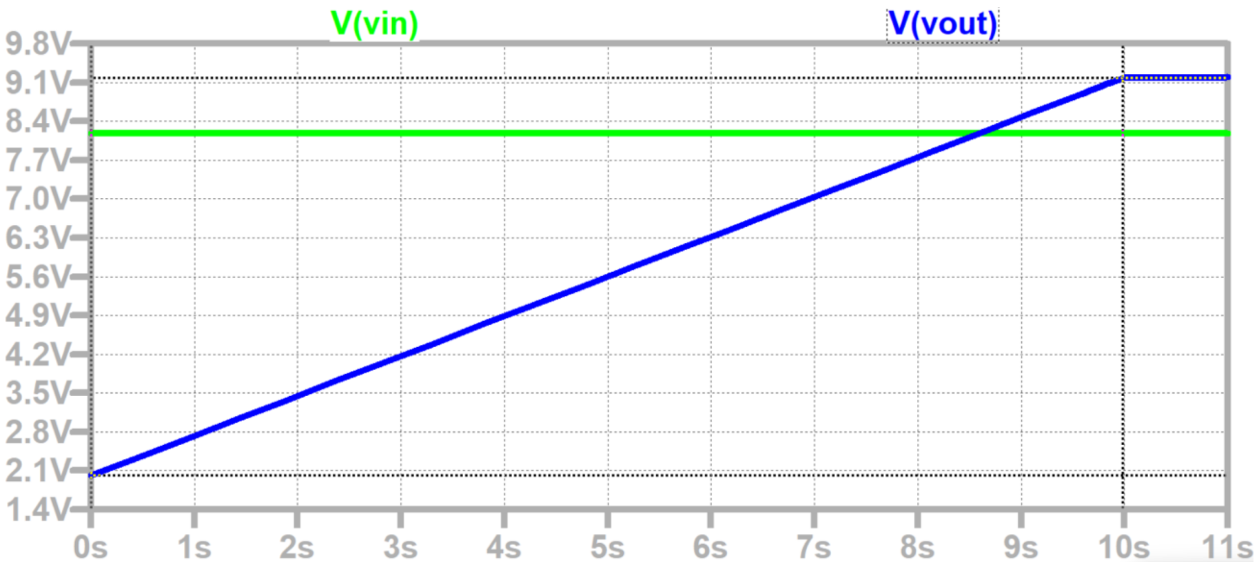


Fig.11

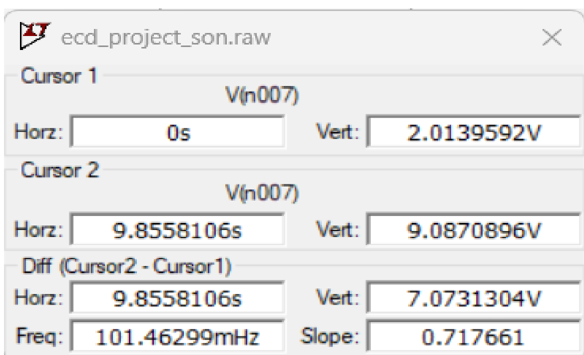


Fig.12

As we can see in the figures above circuit, amplification part is working as desired. Fig. shows the relation between Vin and V_{out}. When a thermocouple's voltage is 0 V output is 2.01V and when thermocouple's Voltage is 1.4mV (represents the temperature which is above 35 C° room temperature), V_{out} is 9.1 V which is a bit higher than indented value.

