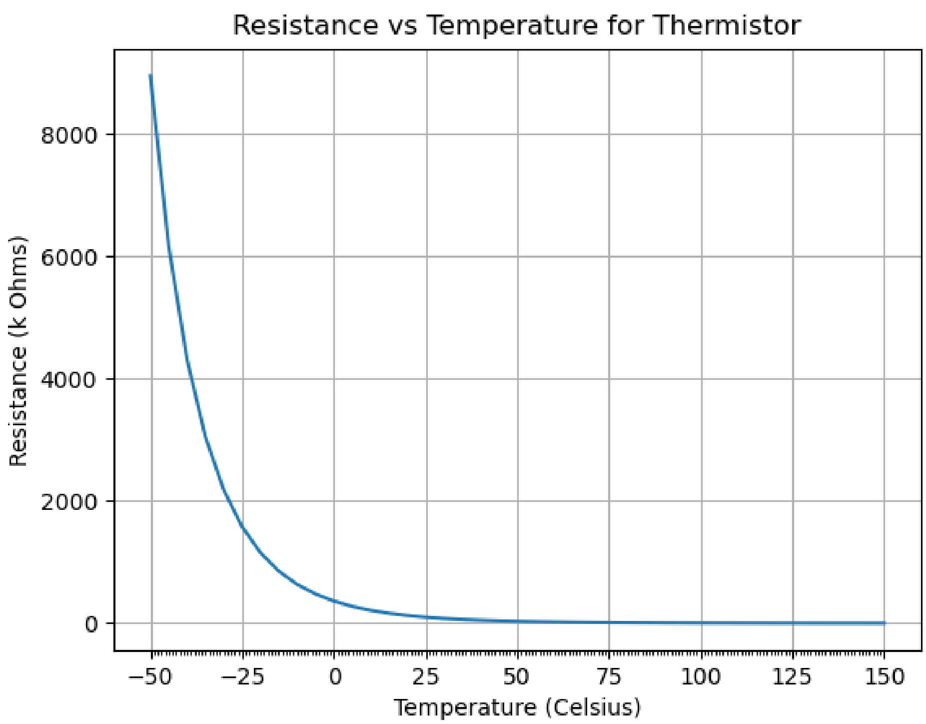
ECDL TEC Document

This document will include a detailed study of the temperature control circuit used for ECDL's. I will include all the necessary table, graphs, and values to fully break down and analyze this circuit.

Thermistor Properties

First, I will start with the thermistor in use. The thermistor we have is an NTC Type MS, with the following R vs. T graph.



For ranges of $0 - 50°C$ we can obtain this relationship between the resistance and temperature.

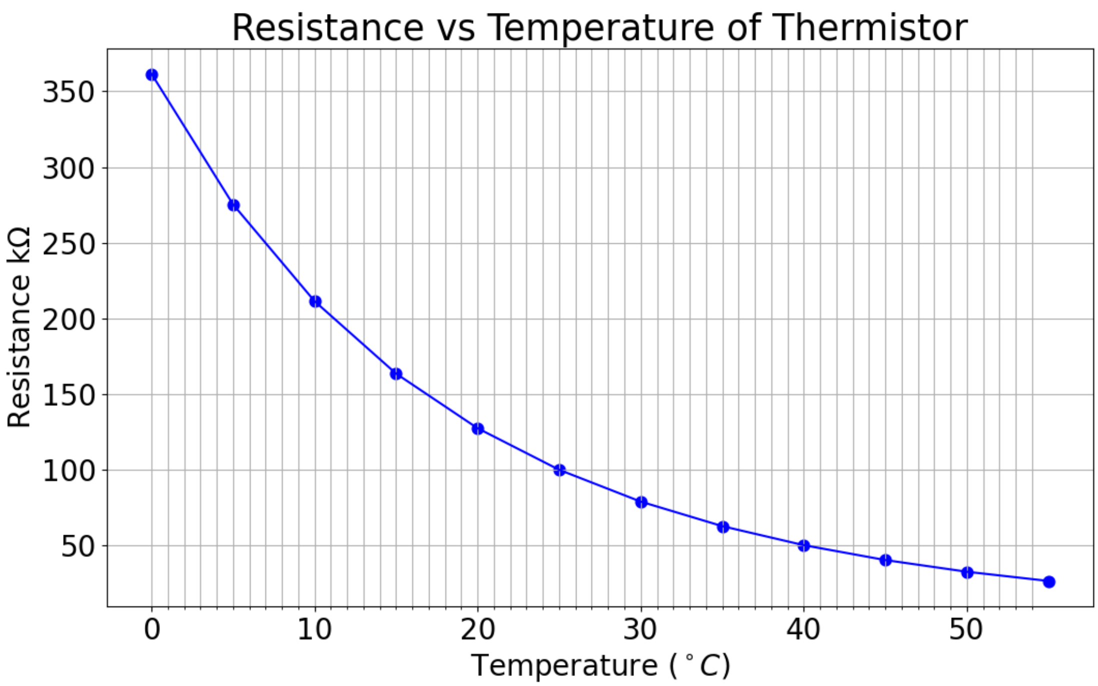
$$R_T = R_{25}e^{\left(A+B/T+C/T^2+D/T^3\right)}$$

