Real-Time Adaptive Signal Conditioning System for Wide Dynamic Range Inputs

I. Plain explanation

The diagram represents a **Real-Time Adaptive Signal Conditioning System for Wide Dynamic Range Inputs**.
The system automatically regulates the amplitude of an input signal by applying level-dependent gain control.

It continuously monitors the input signal level, compares it to a predefined threshold, and dynamically adjusts the gain of a voltage-controlled amplification stage to maintain the output signal within a controlled range.

The system operates in real time using a feed-forward control architecture, enabling fast response to changes in input amplitude without directly feeding back the output signal.

II. Detailed explanation of how the system works

1. Signal Input

The system receives an analog input signal whose amplitude may vary significantly over time.

2. Voltage-Control

The input signal is fed directly into a Voltage-Controlled Amplifier.
This block applies a gain to the signal, where the gain value is controlled by an external control voltage. The VC is responsible for increasing or decreasing the signal amplitude in real time.
At this stage:

The signal path remains continuous

No frequency modification is intended

Only amplitude scaling is applied

3. Envelope Detector

In parallel with the main signal path, the input signal is routed to an Envelope Detector.

The purpose of this block is to extract a representation of the signal's amplitude (or level), independent of its frequency content. This is typically achieved through rectification followed by low-pass filtering, producing a slowly varying control signal.

This block provides the system with real-time information about how "strong" the input signal is.

4. Signal Comparator

The output of the Envelope Detector is fed into a Signal Comparator, where it is compared against a predefined reference threshold level.

If the detected signal level is below the threshold, no gain reduction is required.

If the detected signal level exceeds the threshold, the comparator generates a control signal indicating that gain reduction should be applied.

This block implements the decision logic of the system.

5. Control Signal Generation

The output of the Signal Comparator is converted into a control voltage that determines how much gain reduction is applied by the VC.

The magnitude and timing of this control signal govern:

How quickly the system responds to increases in input level

How smoothly the gain returns to normal when the input level decreases

This behavior defines the system's dynamic response characteristics.

6. Signal Output

The processed signal exits the system through the output block.
As a result of the adaptive gain control, the output signal exhibits a reduced dynamic range compared to the input, remaining within a controlled amplitude range even when the input varies significantly.

7. System block illustration

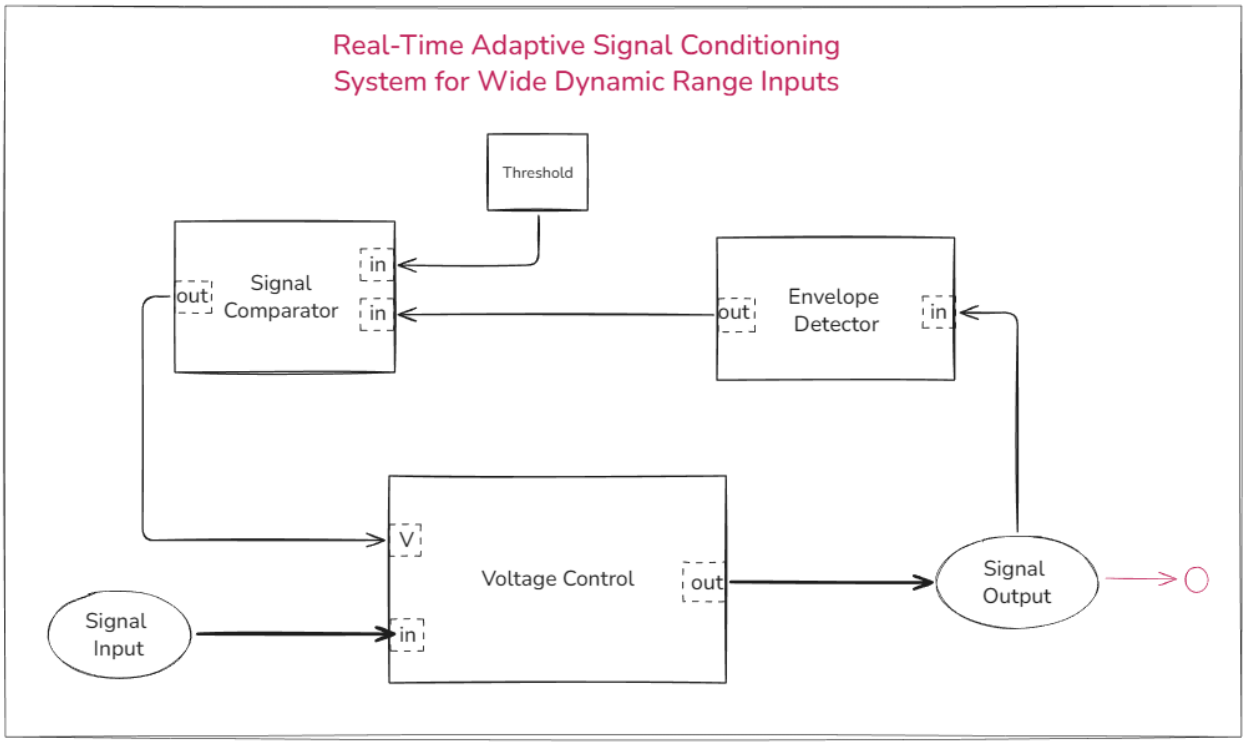

Fig. 1. block diagram

III. Deployment

1. Voltage-Control

Available methods

-Multi Variable Resistors Low Pass filtering

-Diode ladder filtering

Chosen Method:

Diode ladder filtering this method consists combining a multi set 1N4138 diodes in series will act as a variable resistance in function of the control-voltage applied to the input of the CV (V).

this method will cause less distortion and more control of the CV and its generally more cost-effective and easy to assemble.

1.1 functioning

I have selected the diode technique, which involves utilizing many diodes as resistors. It functions by supplying symmetric voltages to the diode ladder's beginnings and a non-inverted buffered input at the center. This is the fundamental idea behind the diode ladder. The output signal is picket as is from the middle of the ladder if the symmetric voltages are zero. If the symmetric voltages are not equal to zero, there will be a current flowing from the positive rail to the negative rail and simultaneously dragging some of the current from the input signal, so the output signal will be the same as the input but lower in amplitude (volume). Therefore, the more the symmetric voltages increase, the lower the input will become.

