Industrial Machinery Vibration Monitor

Automatic Safety Cut-off System

Course: EE-117 (Section C)
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1 Abstract

This project details the design and simulation of a discrete transistor-based protection circuit titled the **“Industrial Machinery Vibration Monitor.”** Designed to mitigate catastrophic mechanical failures in rotating equipment, this system detects vibration anomalies using a piezoelectric-style sensing model. It utilizes a two-stage amplifier and a latching switch to trigger an automatic safety cut-off. Simulation results confirm a fast response time and reliable performance under varying industrial conditions.

2 Introduction

2.1 Problem Statement

Vibrations in industrial turbines and motors are often the first sign of bearing failure or structural imbalance. If these vibrations exceed safety limits, they can cause catastrophic mechanical failure, leading to expensive repairs and safety risks.

2.2 Solution

We propose a cost-effective, automatic electronic cutoff system. By using discrete transistors, we can create a robust circuit that monitors vibration in real-time and cuts power to the machinery if a threshold is crossed, without the need for expensive PLC-integrated sensors.

2.3 Theoretical Framework

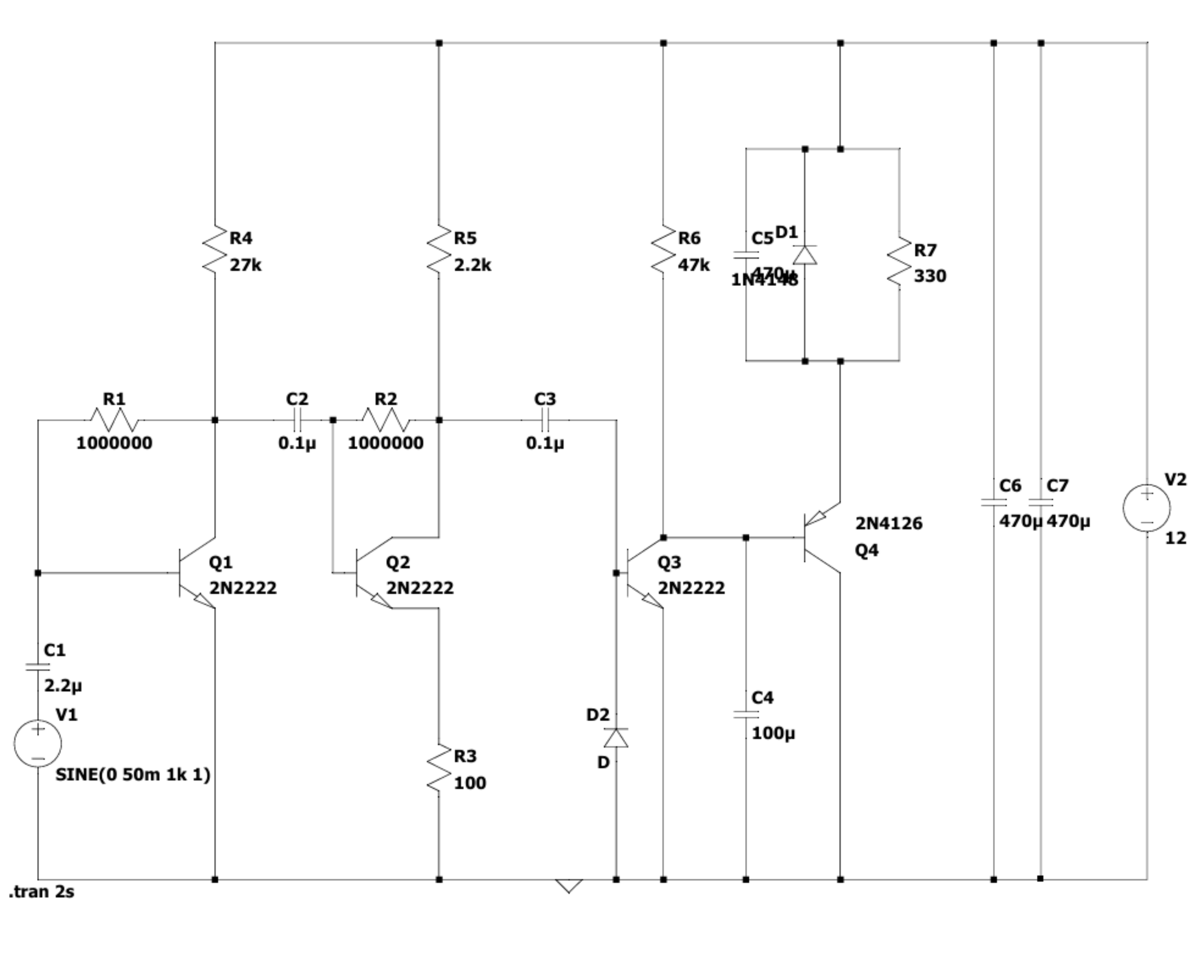
The system relies on two core principles:

- **Piezoelectric Sensors:** These act as the input, producing an AC signal proportional to the mechanical stress/vibration.
- **Common Emitter Amplifiers:** Transistors T1 and T2 are configured as Common Emitter stages to provide the high voltage gain necessary to convert millivolt-level vibrations into logic-level signals.