A = -18.4129

B = 7218.8125

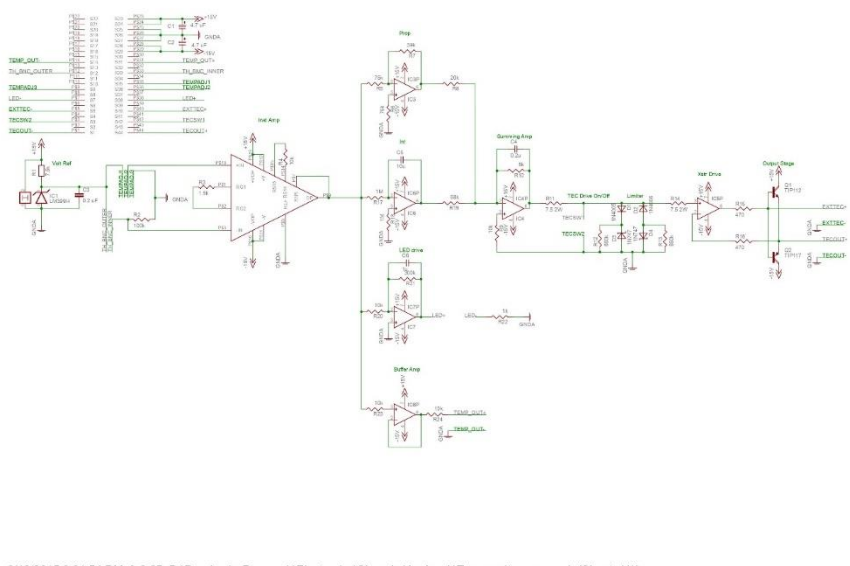
C = -661700.0718

D = 43587525.0237



General Circuit

This is a copy of the schematic:



This is the entire circuit, where we have an instrumental op-amp (amp-01) followed by a proportional and an integrator part, then a summing amp. After that we have a voltage clamp that limits the current drawn, followed by a Darlington push-pull pair for supplying current that goes into the TEC.

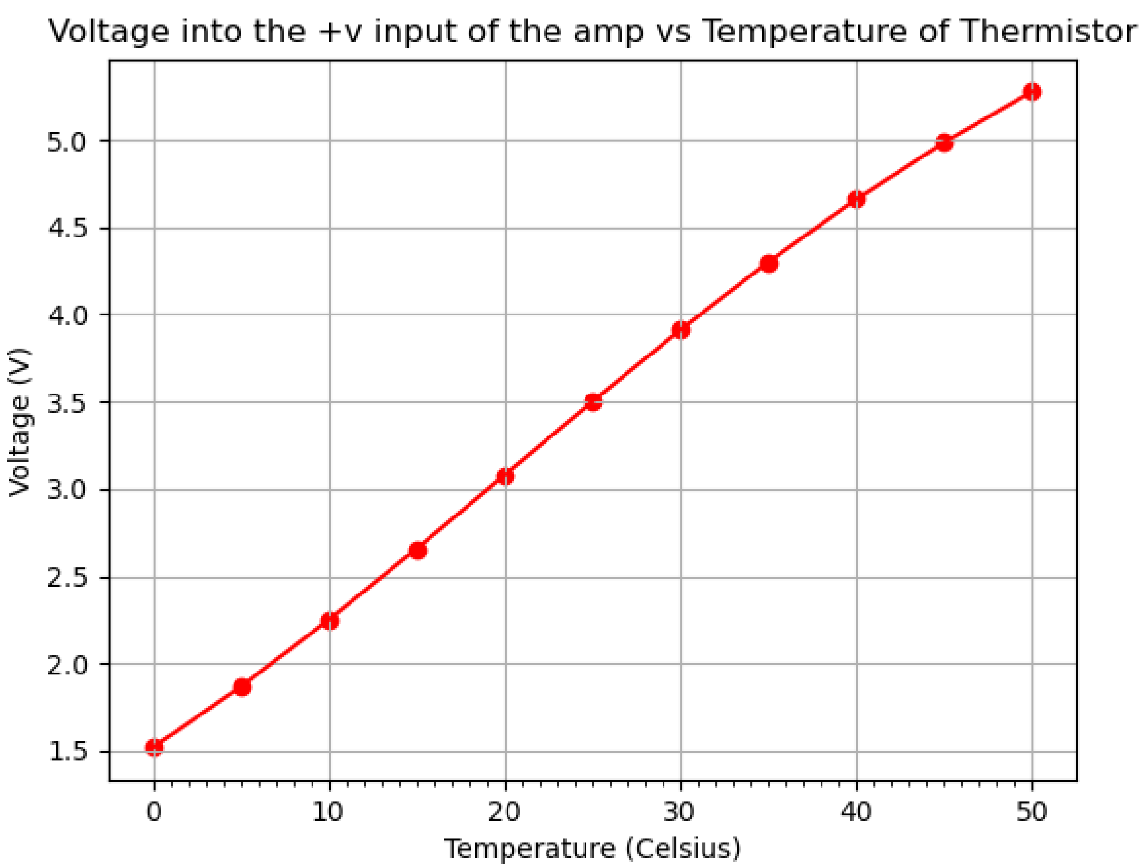
This is a negative feedback loop that aims to theoretically keep the temperature stabilized within a degree of 0.1 mK.

In the real circuit, before the non-inverting input of the amp-01 there is a grounded Vishay resistor that determines the voltage to the non-inverting amp. The voltage divider equation we get is:

$$V = V_{ref} \frac{R}{R + R_T}$$

R = 100kΩ is the Vishay Resistor
V_{ref} = 7V is a constant determined by the initial part of the circuit
R_T is the Thermistor resistance.