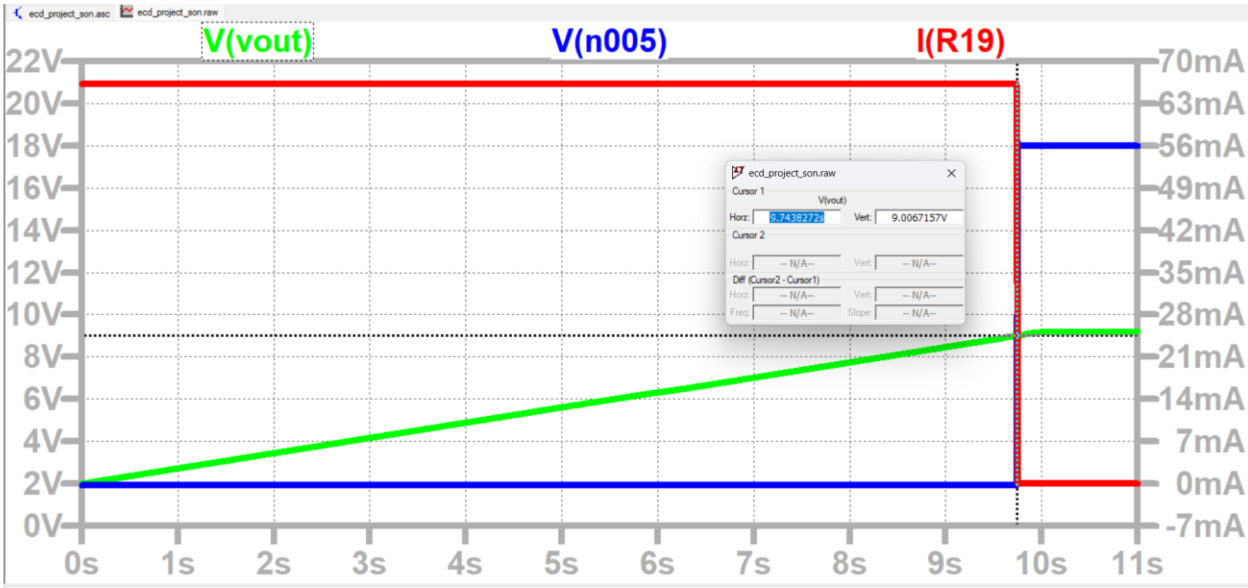


Fig.13

As it is seen in figure above when V_{out}= 9V BJT closes. $I(R_{19})$ is the current on the resistor that is getting heated up. When V_{out} is 9V there is no current on the load resistor.