3 Circuit Design

3.1 LTspice Schematic

The schematic below illustrates the signal path from the AC vibration source through the amplification, rectification, and switching stages.



3.2 Component Justification

Component	Justification
Transistors Q1 & Q2 (NPN - 2N2222)	Selected for high gain and low noise. Configured as a two-stage Common Emitter amplifier to boost the millivolt-level vibration signal into a usable voltage swing. **Biasing**: Biased in the active region to ensure linear amplification without signal distortion.
Transistor Q3 (NPN - 2N2222)	Functions as the Detector Switch. It discharges the timing capacitor (C4) whenever a vibration signal exceeds the 0.7V base-emitter threshold.
Transistor Q4 (PNP - 2N4126)	A PNP transistor used for "High-Side Switching." It remains OFF when the system is idle (Base High) and turns ON to power the load when the detector stage pulls its Base voltage Low.
Detector Diode D2 (1N4148)	Acts as a Negative Clamp. It prevents the AC signal from swinging negative at the base of Q3, protecting the transistor and ensuring only positive pulses trigger the switch.
Flyback Diode D1 (1N4148)	Connected in parallel with the inductive load (Relay). It protects Transistor Q4 from high-voltage spikes (Back EMF) generated when the relay coil is suddenly turned off.
Timing Capacitor C4 (100μF)	Acts as the Hold Timer. It smooths the rapid pulses from the detector into a steady DC signal, preventing the relay from "chattering" (rapidly clicking on and off) during vibration.
Power Supply Capacitor C7 (470μF)	Acts as a Bulk Decoupling Capacitor. It stabilizes the 12V power rail, preventing voltage dips when the relay activates and filtering out noise from the power supply.

Coupling Capacitors C2, C3 (0.1μF) & Input C1 (2.2μF)	These isolate the DC bias of each stage while allowing the AC vibration signal to pass through.
Load Resistor R7 (330Ω):	Represents the resistance of the 12V Relay Coil or the safety actuator being driven.
Gain Resistor R3 (100Ω)	Sets the high gain of the second amplifier stage, ensuring the system is sensitive enough to detect even minor fault vibrations.