Using this equation, we get this graph:



Voltage Induced

Since we are trying to calculate the change in voltage due to a very small change in temperature, around $0.1°\mathrm{mK}$ then we can estimate the change in $\mathrm{R_T}$

$$\Delta \mathrm{R_T} = \mathrm{R_i} \Delta \mathrm{TC}.$$

This greatly simplifies our calculations as seen below.

$$\frac{dV}{dT} = V_{ref} \frac{-R}{(R + R_T)^2} \cdot \frac{\Delta R_T}{\Delta T}$$

$$\frac{dV}{dT} = V_{ref} \frac{-R}{(R + R_T)^2} \cdot R_{25} C_T$$

$$\Delta V = V_{ref} \Delta T R_{25} C_T R / (R + R_T)^2$$

First, we find a number for ΔV from the above equation. Assume a temperature of $25°\mathrm{C}$

At this temperature $\mathrm{R} = \mathrm{R_T} = \mathrm{R_{25}}$. Let $\Delta \mathrm{T} = 1\mathrm{K}$. At these $\Delta V = 8.37\ V$

$$\frac{\Delta V}{\Delta T} = 0.0837 V/°K \quad \text{(Before amplification)}$$

$$\frac{\Delta V}{\Delta T} \times Gain = 11.132 V/°K \quad \text{(After amplification; depends on the value of the Gain)}$$

So, for each unit of change in temperature the voltage output of the amp-01, is around 11 V.

For change of 0.1mK, the voltage output of the amp -01

$$\Delta V = 1.11\ mV$$

Dial Calibration

When the system is stabilizing, $V_{out} = 0V$. Which means that both voltage inputs at the amp-01 are equal.

$$V_{ref}\frac{R}{R+R_T} = V_{ref}\frac{R_k}{100}$$

$$R_T = \frac{(R^2 - RR_k)}{R_k}$$

$$R_k = \frac{R^2}{R+R_T}$$

Where R_k is the resistor reading on the potentiometer.

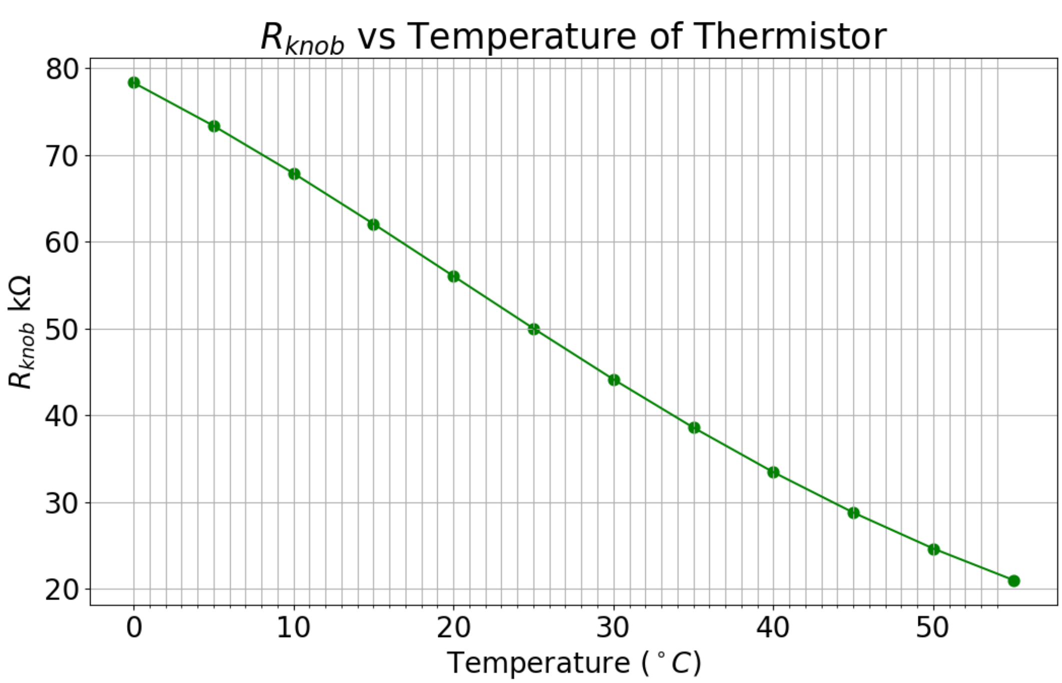
The idea here is that changing R_k, would induce a certain voltage. Every time R_k changes, a voltage is induced by the amp-01, which changes the temperature through the TEC mechanism. This in turn changes the thermistor resistance, restoring the voltage back to zero. So, we don't have to worry about the change in voltage. Because the thermistors resistor value corresponds to a certain temperature, we can relate R_k to a temperature.

In effect however R_k is switched. Meaning a reading of 70 on the dial would mean $30k\Omega$

instead of 70 $k\Omega$

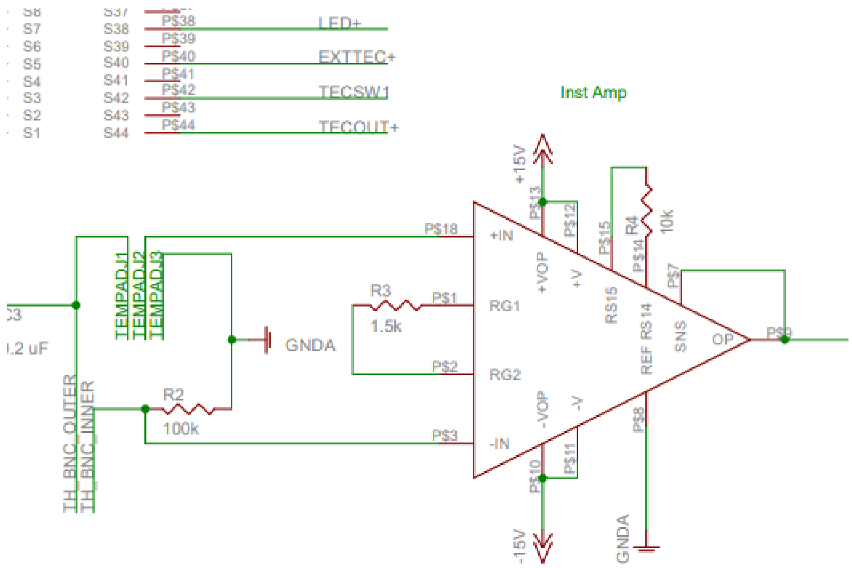
$$R_k = R - \frac{R}{R+R_T}$$

Putting all this together provides us with this graph.