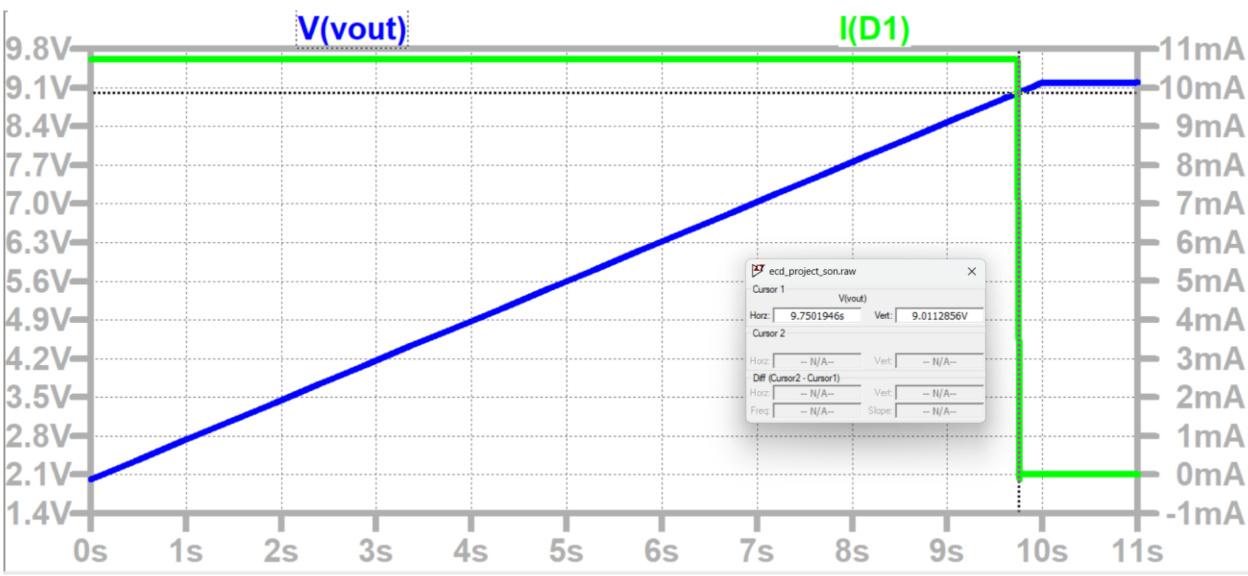
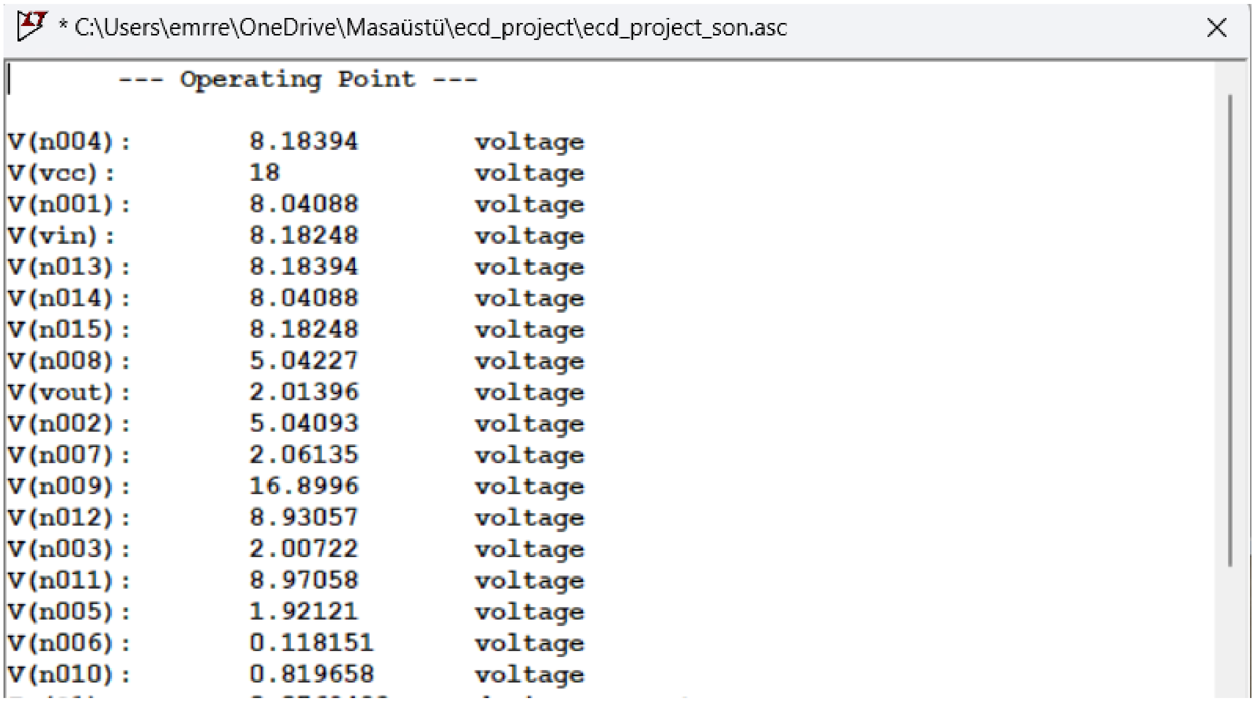


Fig.14

Fig. Shows the relation between V_{out} and I_D (LED current).

4.2)OP. Analysis



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--- Operating Point ---

V(n004):	8.18394	voltage
V(vcc):	18	voltage
V(n001):	8.04088	voltage
V(vin):	8.18248	voltage
V(n013):	8.18394	voltage
V(n014):	8.04088	voltage
V(n015):	8.18248	voltage
V(n008):	5.04227	voltage
V(vout):	2.01396	voltage
V(n002):	5.04093	voltage
V(n007):	2.06135	voltage
V(n009):	16.8996	voltage
V(n012):	8.93057	voltage
V(n003):	2.00722	voltage
V(n011):	8.97058	voltage
V(n005):	1.92121	voltage
V(n006):	0.118151	voltage
V(n010):	0.819658	voltage

Fig.15

Fig.15 Is a table of voltages after DC .op analysis when thermocouple is at room temperature. Live circuit and results can be observed from Fig.