4 Circuit Operation & Analysis

4.1 Transient Response & Amplification

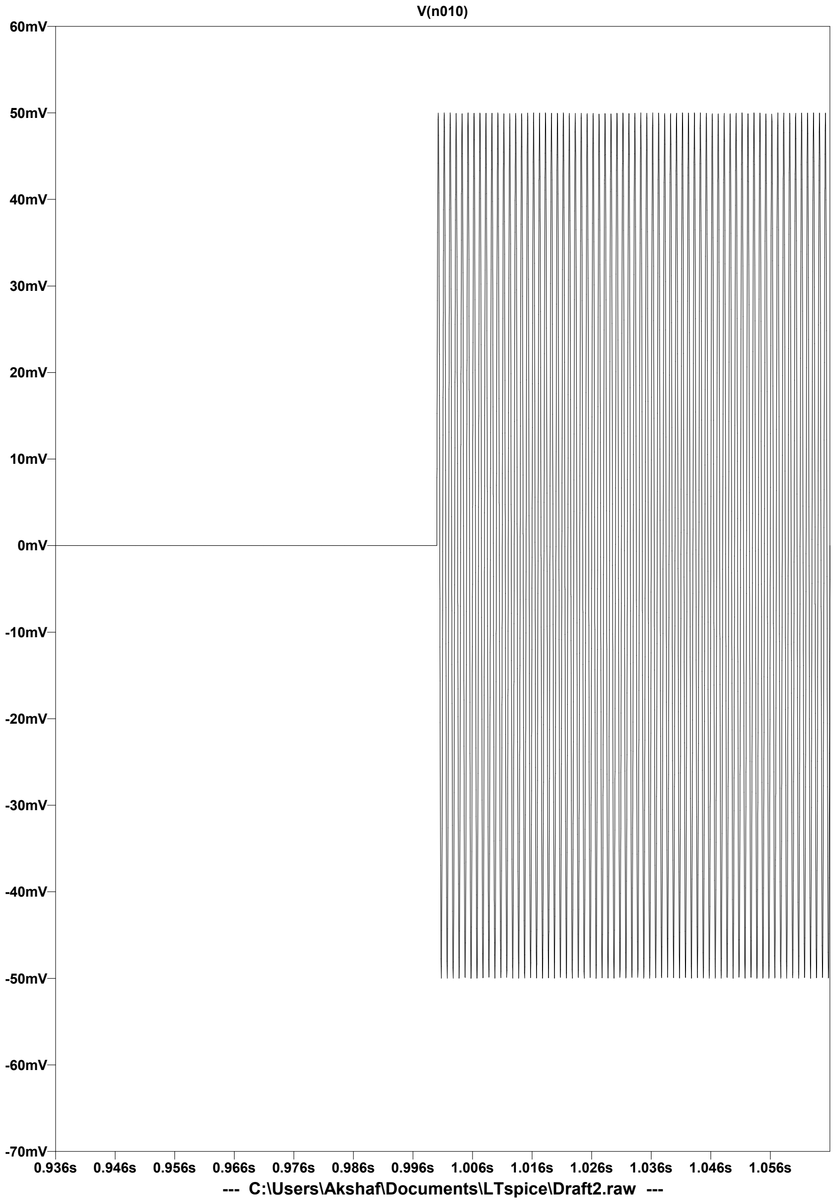


Figure 1: Input signal supplied by a Sine voltage source with an amplitude of 50mV, used to simulate the sensor with a delay of 1s

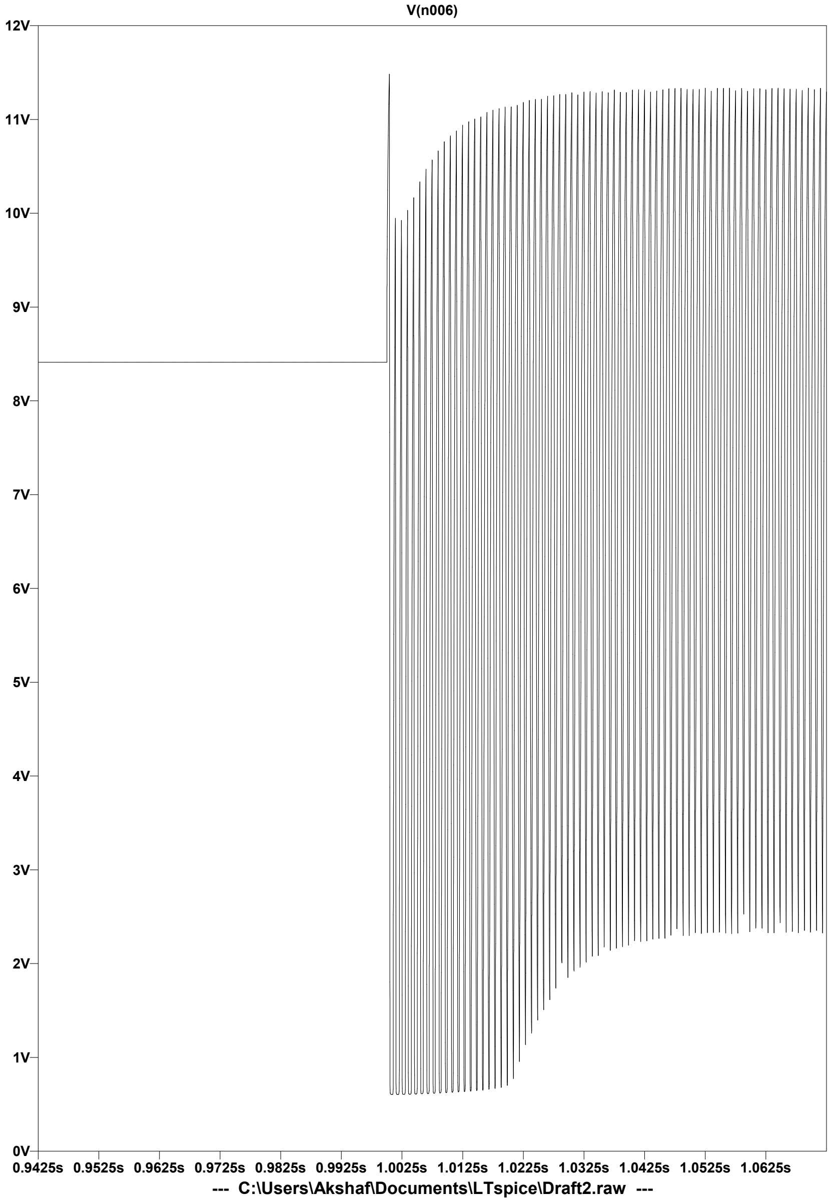


Figure 2: Amplified input signal at Q2_collector, amplified by the two stage common emitter amplifier