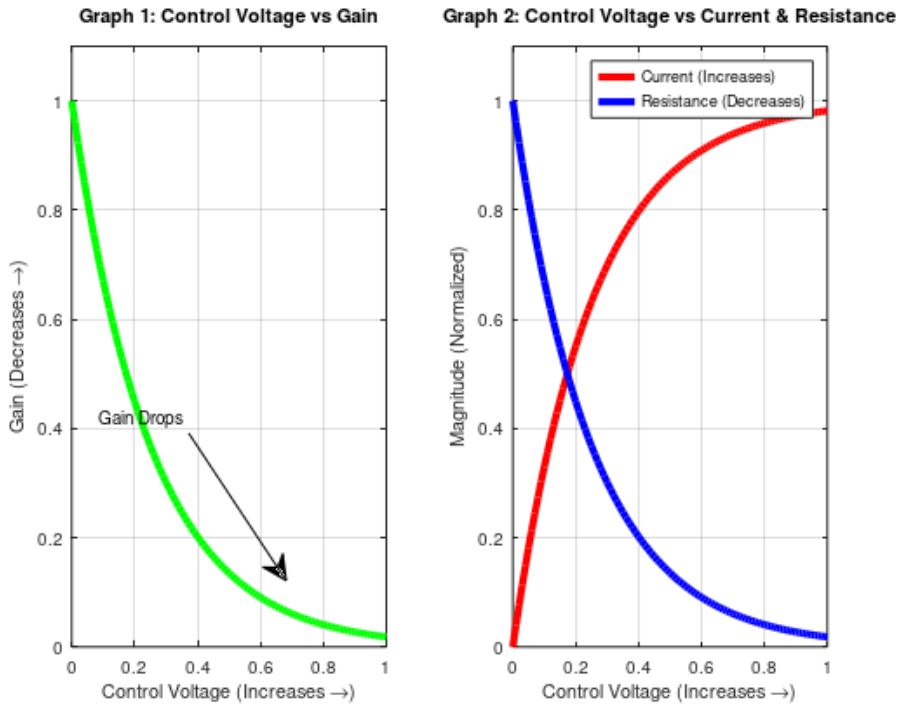

Fig.2,3. Diode Ladder Control Characteristics

1.2 Schematic

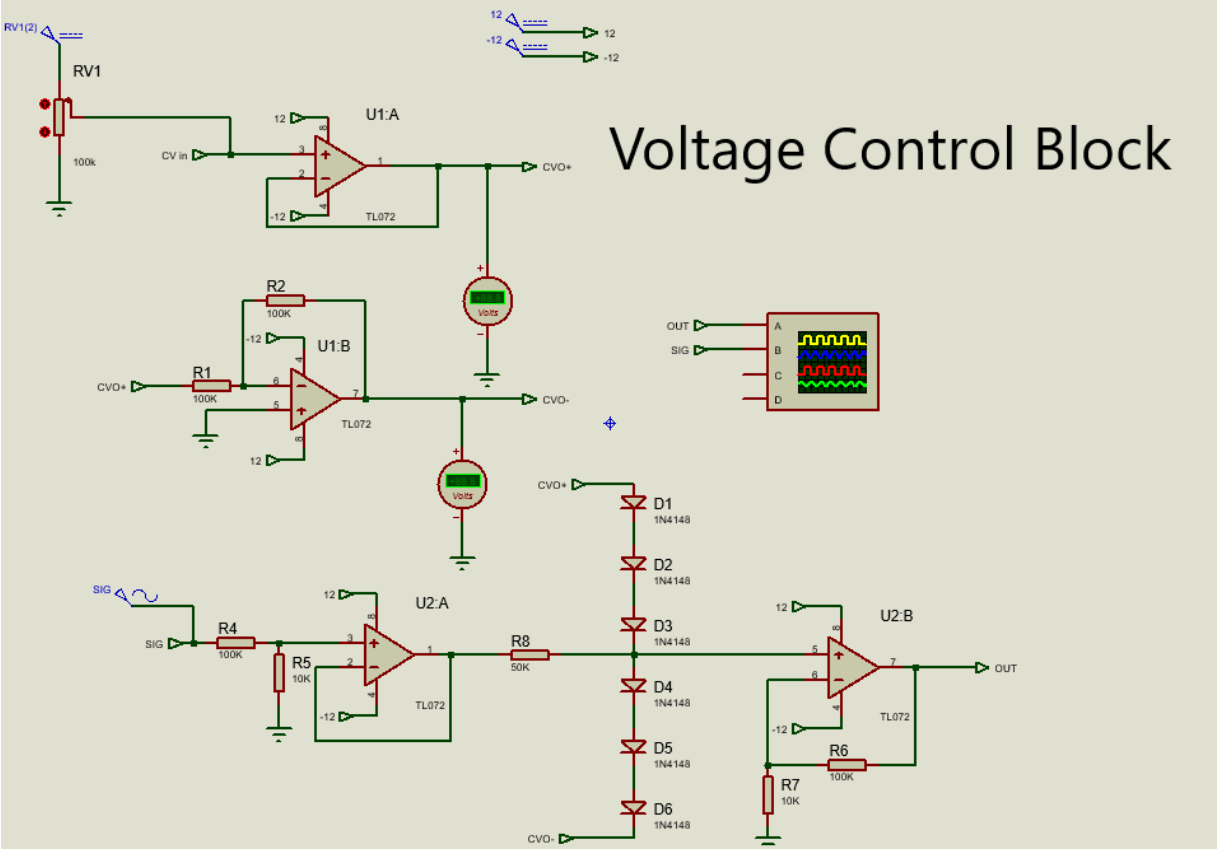

Fig. 4. Voltage Control Block schematic

1.3 Simulation

CV=0

During this simulation the CV=0 → Gain =1

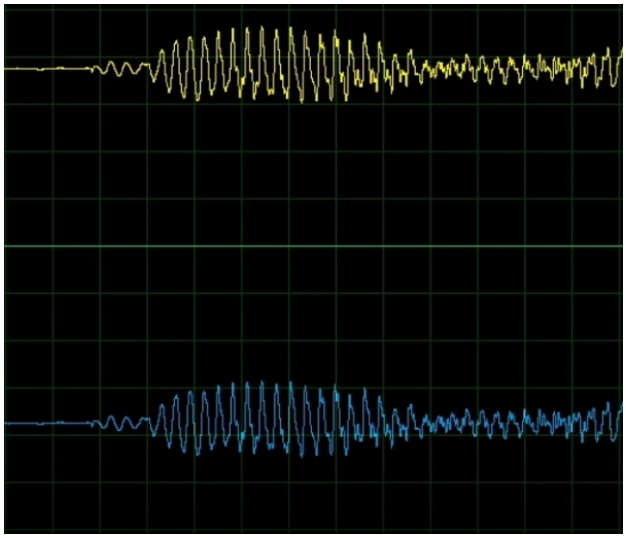

Fig. 5. Simulation 1

CV=2

During this simulation the CV=0 → Gain < 1

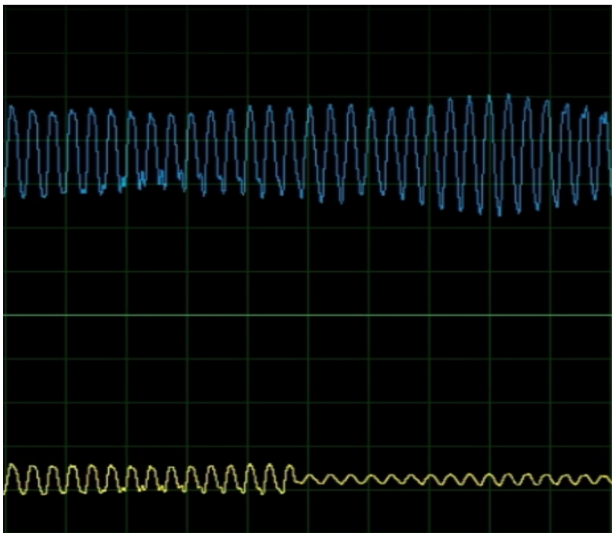

Fig. 6. Simulation 2

2. Peak Detector

Available methods

There are several approaches of obtaining in the framework of peak detection, and these are a few of them.
Diode-capacitor Circuit
Diode-capacitor-Amplifier
Diode-capacitor-RC coupling

Chosen Method:

The Diode-Capacitor-RC coupling is the technique I have selected because of its simple circuit, high efficiency, and high response time.

2.1 functioning

We can create a peak detector by wiring a buffer op amp through a diode and an RC coupling. When the input signal increases, the capacitor charges, and when the input signal decreases, the current flowing from the capacitor will drain through the resistor to ground (the diode blocks the other sense of current flow). This allows us to detect the output from the resistor.