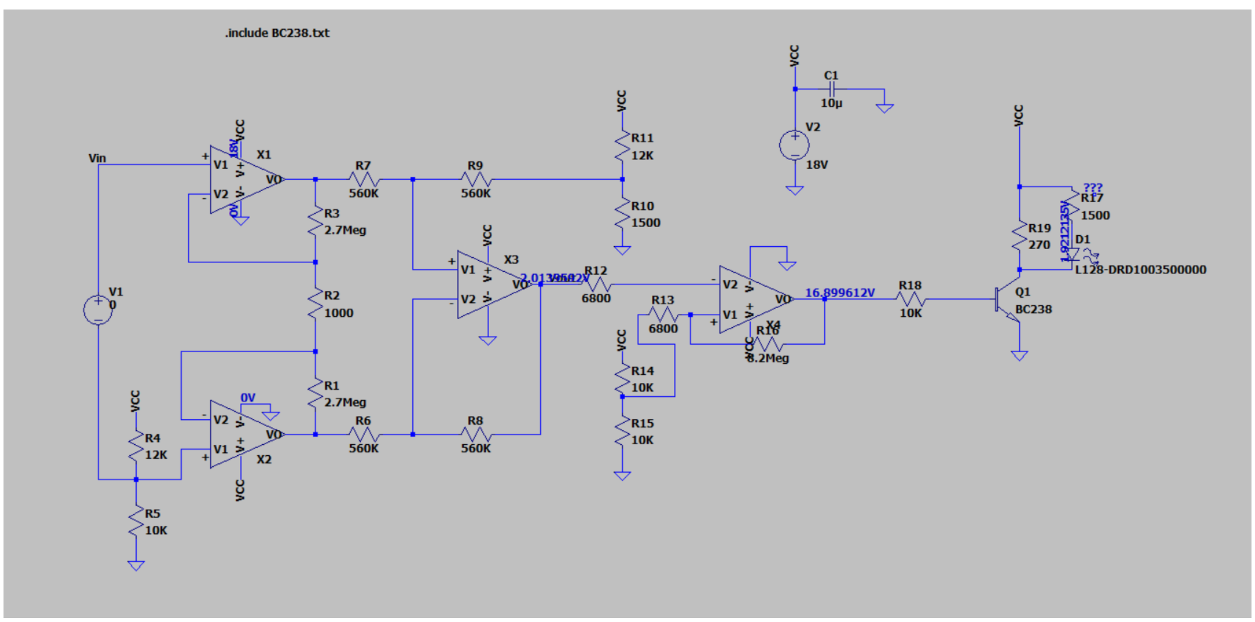


Fig.16

Fig.17 is a table of voltages after DC .op analysis when thermocouple is at desired temperature. Live circuit and results can be observed from Fig.18 .

V(n004):	8.1853	voltage
V(vcc):	18	voltage
V(n001):	11.6281	voltage
V(vin):	8.18388	voltage
V(n013):	8.18398	voltage
V(n014):	4.45504	voltage
V(n015):	8.18248	voltage
V(n008):	6.83805	voltage
V(vout):	9.19133	voltage
V(n002):	6.83667	voltage
V(n007):	9.19004	voltage
V(n009):	-0.0193116	voltage
V(n012):	8.99061	voltage
V(n003):	2.01149	voltage
V(n011):	8.99602	voltage
V(n005):	18	voltage
V(n006):	18	voltage
V(n010):	-0.0193114	voltage