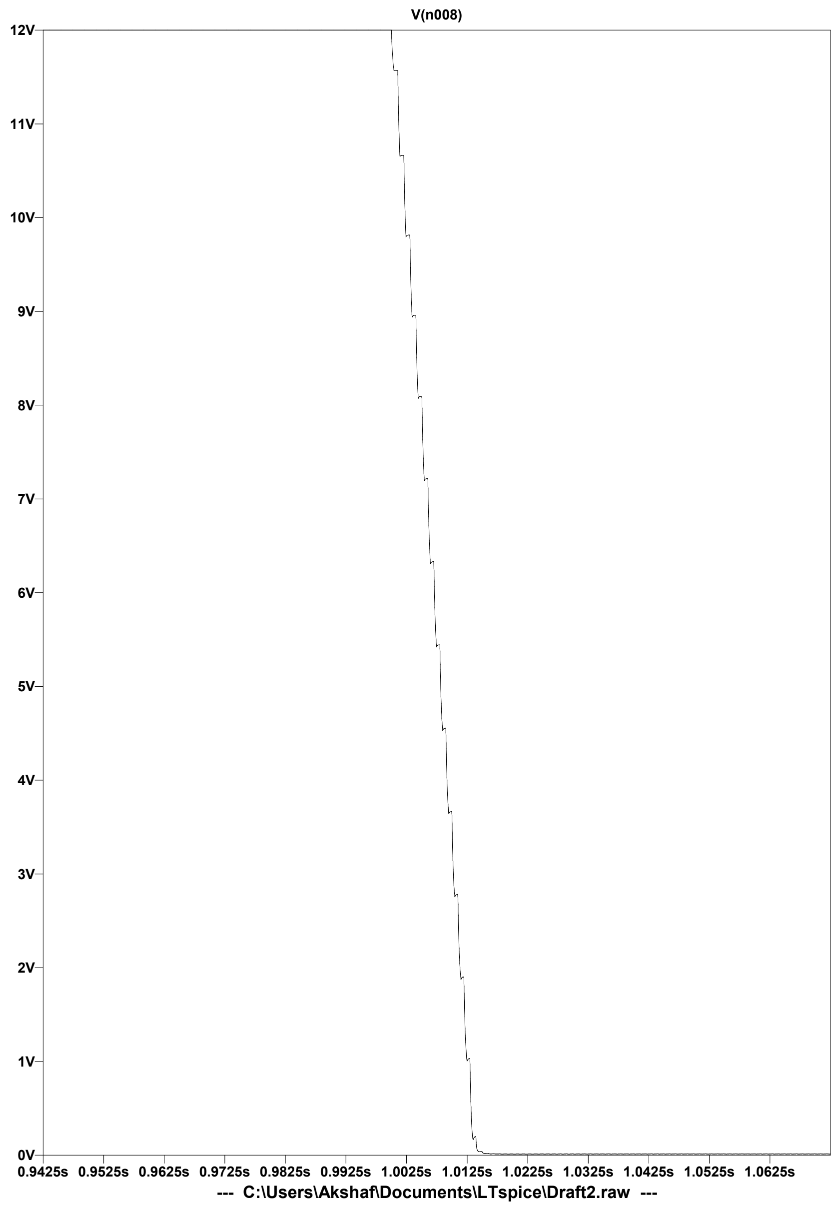


Figure 3: The capacitor C4 discharging/dropping to 0V as the voltage exceeds 0.65V at the base of Q3, which in turn, turns the PNP Q4 ON, and the relay/load is activated.