2.2 Schematic

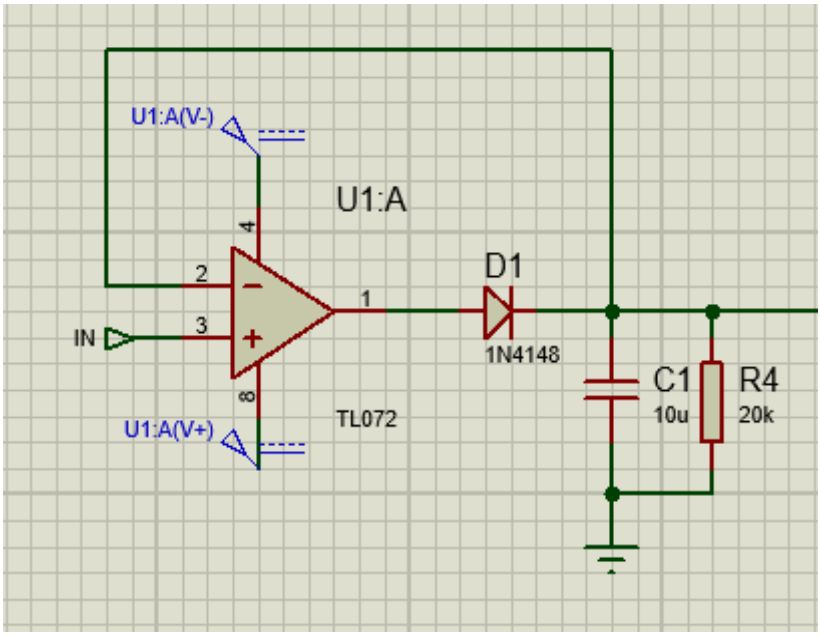

Fig. 7. Simulation Peak detector

2.3 Simulation

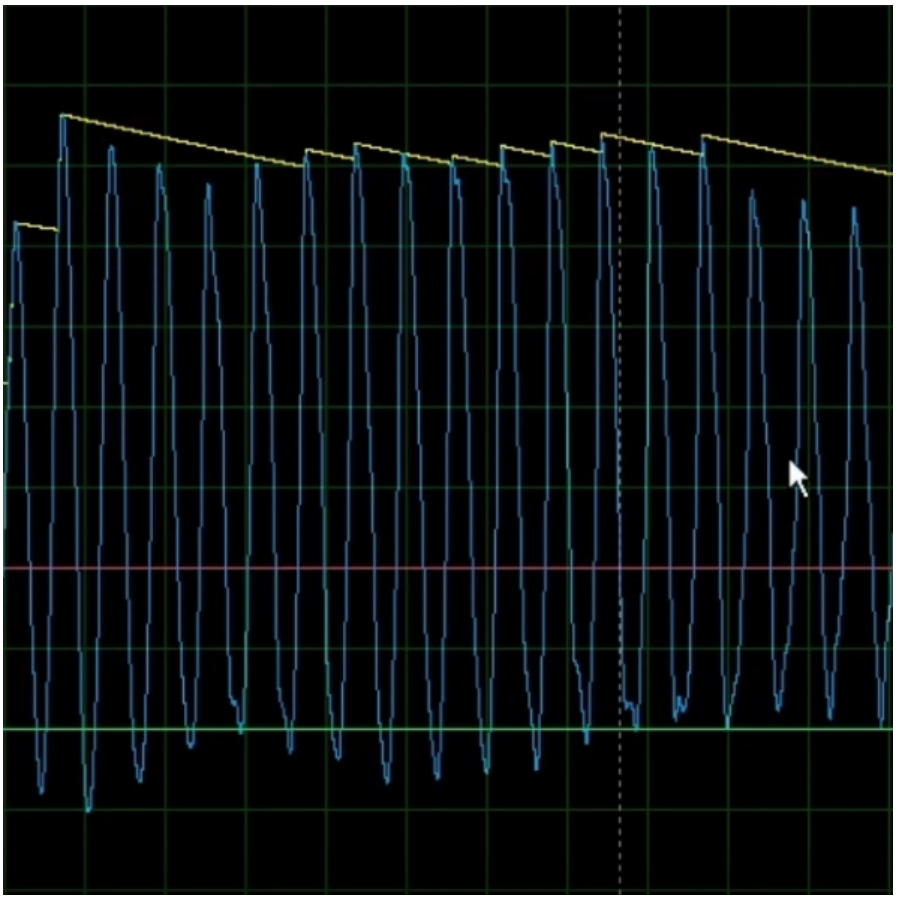

Fig. 8. Simulation Peak detector

Note

Because of its orientated diodes, our control voltage block (built on the preceding block) does not require the negative peaks. In any case, since all of the signals will be somewhat sinusoidal, we do not require the negative sections.

3. Signal Comparator Block

3.1 functioning

The comparator block's operation is really simple, and we do it by utilizing a differential amplifier with gain 1.
The threshold voltage is wired to the amplifier's non-inverting input, so a negative output indicates no change in the signal because the input it is below the threshold, and a positive output indicates a decrease in the signal because it is above the threshold. The output of the comparator block will be the input of the VC block.

Since our input is maximum at 12 volts peak to peak, the threshold element will be a variable voltage that swings between 0 and 6 volts.

3.2 Schematic

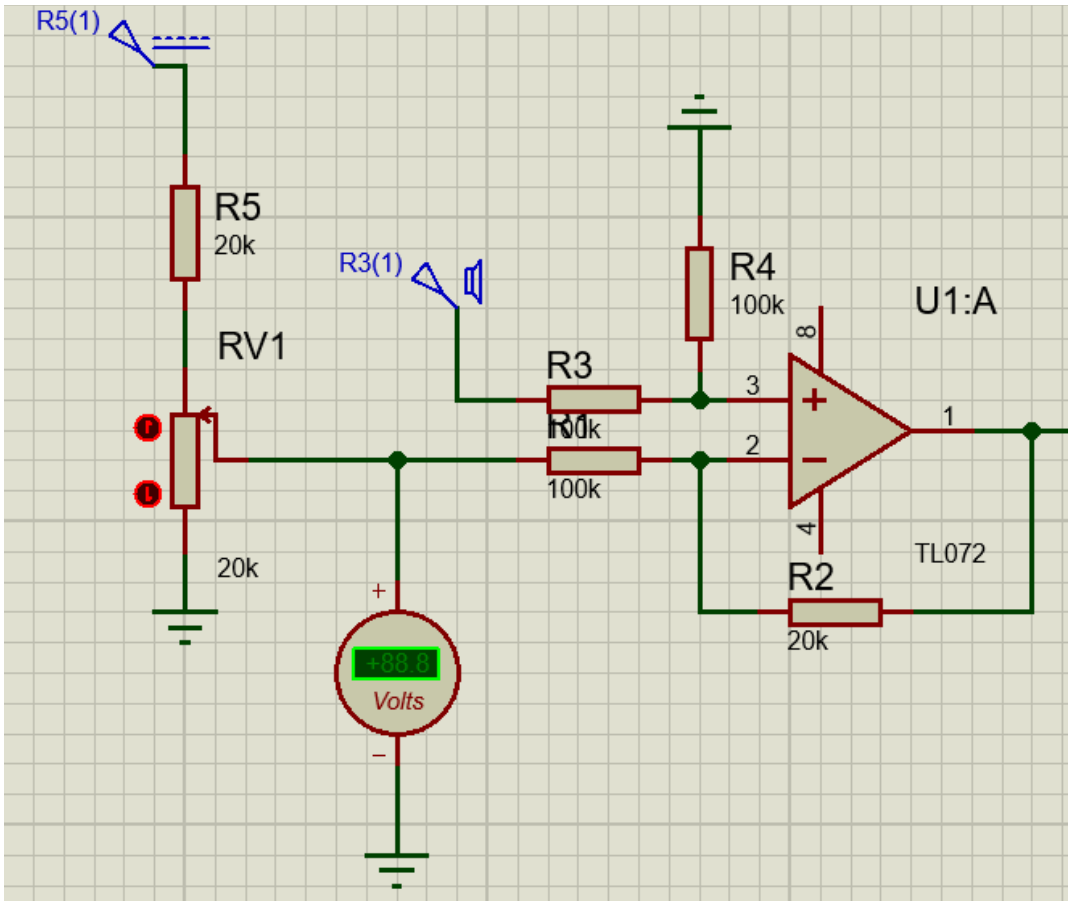

Fig. 9. Comparator Block

4. Assembling

The assembly process is straightforward, combining the previous blocks together and fine-tuning the wiring and input/output pins.