Fig.17

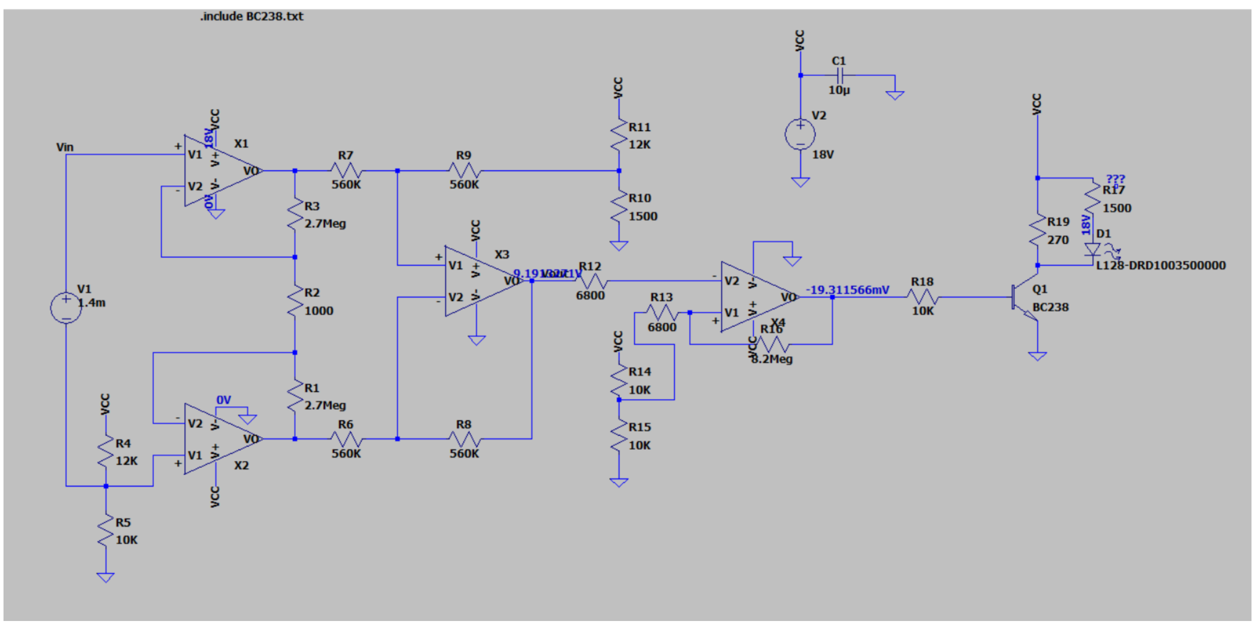
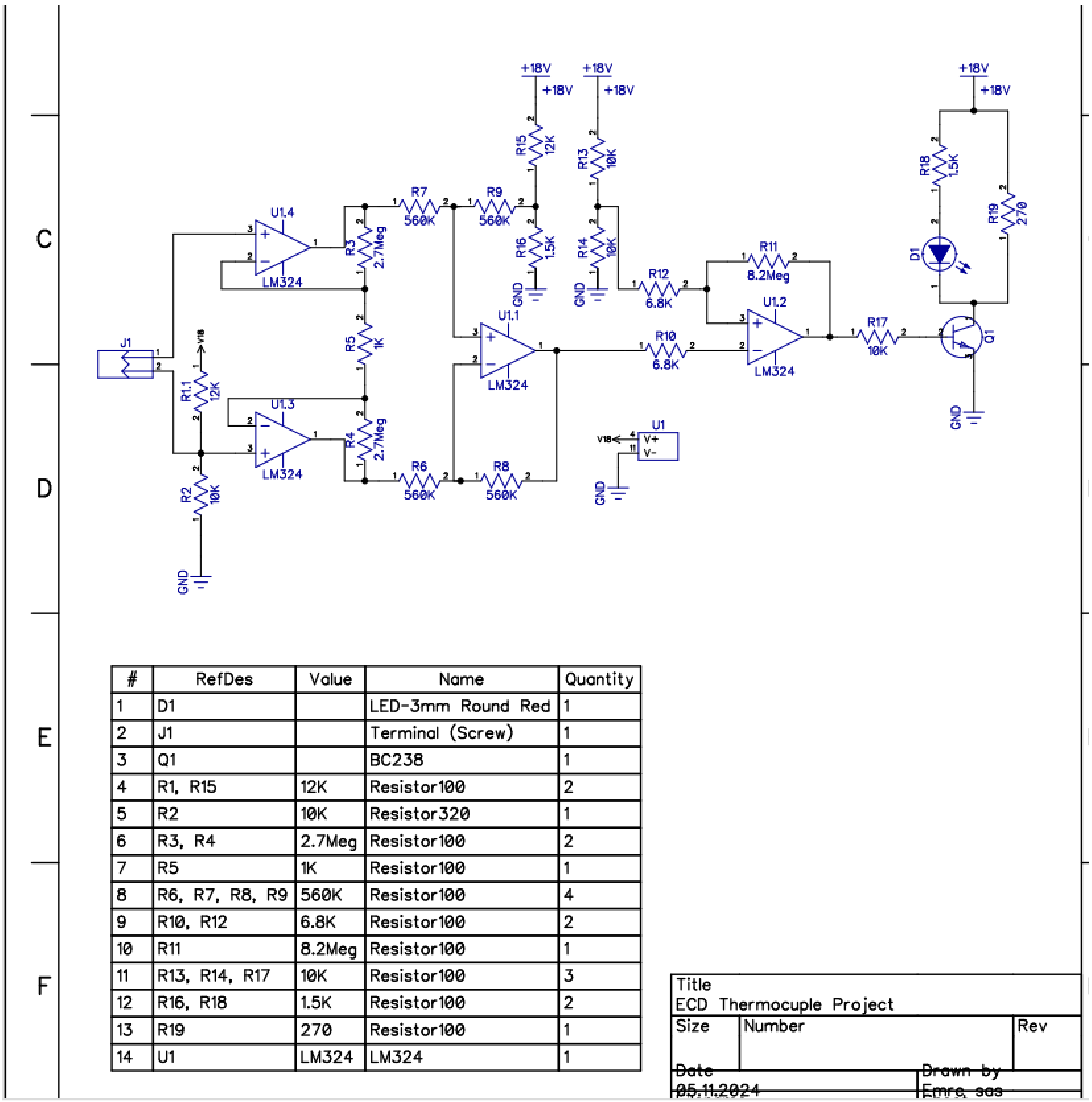