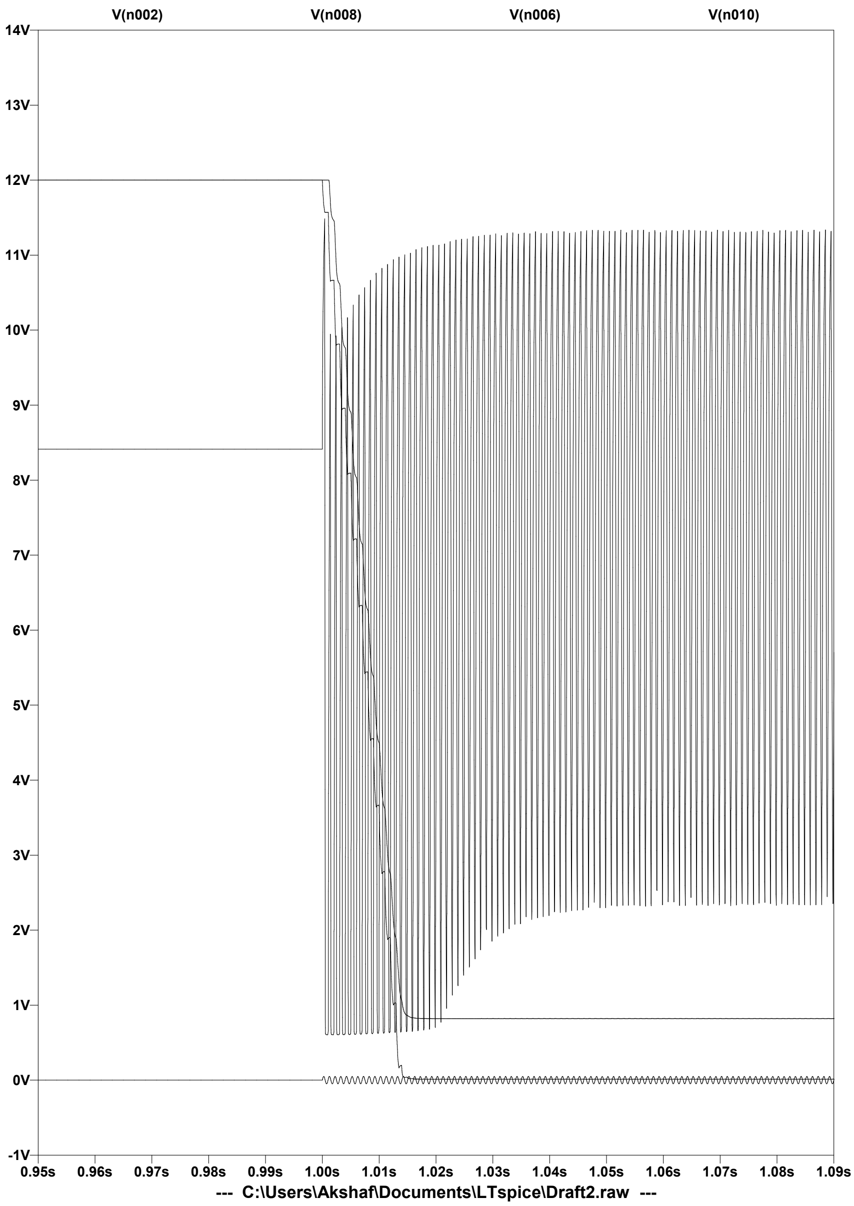
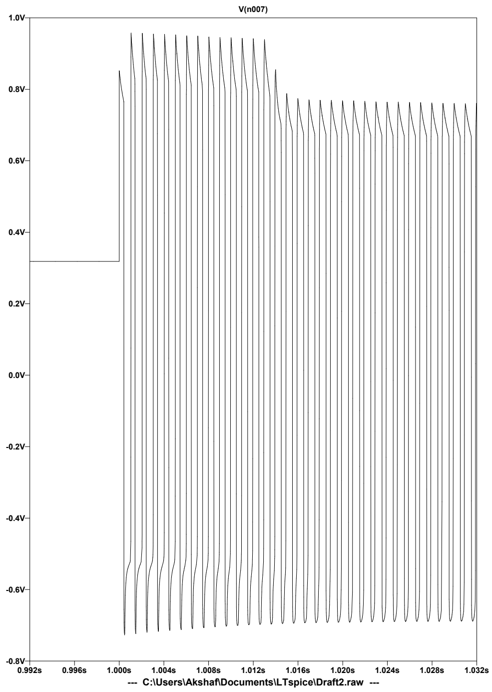


Figure 4: A combined transient graph of the whole circuit

4.2 Detection & Rectification



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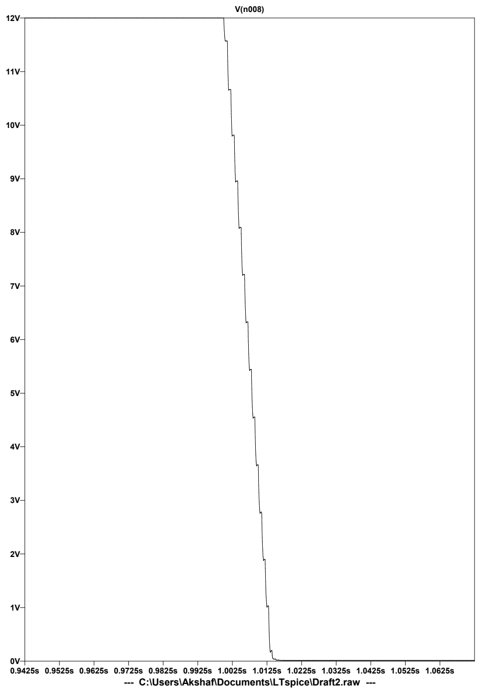

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The rectification stage (T3) successfully converts the amplified AC pulses into a logic LOW signal. This signal is used to discharge the timing capacitor, initiating the cutoff sequence.