4.1 Schematics

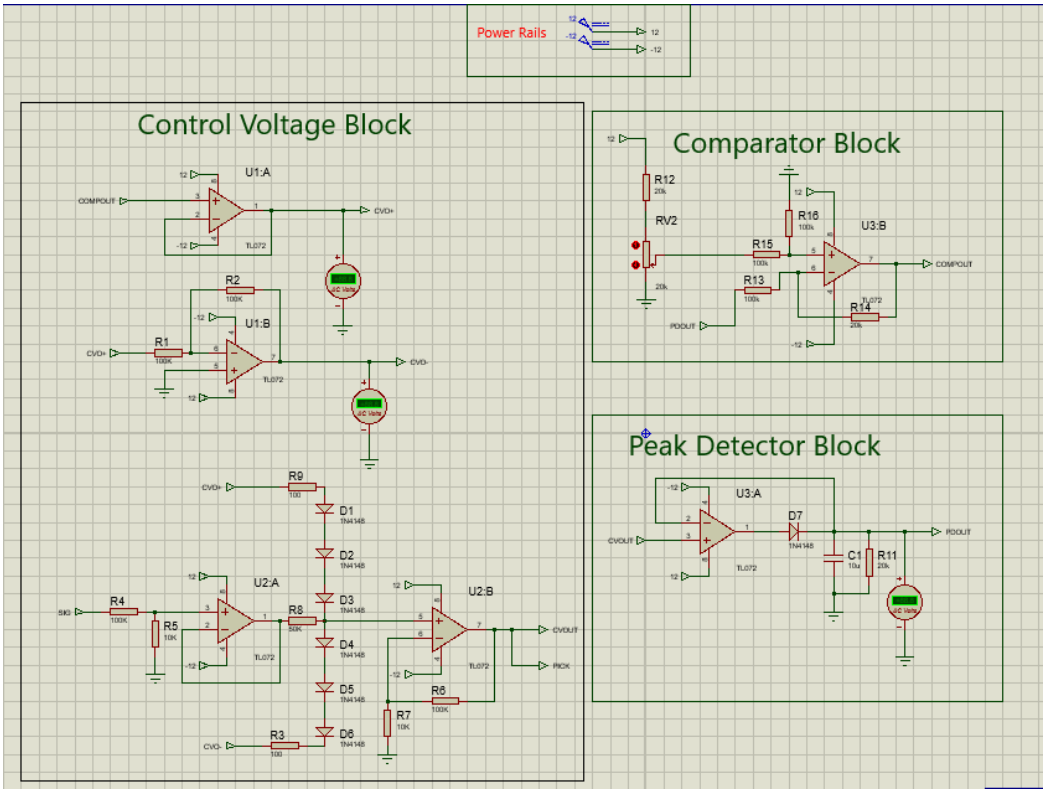

Fig. 10. Assembled Blocks

5. Analyzing

From the tests that I have made through the simulation and my own thinking, I identified a few problems that have caused the system not to fail completely, but it is not behaving as we would like. First, the control voltage inputs (same as the comparator outputs) are always positive even when the threshold is set at 0 volts, so the output signal from the CV will always be shrunken down by some unwanted factor. I also noticed that in the CV input, if the input difference went above 2 volts, the output will be completely silenced, and the signal in the output is somewhat distorted.

6. Proposed Solutions

The main issue with the output being silenced is that the CV input is becoming far too high (approximately 2.5 volts), which will widely open the diodes and drain the output signal completely to ground. My solution to this is to connect a voltage divider of 1/2 between the comparator output and the CV input.

Through experimentation, I discovered that using a 30K resistor and a 10K resistor with a variable potentiometer works best for our desired work.

Schematics After adjustment

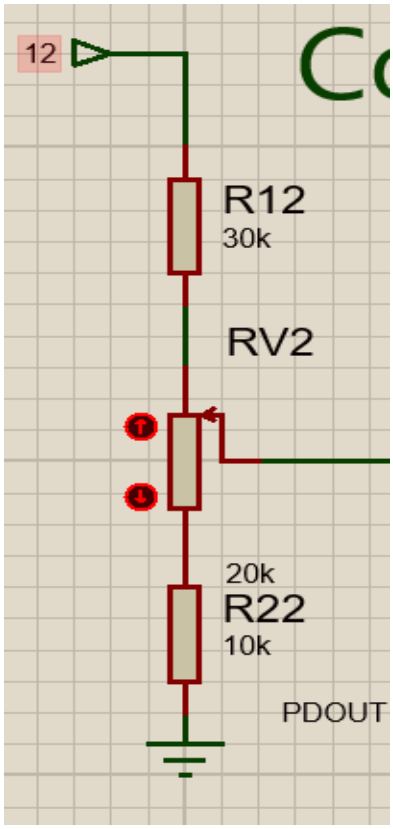

Fig. 11. Refined POT

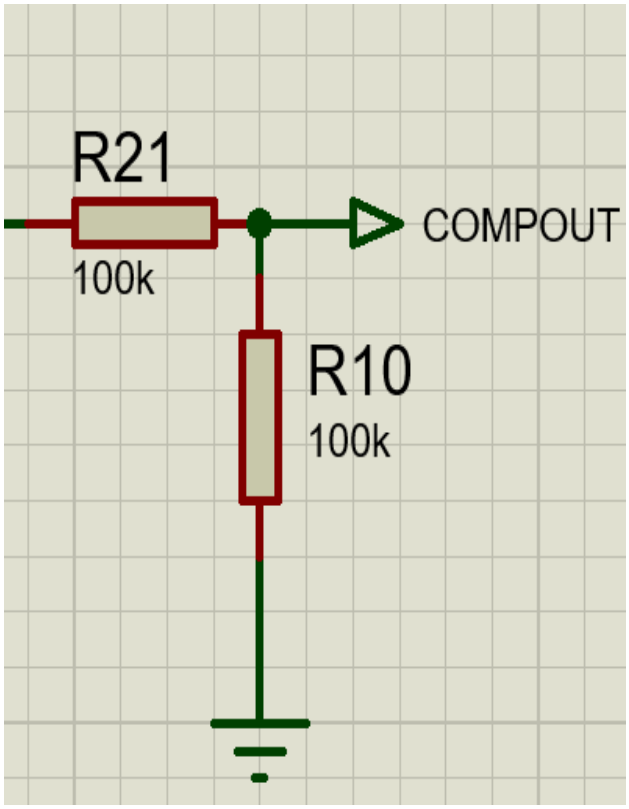

Fig. 12. Refined Compout

7. Adding features

7.1 Attack

Definition

Attack is how quickly the system starts reducing volume after a signal exceeds the desired threshold.

in other-words is how much does the system should wait before reducing the volume of the input.

Explanation

During the testing and debugging phase of the project and its simulation, I identified a simple and effective method for implementing the attack control. This approach is based on manipulating how quickly the peak detector capacitor responds to the incoming signal peak. By slowing the charging rate of the capacitor, the peak detector responds more gradually, which automatically reduces how quickly peak information is passed to the comparator.

As a result, replacing the fixed resistor between the diode and the capacitor with a variable resistor provides a practical solution for implementing the attack feature. In this design, a 100 kΩ potentiometer was used for this purpose.

7.2 Release

Definition

When the input signal level drops below the threshold, the release time is the amount of time needed for the control system to eliminate gain reduction and return to its nominal condition. It controls how the system recovers after attenuation.

Explanation

The release time is implemented using a simple RC-based approach.

The release time constant is defined as $\tau = R \cdot C$, where 10 µF is the fixed value of the capacitor.

The release time is controlled by varying the resistance in the discharge path using a 100 kΩ potentiometer.

To prevent the discharge path from being shorted to ground when the potentiometer is set to its minimum value, a 5 kΩ fixed resistor is placed in series with the potentiometer. This ensures a non-zero minimum resistance and provides safe, stable operation.

As a result, the release time constant is adjustable over a range defined by:

$\tau = (5\ k\Omega \text{ to } 105\ k\Omega) \times 10\ \mu F$ or $\tau \in [50\ ms, 1.05\ s]$.