Component analysis

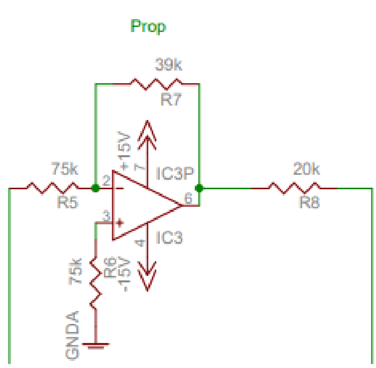
Instrumental Op-amp (Amp -01):



The Gain of the [amp -01](#) is

$$V_{out} = \frac{(20 \times R_4)}{R_3} \cdot (V_+ - V_-)$$

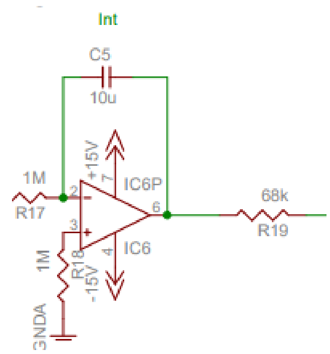
Proportional (OP-27):



In this part we see the proportional part of the PID. This is an inverting amplifier with gain

$$V_P = -\frac{R_7}{R_5} V_{in}$$

Integrator (AD-795):



This is the integrator part of the PID circuit. The gain is as such

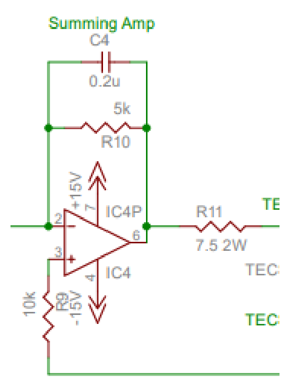
$$V_{out} = \frac{1}{RC}\int V_{in}\, dt$$

$$V_{out} = \frac{1}{j\omega RC} V_{in}(t)$$

$$V_I = -\frac{V_{in}t}{R_{17}C_5}$$

Where the last equation comes from the fact that V_{in} is not oscillating aggressively and can thus by modelled as a constant.

Summing amp (OP-27):

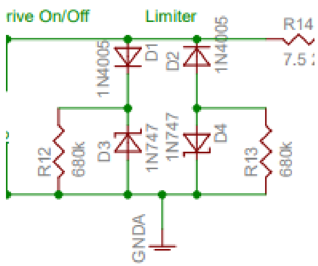


The gain in this summing depends on both the P & I components.

$$V_{out} = -\left(\frac{R_{10}}{R_8}V_P + \frac{R_{10}}{R_{19}}V_I\right)$$

$$V_{out} = V_{sum} = \left(\frac{R_{10}}{R_8}\frac{R_7}{R_5} + \frac{R_{10}}{R_{19}}\frac{t}{R_{17}C_5}\right)V_{in}$$

Clamp (Diodes, Zeners):



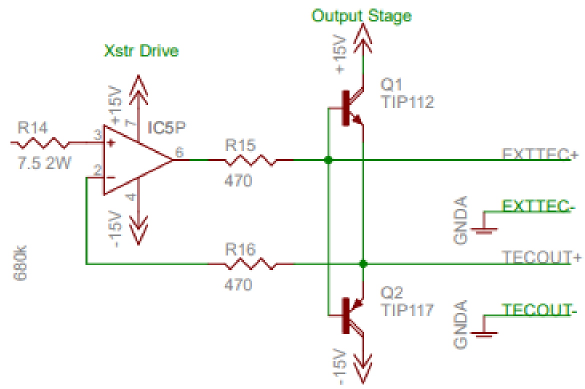
This Diode clamp limits the voltage output to a certain range. This is used to protect the TEC from drawing excessive currents.

The 1N747 Zener diode has reverse break down voltage of 3.6 volt, and the 1N4005 diode has a forward voltage of 1.1 V.

Since these two configurations are in parallel and opposite in direction, we get a voltage clamp of [-4.7V,4.7V]

So, if the voltage output from the summing amp is anything outside of this range, this voltage limiter clamps the voltage to the range found above.

Output Stage (OP-27, transistors)



This is the stage where the current is being drawn and fed into the TEC. Previously there was very little current being drawn from the circuit. This configuration is called a Darlington push-pull pair. The EXTTEC components are not very significant as they are just monitor outputs. The TECOUT+ however is what the TEC takes out from the circuit. Hence that junction is important for our purposes.