4.3 DC Sweep: Threshold Analysis

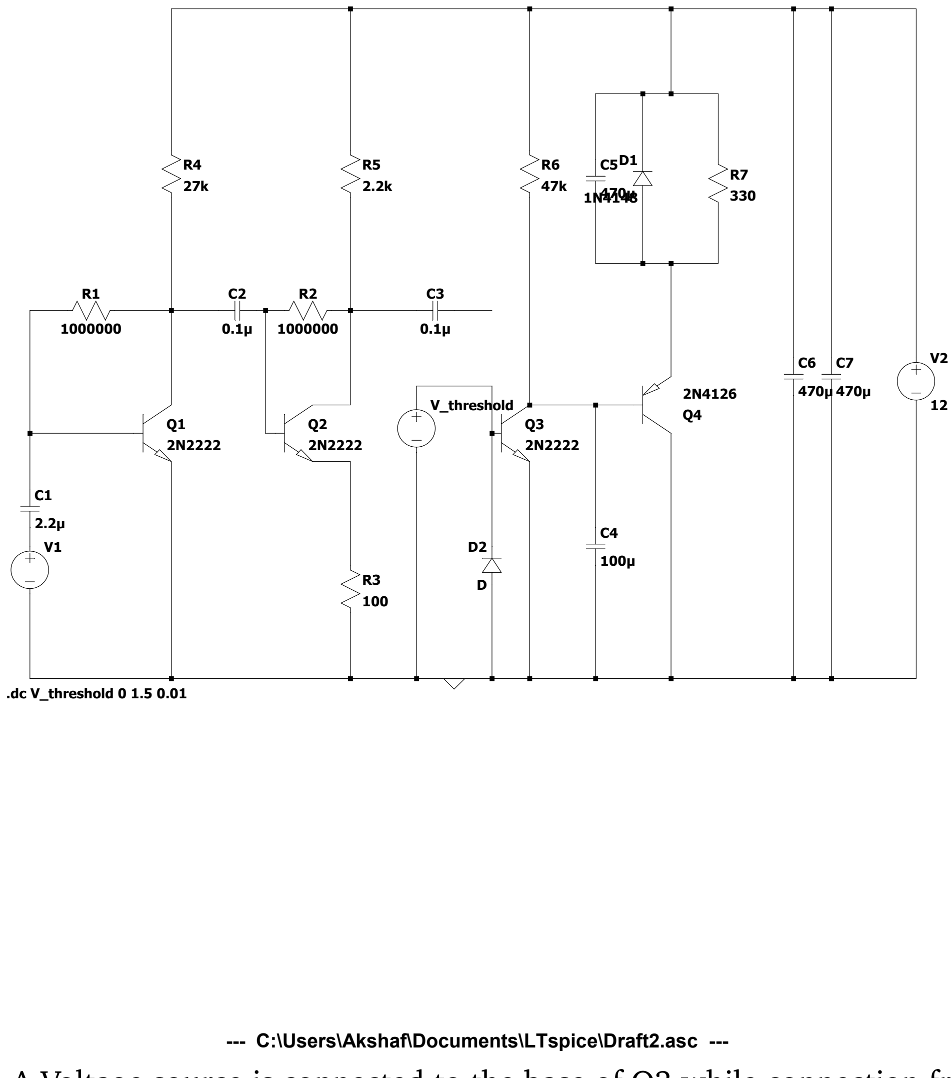

Figure 5: A Voltage source is connected to the base of Q3 while connection from input signal from Q2 is removed