Schematics After adjustment

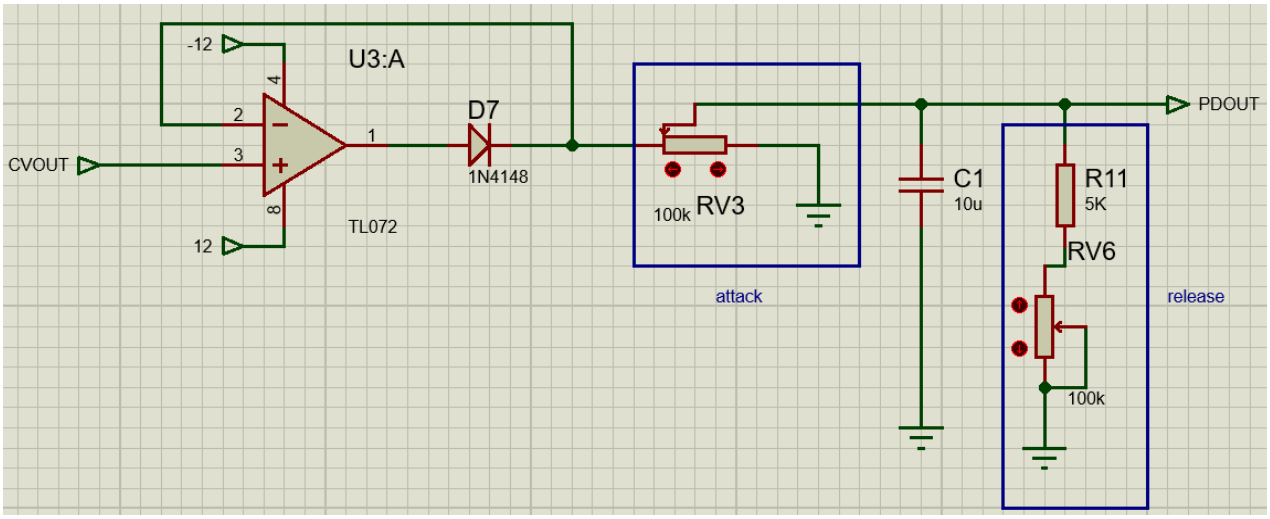

Fig. 13. Attack & Release

7.3 Ratio

Definition

Compression ratio defines how much the system reduces the output signal level relative to the amount by which the input level exceeds a defined threshold.

Explanation

The ratio determines the relationship between input level exceedance and the resulting gain reduction applied by the system. In the proposed design, the ratio is implemented by scaling the comparator output using a variable voltage divider. By attenuating the control voltage that drives the gain-control stage, the system adjusts how aggressively gain is reduced once the threshold is exceeded. Higher divider output results in stronger gain reduction (higher ratio), while lower divider output produces gentler compression behavior (lower ratio).

Schematics After adjustment

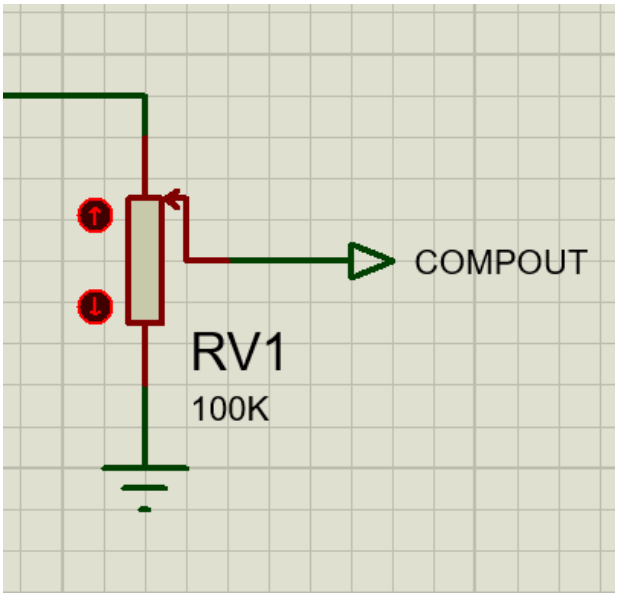

Fig. 14. Ratio

7.4 Gain Amplifier

Definition

I wanted to include a feature that may have a gain amplifier in case the input is a bit too quiet. There will be two types of Either the output remains unchanged or it is amplified using a variable resistor.

Explanation

Adding a non-inverting amplifier with variable gain and controlling it with a variable resistor in series with a constant one will make the gain application quite simple. As a result, the gain is only an amplifier and cannot function as an attenuator.

Schematics After adjustment

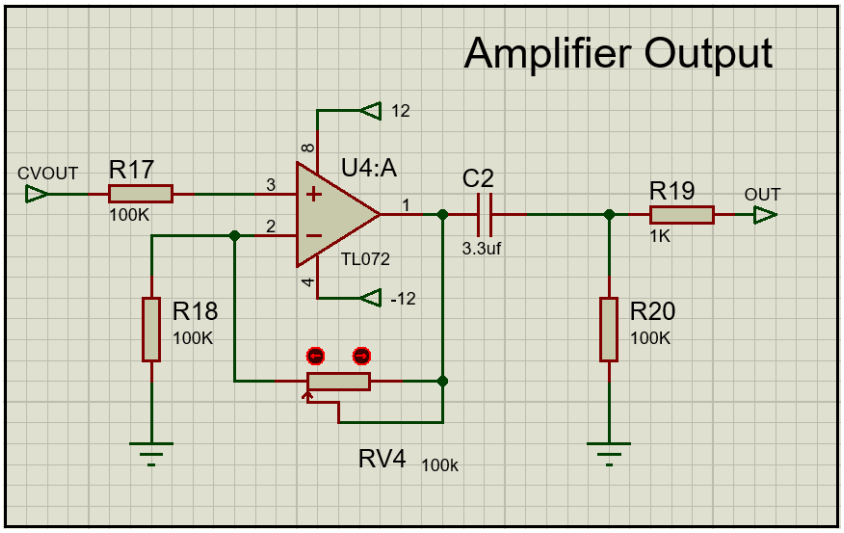

Fig. 15. Variable Gain Amplifier

8. Analyzing

According to my observations, the existing circuit is usage of a negative threshold to force the signal to zero will not result in smooth attenuation, instead it will appear to be a cutoff point that the user may not be comfortable with.

I also want to add a led indication or an LED-follower for a basic led visualisation on the output, which would be a wonderful addition.

I have also noticed that, given the current state of the project, I have decided to separate the amplifier and LED visulizer blocks as an addition because the system has become unaffordable and

those two blocks are not necessary for the core system. Therefore, they will function as a subsystem to the core, and whether or not to obtain them is completely optional

Since our threshold is set at 6 volts, I would add a system that would clamp the input at a maximum of 6 volts, or 12 volts peak to peak, to ensure that the system operates flawlessly and without distortion or damaging the components.

8.1 LED-Follower

Explanation

I utilized a couple of 2N2222 transistors for the LED follower block. Since the peak detector is already operational, we can use it, amplify it and detect the opening and shutting of certain LEDs with a level utilizing potential voltage deviders for each level.