Note that at this junction, V_E, the voltage must be equal to the inverting/non-inverting terminals of the op-amp. Hence the output here does not influence the voltage at that current junction directly. All what the output voltage does is control the transistor base voltage V_b, to have the two input terminals equal. If it's positive, then it activates the top transistor (NPN) and if negative then it activates the bottom one (PNP).

$$V_b = V_{out}$$

$$V_E = V_- = V_+$$

$$I_{TEC} = \frac{V_+}{R_{TEC}}$$

Note that $V_+ = V_{sum}$

$$\boxed{I_{TEC} = \left(\frac{R_{10}}{R_8}\frac{R_7}{R_5} + \frac{R_{10}}{R_{19}}\frac{t}{R_{17}C_5}\right)\frac{V_{in}}{R_{TEC}}}$$

So now we have a value for the current output as a function of the volage induced by the amp-01

After performing V and I measurements, we get $R_{TEC} = 4.27\ \Omega$ (depends on the TEC used)

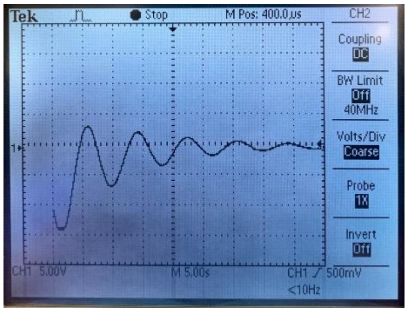
Now that we have the general framework of the circuits and its behavior, we can start tweaking our resistor and capacitor values to get the responses we want.

Response Curve Optimization

In this section, we try to tune the Resistor values listed above to create the best response curves for our temperature control. This study will be based off this article.

$$u = K_p \cdot e + K_I \int e\ dt$$

We first start off with this response curve when both P & I are connected



This response curve is undamped and oscillates more than desired.

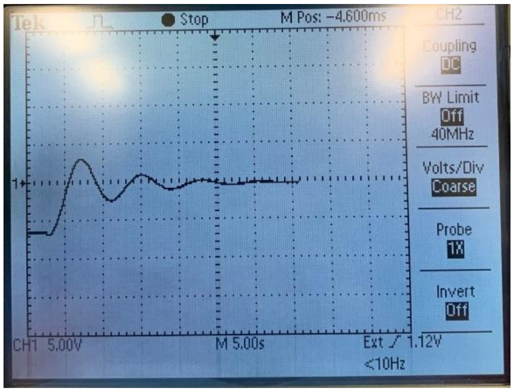
Proportional Component Tuning

To fix this, we first disconnect the Integrator and examine the Proportional component only.

We first started with a Gain of

$$K_P = \frac{R_7}{R_5}\frac{R_{10}}{R_8} = \frac{39k \cdot 5k}{75k \cdot 20k} = 0.13 \qquad \text{(Before)}$$

Where this is the response curve:

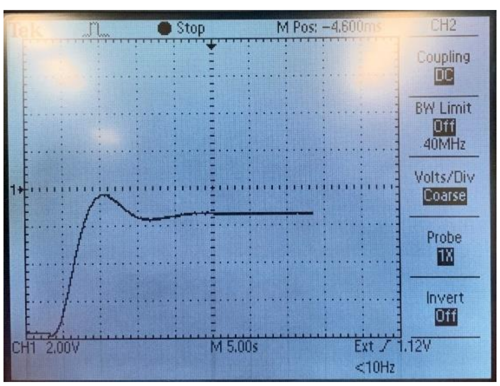


As we see here, this response curve oscillates a great deal. So, we must decrease the gain of P.

Reducing the gain of P by reducing R_{10} from 5k to 1k:

$$K_P = \frac{R_7}{R_5}\frac{R_{10}}{R_8} = \frac{39k \cdot 1k}{75k \cdot 20k} = 0.026 \qquad \text{(After)}$$

This produces this response curve.



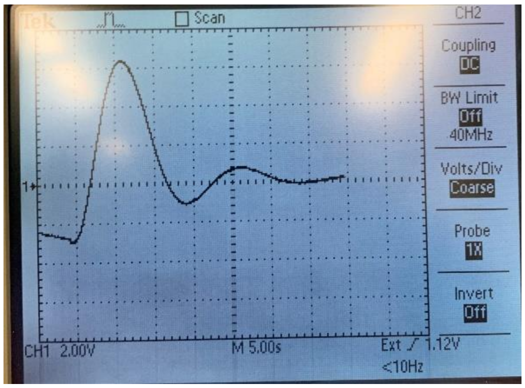
As we see here, this response curve displays the desired behavior based off the article.

Integrator Component Tuning

After having fixed P, we know tune the I component. We start off with an I gain of

$$K_I = \frac{R_{10}}{R_{19}} \frac{t}{R_{17} C_5} = \frac{1k}{33k \cdot 1Meg \cdot 10u} t = 3.03 \times 10^{-3} t \quad \text{(Before)}$$

Which produces the following response curve:



As we see here, this response curve oscillates more than desired. So, we must decrease the gain of I.

To do this without affecting the behavior of P, we increase the value of R_{19} from 33k to 57k, Decreasing the gain to

$$K_I = \frac{R_{10}}{R_{19}} \frac{t}{R_{17} C_5} = \frac{1k}{57k \cdot 1Meg \cdot 10u} t = 1.754 \times 10^{-3}\, t \quad \text{(After)}$$

To which we obtain the following response curves. Note that each spike is an induced change in temperature, and the following decay is the response curve. So here we have 6 response curves.

These are the desired curves based on the article!

The mean time for stabilization after inducing a 2-3 V at the amp-01 is **10-15 seconds**

Differentiator Component Tuning

In this analysis I have also tried including a differentiator. However, I did not see any improvements on the system when I added this component. I have tuned the parameters as much as possible going to both extremes, in the hopes of seeing an effect. What I noticed, is that the best behavior I see is when I decrease the gain of the differentiator to extremely low values (negligible effects). This indicated that the best behavior for the PID is when it converges to PI behavior.