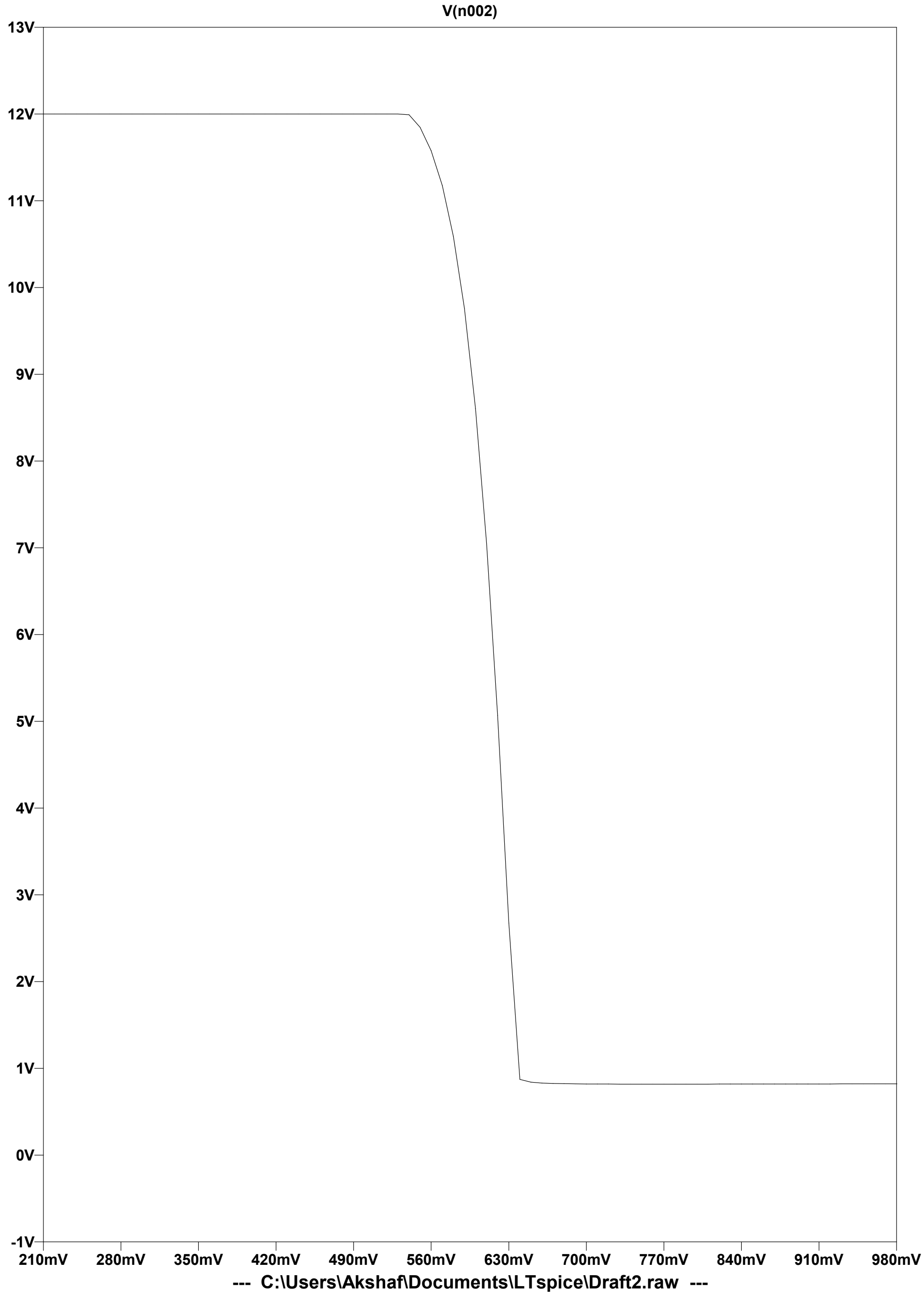

Figure 6: Precise trigger threshold of 632mV

Since the input stages are AC-coupled, a standard DC sweep cannot be performed at the input. Instead, we performed a DC sweep on the Detector Stage (Q3). The graph confirms that the switching mechanism has a precise trigger threshold of $0.65V$. This proves that the Rectifier stage must charge Capacitor C6 to at least $0.65V$ to activate the safety cutoff.

4.4 AC Analysis

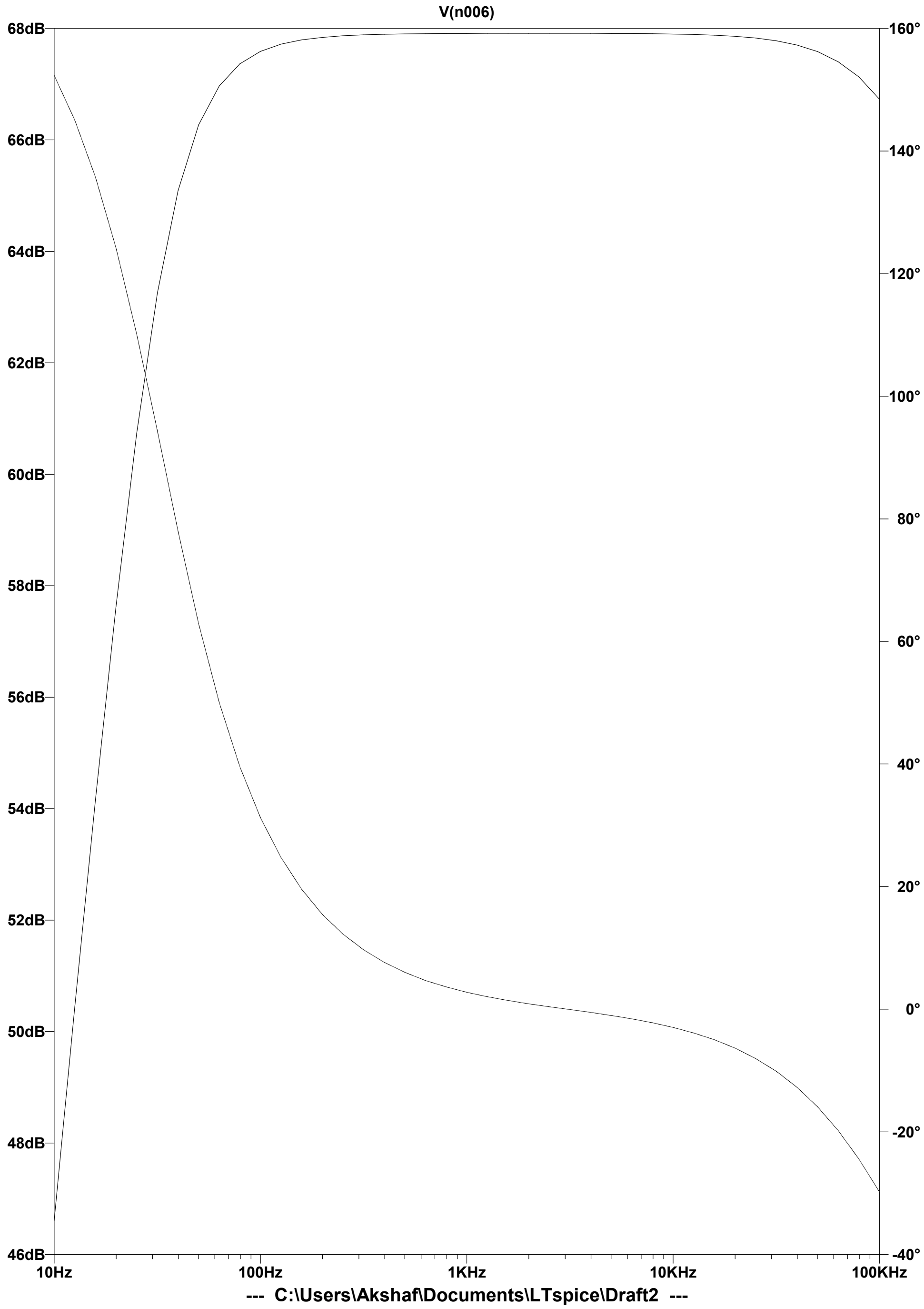

Figure 7: Frequency Response (Bode plot)