Schematics After adjustment

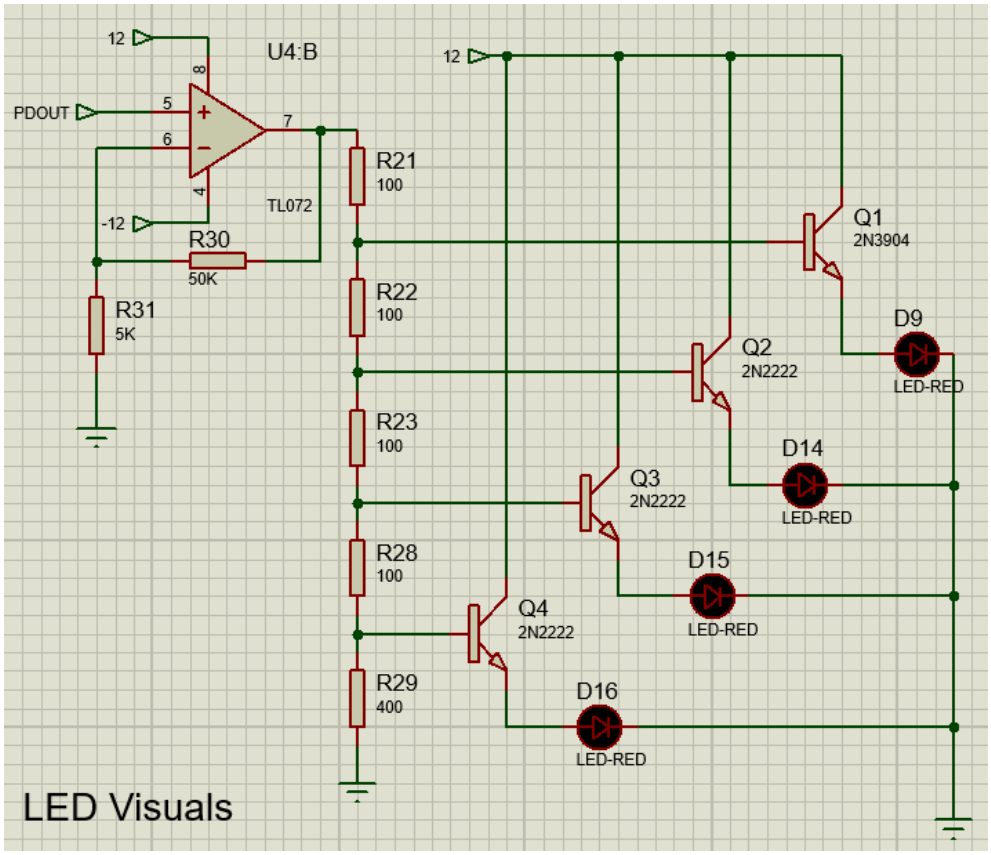

Fig. 16. Led-Visuals

8.2 Attenuation problem

This is a simple solution. The issue vanished after I replaced the liear potentiometer with a logarithmic one.

8.3 Maximum input

This is a simple solution. Since our threshold is about 6 volts, I will be adding a zener diode calamp to the system's input. After a brief search, I discovered that a zener diode using two 1n5232b diodes will clamp the input to a maximum of about 6.2 volts, which is acceptable in our situation and should make the input clamped to that voltages and ensure good system functioning.

Schematics After adjustment

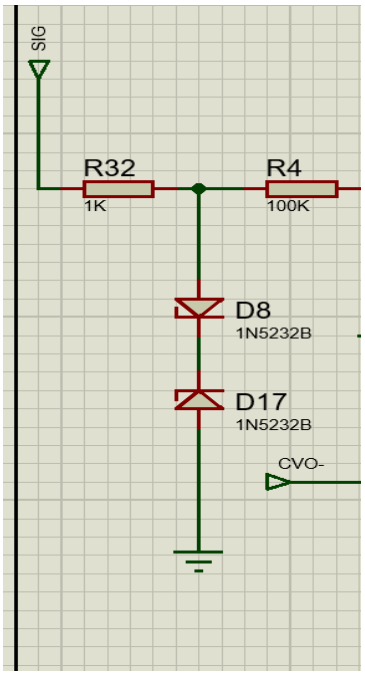

Fig. 17. Input Clamping

9. Changing the CAD

Since the CAD program I have been using (PROTEUS or "ISIS") from LabCenter is a paid program, I wanted this project to be open source, accessible to everyone in the community, and available on a free CAD. For this reason, I chose KICAD, the most popular and widely used program.

9.1 Changes

Since this is the final revision to the schematics, a number of changes had to be made before moving on to the layout:

-all inputs are now made to receive an external signal.

-Three connectors for +12, -12 volts for power, and ground

-To ensure that the system is powered on, an indicator LED connected to 12 volts was added.

-Two audio jacks were added, one for input and one for output.

-I added a switch to alternate between amplified output and raw output because our system has optional sub blocks (you can tie the other switch pin to ground if the sub amplifier system is not in use).

-As the led follower and amplifier inputs are subsystems that are optional to use, there will be two pinheads that will ensure the connection between them and the system using jumper wires. I attached these pinheads to the peak detector input and CV output pins so they can be used.

-Since our core system has six amplifiers in total, I used one TL074 quad amplifier and one TL072 amplifier instead of three TL072 dual amplifiers, which would have cost money and taken up space. The sub blocks (led follower and amplifier) that are connected together will be powered by a single TL072 dual amplifier.

-Adding two pins for the 12v and -12v for the subsystems standalone.