Now since we have all our desired response curves, I can list out all the resistor/capacitor values. I will only include the component values that I have changed. If a component is not listed here, it means that it has not changed from the original circuit.

$R_{10} = 1\ k\Omega$

$R_{19} = 58\ k\Omega$

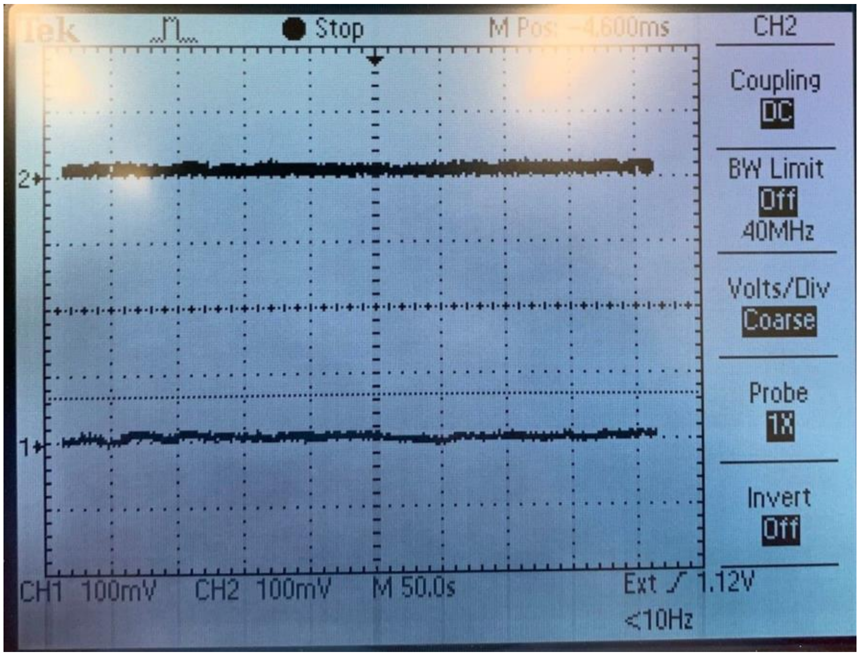
$R_{11} = 470\ \Omega$

*Note R_{11} is changed in order not to draw excessive currents when the switch is closed (off).

Testing

In this section we will evaluate our circuit and its stability on the system. First, we go over the setup of the test apparatus. We attach another thermistor to the set up so we can measure the temperature on the test thermistor. So here we have thermistor- TEC pair that is used for control, and we have a second “test” thermistor that is used to read off the general temperature of the system.

Ideally changing the temperature of thermistor would change the temperature of another.



In this graph Channel 1 is the thermistor-TEC control pair. This should be stabilized, as this is where the circuit is getting its feedback. Channel 2 is the test thermistor that is attached close to the first thermistor. It tells us how the system is behaving, as it not directly connected to the PID controller.

Over the range of 8 minutes the system stabilizes properly, with fluctuations that are minimal (controlled efficiently).

Theoretically, these graphs should be seen when the knob dials are the same, however in the apparatus there is a 2-tick difference ($0.2\ \mathrm{k\Omega}$) between the two knob dials.

Testing on the Laser System

So far, all the tuning work has been done only on the toy model, where the TEC is placed very close to the thermistor. In the real laser system however, this is not the case. The TEC is farther away from the thermistor, which means there is a time lag between the increase in temperature and change in the thermistor value. Hence the R & C parameters must be changed accordingly.

In the beginning I have tried following the above methods, but I could not obtain the desired response. Often it would not stabilize in the long term. While the above methods are helpful for general responses, they did not do well when we range of voltage had to limited a degree of 5 mV. I have tried employing other heuristic techniques such as the Ziegler–Nichols's method and Cohen-Coon methods. But I could not properly configure the open loop circuit.

I resorted to the help of a Stanford Research Lab laser controller device. This device contains an automatically tunable PID control circuit specifically designed for temperature control of lasers. When optimizing their PID's, they spit out the respective PID values.

This looks very promising, however there is non-linearity between the two PID circuit outputs.

Their PID output function is the following:

$$u = K_p \left(e + \frac{1}{T_I} et + T_D \frac{de}{dt} \right)$$

Where e is:

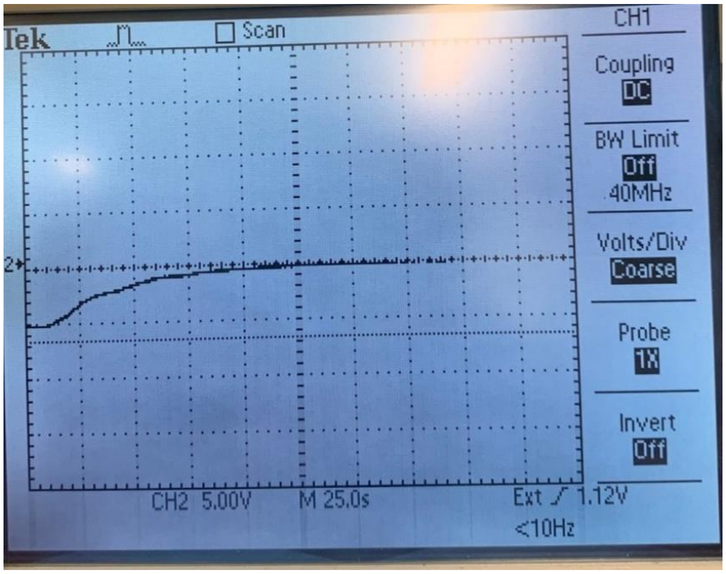
$$\epsilon_{Stan} = R_{set} - R_{meas}$$

Our error function is the following:

$$\epsilon_{us} = \left(\frac{R_{set}}{100} - \frac{100}{100 + R_{meas}} \right) \cdot V_{ref} \cdot 133.33$$

These two error functions cannot be linearly related to one another. Hence the values we obtain for PID on the system cannot be mathematically transformed to our gains. However, we could empirically obtain values for control values by mimicking our P & I response to theirs.