Fig.18

As it can be observed from operating point analysis when the thermocouple is at room temperature Vout=2 and when it is 34C above the room temperature Vout= 9V . Therefore, we can say that the first two criteria were satisfied and by observing that until the temperature of the load resistance is 34C higher than the room temperature, there is current flowing both on load resistor and LED. Therefore we can say that we have accomplished the final criteria too.

5)DipTrace Schematic and BOM list

In order to create the GERBER file of the schematic which also requires some preliminary work related to PCB design, we should first create the schematic on the DipTrace by using the provided library. There are many things to consider while designing the PCB but these will be further studied in the second part of the project. Therefore, at this point there are only two tasks to accomplish. The first task one is to create a nice looking schematic and BOM list which includes to components. BOM list is essential while gathering the required components from manufacturers. Schematic can be seen in Fig.19.



#	RefDes	Value	Name	Quantity
1	D1		LED-3mm Round Red	1
2	J1		Terminal (Screw)	1
3	Q1		BC238	1
4	R1, R15	12K	Resistor100	2
5	R2	10K	Resistor320	1
6	R3, R4	2.7Meg	Resistor100	2
7	R5	1K	Resistor100	1
8	R6, R7, R8, R9	560K	Resistor100	4
9	R10, R12	6.8K	Resistor100	2
10	R11	8.2Meg	Resistor100	1
11	R13, R14, R17	10K	Resistor100	3
12	R16, R18	1.5K	Resistor100	2
13	R19	270	Resistor100	1
14	U1	LM324	LM324	1

Fig.19

Power connections of the OPAMPS are not shown in Fig.4 not to crowd the picture. They can be seen in full schematic in the appendices.

Bom list as follows:

	RefDes	Value	Name	Quantity
1	D1		LED-3mm Red	1
2	J1		Terminal (Screw)	1
3	Q1		BC238	1
4	R1, R15	12K	Resistor320	2
5	R2	10K	Resistor320	1
6	R3, R4	2.7Meg	Resistor100	2
7	R5	1K	Resistor100	1
8	R6, R7, R8, R9	560K	Resistor320	4
9	R10,R12	6.8K	Resistor100	2
10	R11	8.2Meg	Resistor100	1
11	R13, R14	10K	Resistor100	2
12	R16, R18, R19	1.5K	Resistor320	3
13	R17	10K	Resistor100	1
14	U1, U2, U3, U4	LM324	LM324	4