9.1 Schematics after changes

Control Voltage Block

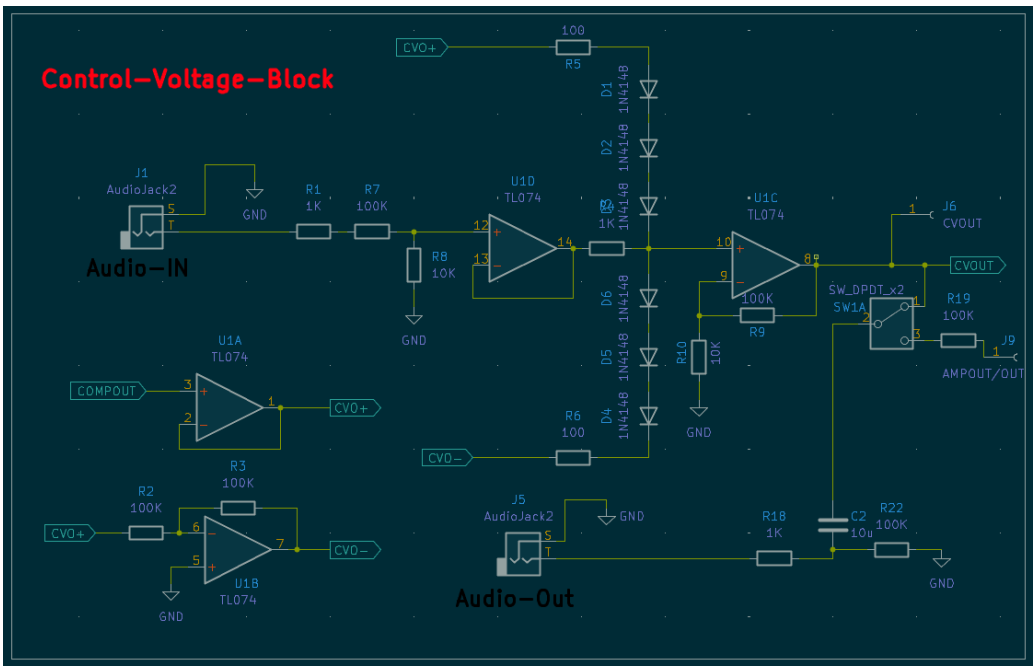

Fig. 18. CV with KiCad

Peak Detector Block

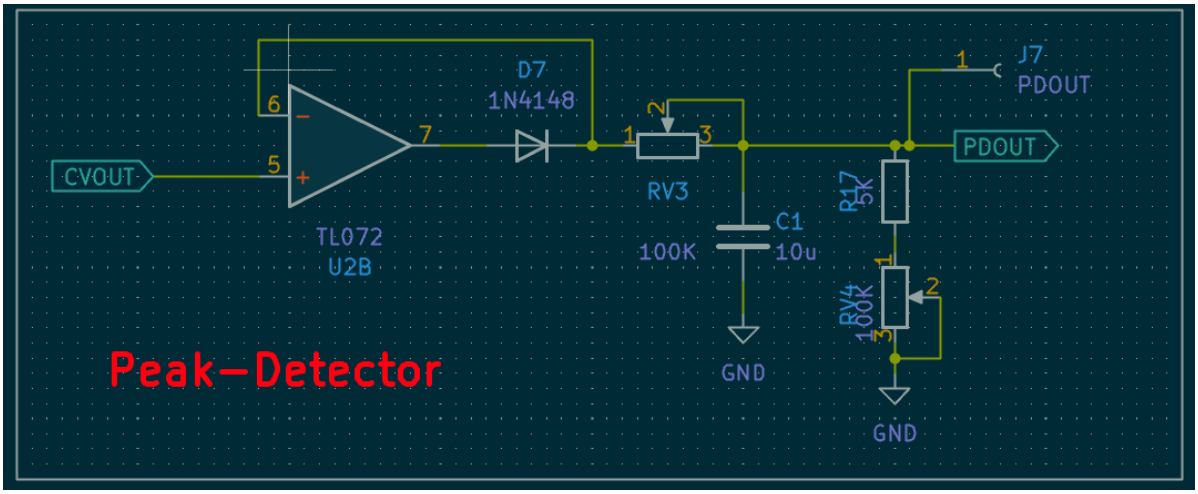

Fig. 19. Peak Detector with KiCad

Comparator

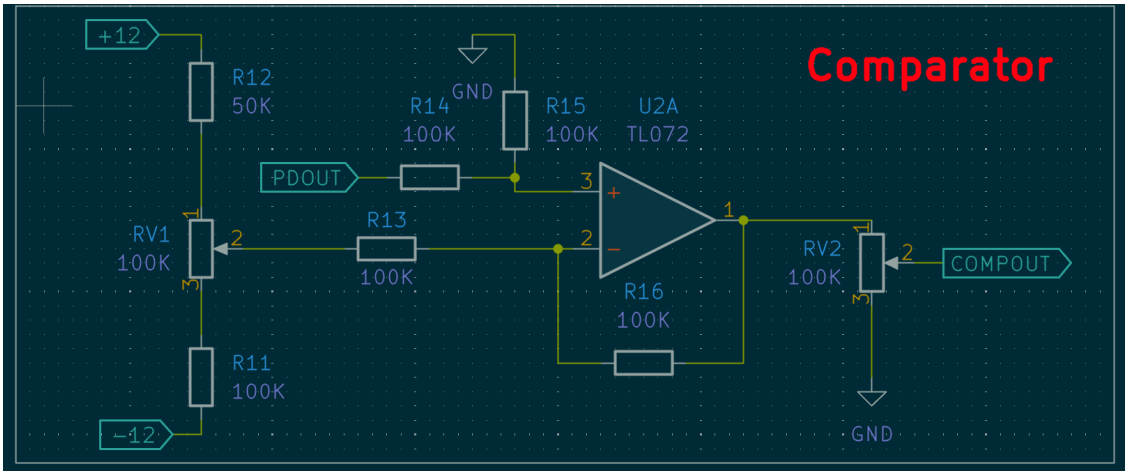

Fig. 20. Comparator with KiCad

Power Rails

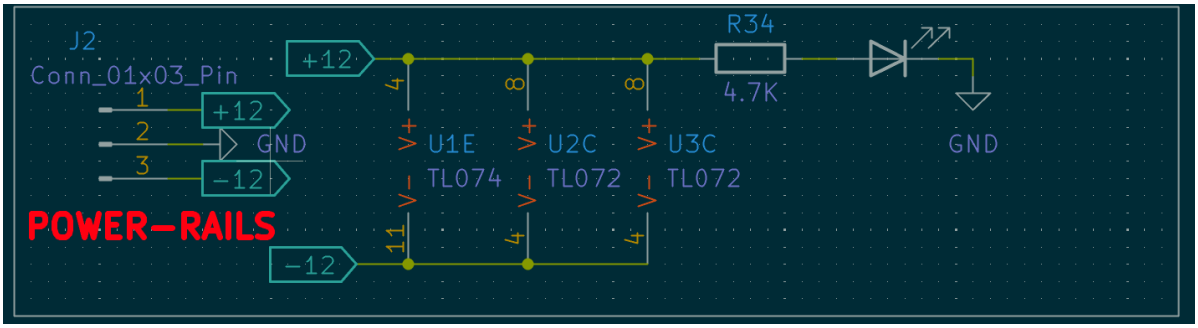

Fig. 21. Power Rails with KiCad

Amplifier

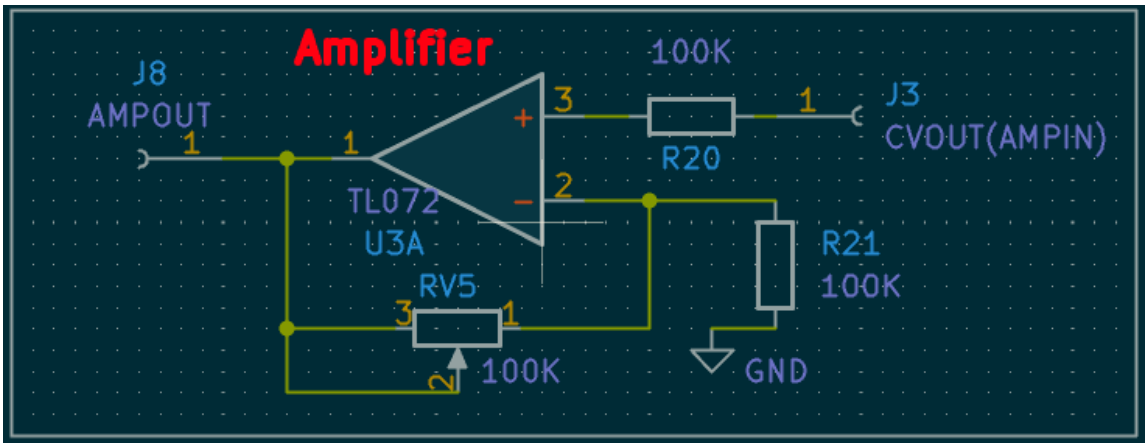

Fig. 22. Amplifier with KiCad

LED Follower Block

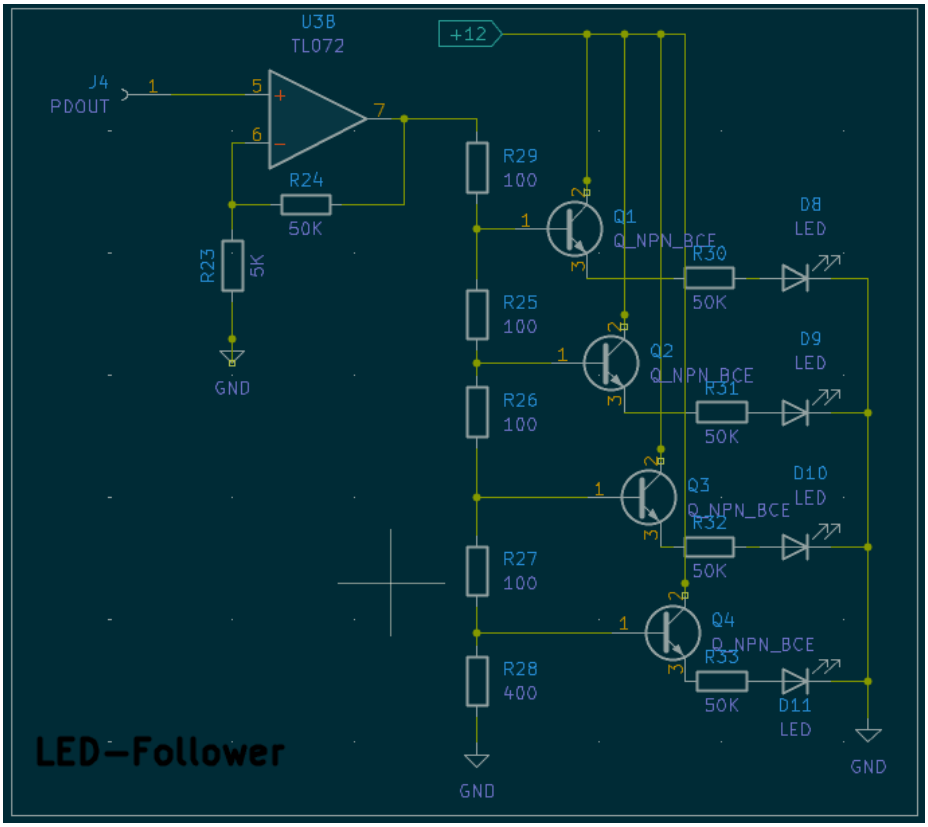

Fig. 23. Led Follower with KiCad

Full schematics

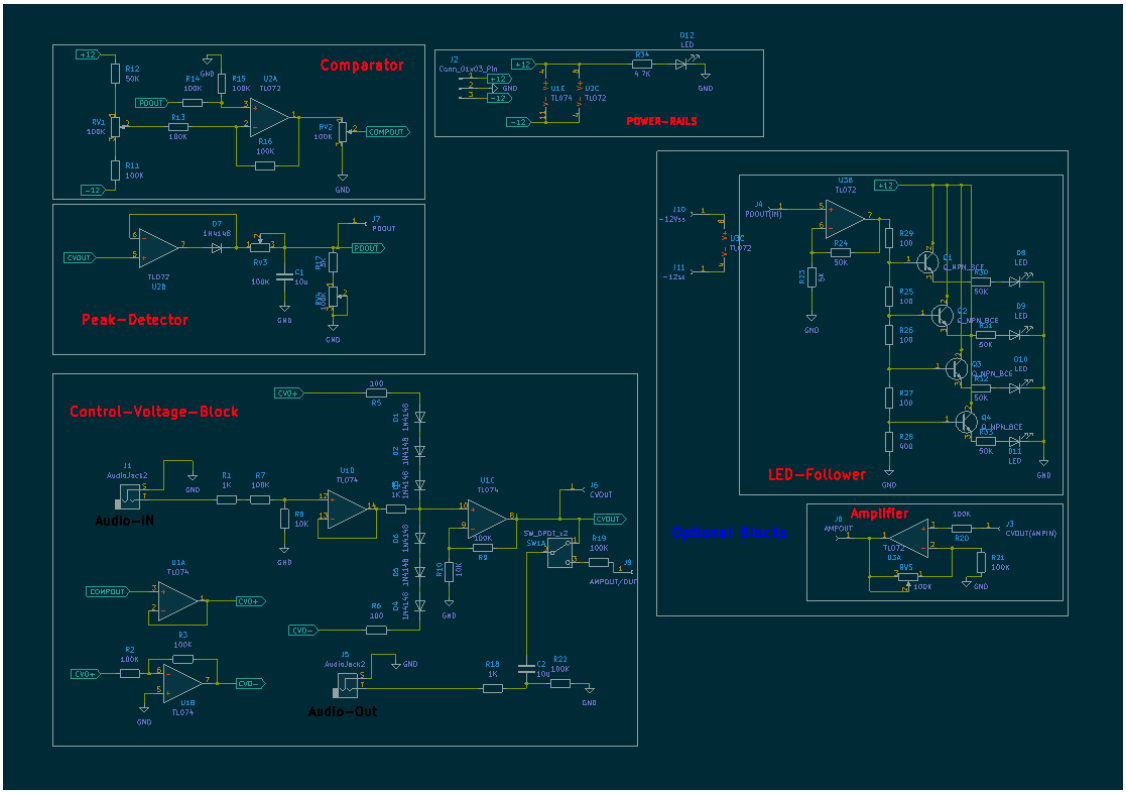

Fig. 24. Full schematics with KiCad

10. Preliminary Bill of Materials and Cost Analysis

10.1 Bill of Materials

Reference(s)	Qty	Component Description	Value / Part
C1, C2	2	Electrolytic capacitor	10 µF
D1–D7	7	Signal diode	1N4148
D8–D12	5	Indicator LED	3 mm LED
J1, J5	2	Mono audio jack (TS)	6.35 mm
J2	1	Power connector	3-pin (+12 V / GND / −12 V)
J3–J11	7	Pin header / test point	1×1
Q1–Q4	4	NPN transistor	General-purpose BJT
R1, R4, R18	3	Resistor	1 kΩ
R2, R3, R7, R9, R11, R13–R16, R19–R22	13	Resistor	100 kΩ
R5, R6, R25–R27, R29	6	Resistor	100 Ω
R8, R10	2	Resistor	10 kΩ
R12, R24, R30–R33	6	Resistor	50 kΩ
R17, R23	2	Resistor	5 kΩ
R28	1	Resistor	400 Ω
R34	1	Resistor (LED limiter)	4.7 kΩ
RV1–RV5	5	Trimmer potentiometer	100 kΩ
SW1	1	Toggle switch	DPDT
U1	1	Operational amplifier	TL074
U2, U3	2	Operational amplifier	TL072

The bill of materials was generated from the finalized schematic in KiCad. Package footprints and PCB-specific details are omitted, as the BOM represents the schematic-level design prior to PCB layout and routing.

10.2 Cost Analysis

Item	Qty	Unit (USD)	Subtotal (USD)	Subtotal (TND)
TL074 (quad op-amp)	1	1.31	1.31	3.82
TL072 (dual op-amp)	2	1.04	2.08	6.05
Trimmer potentiometer Bourns 3386P	5	2.20	11.00	32.02
Neutrik NJ2FD-V mono jack (TS)	2	2.05	4.10	11.93
Phoenix Contact 3-pos power connector (1836309)	1	1.23	1.23	3.58
C&K JS202011CQN DPDT switch	1	0.74	0.74	2.15
2N3904 (or similar) NPN transistor	4	0.15	0.60	1.75
1N4148 diode	7	0.10	0.70	2.04
3 mm LED (indicator)	5	0.40	2.00	5.82
10 µF electrolytic capacitor	2	0.21	0.42	1.22
Resistors (axial, ¼W)	34	0.01*	0.34	0.99
1×1 pin headers / test pins	7	0.05*	0.35	1.02

Estimated total (components only): $24.87 ≈ 72.38 TND