First, I tune the P component and then the P & I together. From there I obtain the following graphs and values. In this experiment, I have added a probe thermistor to the system and used it solely for measuring the response.



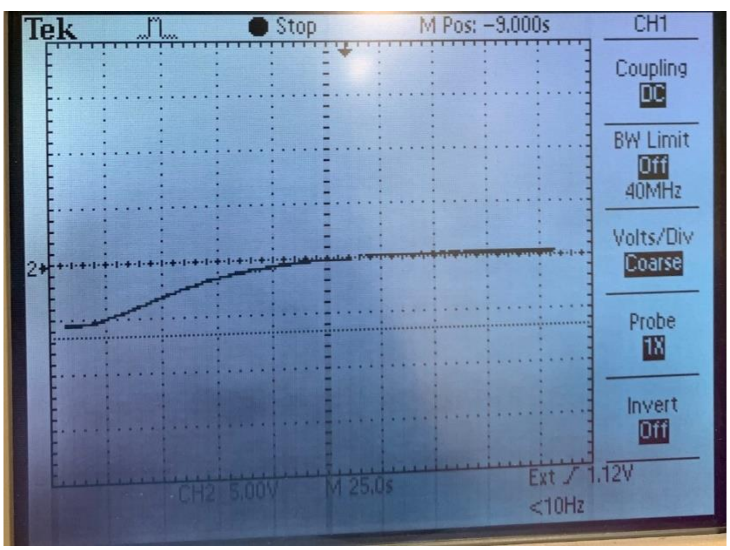
Stanford Laser system P & I response

After changing the Resistor settings to

$$R_{19} = 100k$$

$$R_{10} = 2.45k$$

We obtain this response curve:



Our P & I response

These two response curves are very similar, and in fact our system stabilized very well in the long run. It stabilized to a range of $\pm 10mV$ which corresponds to a temperature degree of $\pm 0.9\ mK$. However, the issue lies in the time. The system takes about 3.5 – 4 minutes to stabilize, making it 30 -45 seconds slower than the Laser Controller PI.

Power loss in transistors

Let us tackle the excessive transistor power dissipation problem. First, we note that the max voltage that could be produced with our gains is 1.3125V

$$K_{P-max} \cdot \frac{R_{10}}{R_8} + K_{I-max} \cdot \frac{R_{10}}{R_{19}}$$

$$= 7.5 \cdot \frac{2.5}{20} + 15 \cdot \frac{2.5}{100}$$

$$= \ 1.3125\ V$$

When measuring the output, I get a maximum of 1.379 V. Which is within the same playing field. Hence, at worst there is a 15-1.379 = 13.621 V Dissipated across the transistor. ($R_{TEC} \approx$ 2.22 for the new laser system)

$$P_{max} = IV = 13.621 \times 0.62 = 8.44W$$

Generally,

$$P_{tran} = \frac{V(15-V)}{R_{TEC}}$$

From the datasheet

“DARLINGTON 2 AMPERE COMPLEMENTARY SILICON POWER TRANSISTORS 60−80−100 VOLTS, 50 WATTS”

So, with proper heat sinking, the transistors can certainly handle this much power.

Theoretically, the clamp contains the voltage to a range of [-4.7V, 4.7V], but let us assume a 5V input.

$$P_{trans} = \frac{5(15-5)}{2.22} = 22.5W$$

which is still below the limit. However, the current at this point would $\approx \frac{5}{2.22} = 2.25A$, which is rated higher than the max current.

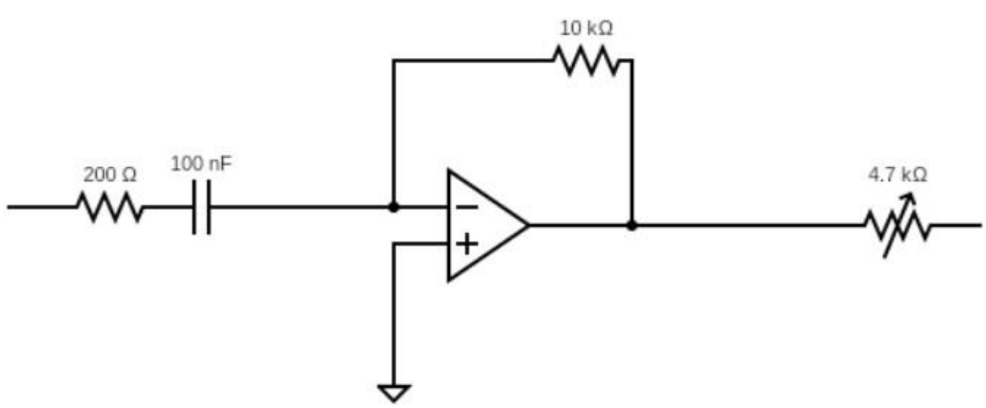
There is still power loss that could be reduced. Reducing the total voltage supply to 11V - the minimum needed to supply the op-amps- could reduce the power loss of the transistors from 8.44 Watts to 6.0 W

$$P_{tran} = \frac{V(11-V)}{R_{TEC}} = 5.97W \approx 6.0W$$

Which I believe is a negligible change.