The cost estimation is based on low-quantity distributor pricing for representative parts. Passive components (resistors, basic headers) are costed using typical bulk pricing. This estimate excludes PCB fabrication, shipping, taxes, and assembly.

11. Power Consumption and Dissipation Analysis

Supply rails

The circuit is powered from a symmetric dual supply:

$V+ = +12\ V$

$V- = -12\ V$

Total power drawn from the supply is:

$P_{TOTAL} = (12 \cdot I+) + (12 \cdot I-)$

11.1 Operational amplifier quiescent current (typical)

The TL07x family datasheets specify typical supply current of approximately **1.4 mA per amplifier** (no load, $T_A = 25\circ C$).

The design includes:

TL074 (quad): 4 amplifiers

Two TL072 (dual + dual): 4 amplifiers total

Total number of amplifiers:

$$N = 4 + 2 \cdot 2 = 8$$

Total quiescent current for all amplifiers:

$$I_{opamp,T} \approx N \cdot 1.4\ \text{mA} = 8 \cdot 1.4\ \text{mA} = 11.2\ \text{mA}$$

For a symmetric supply, a reasonable approximation is that quiescent current is split between the rails:

$$I_{opamp,+} \approx I_{opamp,-} \approx \frac{11.2}{2} = 5.6\ \text{mA}$$

11.2 Indicator LED current and resistor dissipation

Each indicator LED is powered from +12 V with a 4.7 kΩ series resistor. Assuming a typical LED forward voltage of $V_f \approx 2.0$ the LED current when ON is:

$$I_{LED} = (12 - V_f)/R = \frac{(12-2)}{4700} = \mathbf{2.13\ mA}$$

Worst-case LED condition (all 5 LEDs ON simultaneously):

$$I_{LED,total} = 5 \cdot 2.13\ \text{mA} = \mathbf{10.65\ mA}$$

Resistor power dissipation per LED:

$$P_R = I^2R = (0.00213)^2 \cdot 4700 \approx \mathbf{0.021\ W}$$

Therefore, standard 0.25 W resistors provide a large safety margin.

11.3 Rail current estimates

Worst-case (all LEDs ON):

$$I_+ \approx I_{opamp,+} + I_{LED,total} = 5.6 + 10.65 = \mathbf{15.25\ mA}$$

11.4 Total power drawn from the supply

$$P_{TOTAL} = 12(I_+ + I_-) = 12(0.01875 + 0.0081) = 12(0.02685) = 0.322\ \text{W}$$

11.5 Conclusion

The circuit is low-power in design. With a typical TL07x quiescent current of ~1.4 mA per amplifier and worst-case LED activity, the total power drawn from a ±12 V supply is around0.32 W. The maximum resistor dissipation in LED limit resistors is approximately 0.021 W, which is significantly lower than the standard 0.25 W rating. As a result, no special thermal measures are required for normal operation, and the chosen component ratings provide adequate margins.

III. PCB And Layout

Clarifications