Differentiator component of the PID

So far in the laser system, we have not included an implementation of the D component. I have noted from the Stanford Research lab (SRL) controller that adding a Differentiator improves response times by reducing the time needed from 3 minutes to 1.8 minutes. In this section I will go over my implementation of the D component.



$R_2 = 10k, R_1 = 200, R_3 = 4.7k$

Here is a schematic of the differentiator I have built. The last resistor is a tunable resistor that could be used in order to change the gain of the differentiator.

The gain is

$$G(j\omega) = \frac{-j\omega R_2 C}{1 + j\omega R_1 C}$$

Since $R_2 \gg R_1$we can ignore the denominator.

$$V_{out} = -j\omega R_2 C V_{in} = R_2 C \frac{dV_{in}}{dt}$$

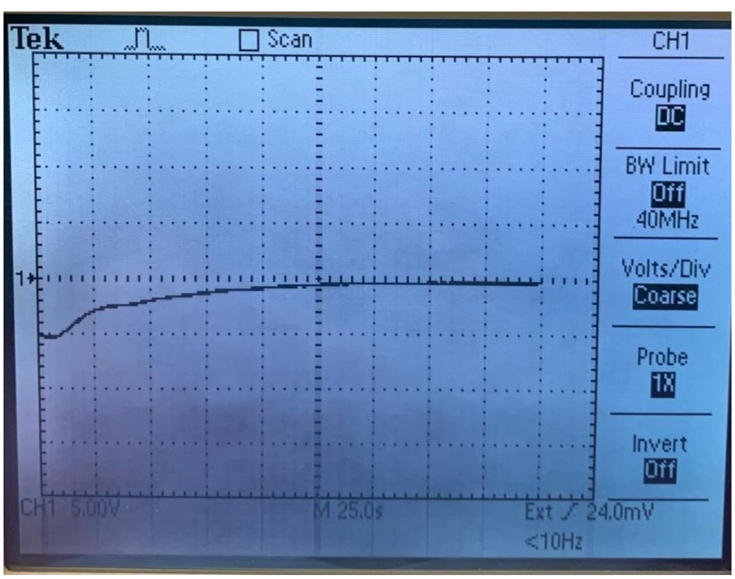
$$V_{out} = 0.001 \frac{dV_{in}}{dt}$$

Then this gain is multiplied by the summing amp gain.

$$V_{diff} = 0.001 \frac{dV_{in}}{dt} \frac{R_{10}}{R_3}$$

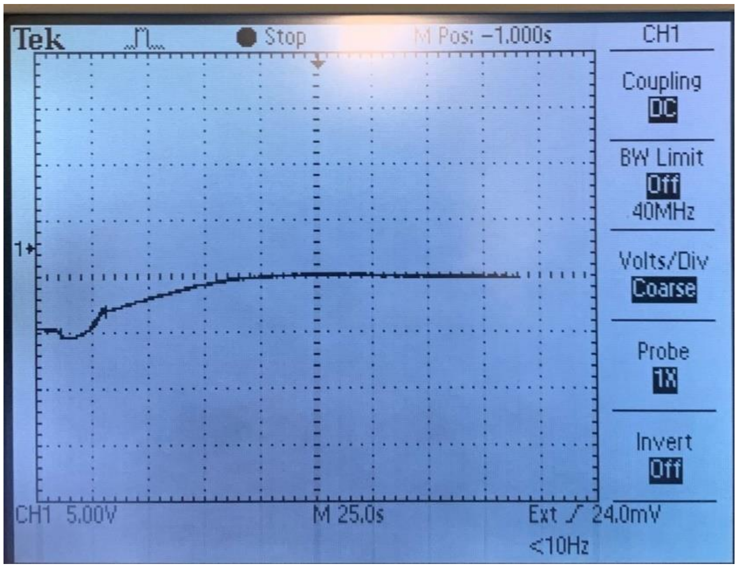
$$K_D = 0.001 \frac{R_{10}}{R_3}$$

After setting up this differentiator using OP-27, we test and compare our results to the SRL results.



SRL PID results

When it comes to our system, I do not see any progress in the response time with the differential component added. Setting $R_3 = 100\ \Omega$ we get this response



Our PID response

we see in the image above that our system's PID response is like the SRS's response for the probe thermistor. However, there is still 1–2-minute time difference between the two systems.

There is potential for the Differentiator to improve the control by a minute or two, but more testing needs to be done to do so. I would firstly suggest to simply optimize the differentiator op-amp individually, before evaluating it on the control circuit. The D component seems to be noisy and not very stable.

Final Parameters & Gains

In this section I provide a quick rundown of the final parameters used for the TEC Laser controller circuit. Below are the resistor values.

$$R_{19} = 100k\Omega$$

$$R_{10} = 2.45k\Omega$$

$$R_3 = 100\ \Omega$$

These correspond to gains of

$$K_P = \frac{R_{10}}{R_8}\frac{R_7}{R_5} = 0.064$$

$$K_I = \frac{R_{10}}{R_{19}}\frac{1}{R_{17}C_5} = 2.45 \times 10^{-3} \quad s^{-1}$$

$$K_D = R_2 C \frac{R_{10}}{R_3} = 0.0245 \quad s$$

Where our final output is the following:

$$u = K_P \cdot e + K_I \int e \ \mathrm{d}t + K_D \frac{de}{dt}$$

$$e = \left(\frac{R_{set}}{100} - \frac{100}{100 + R_{meas}}\right) \cdot V_{ref} \cdot 133.33$$

With this set up, the system stabilizes to a range of 10 mV in 3.5 – 4 minutes. Eventually it reaches a range of 5 mV, which corresponds to a degree of $\pm 0.45^{\circ}\mathrm{mK}$