The simulation results demonstrate a peak voltage gain of approximately 68dB (2500 V/V). The circuit exhibits a high-pass characteristic with a cut-off frequency near 50Hz, effectively rejecting low-frequency noise while maintaining maximum sensitivity for industrial vibration frequencies between 100Hz and 10kHz.

4.5 Noise Analysis

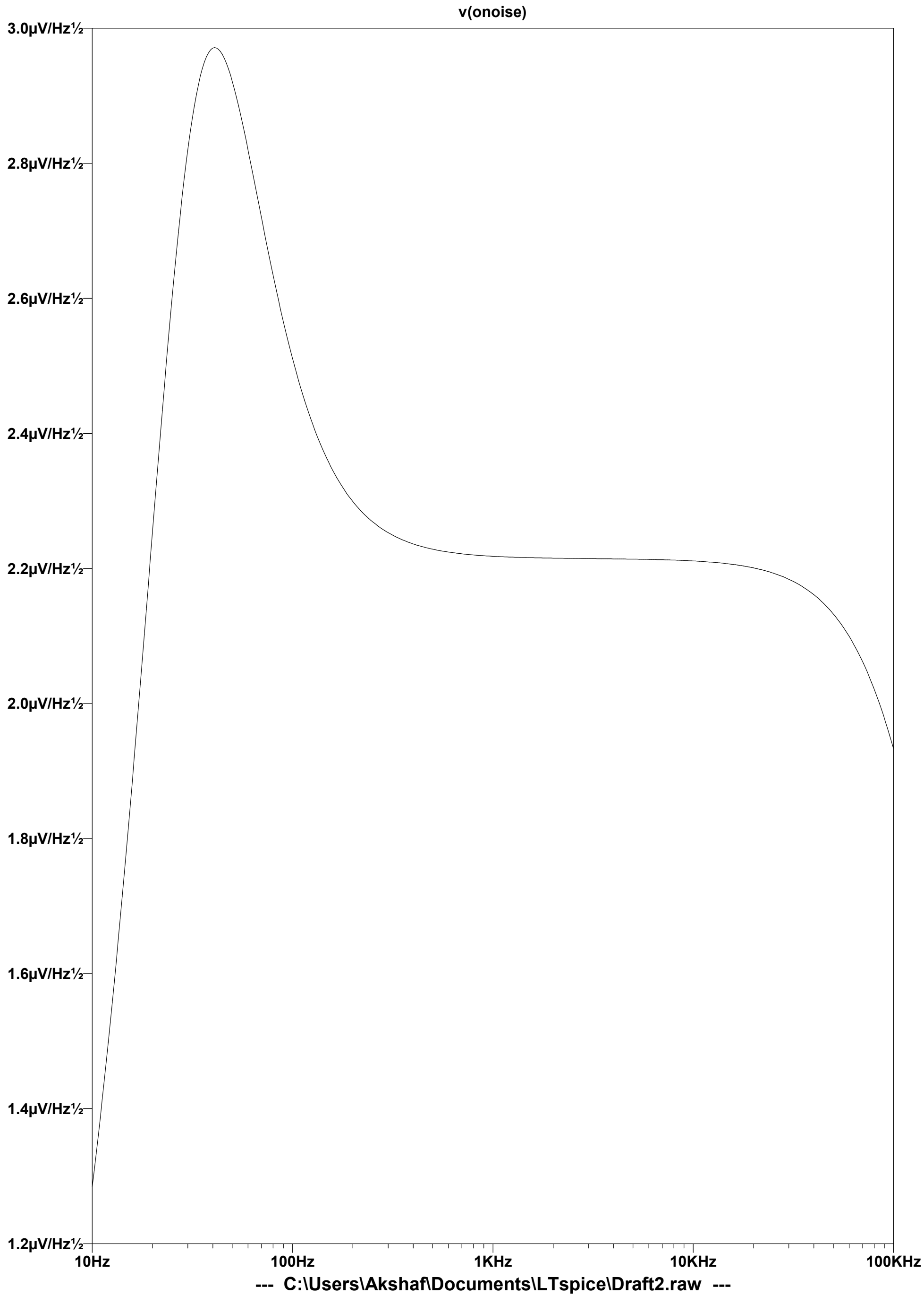

Figure 8: Output Noise Spectral Density

The simulation analyzes the electronic noise generated by the amplifier stage (Q2). The results show a peak noise level of only $3.0\mu\frac{V}{\sqrt{\text{Hz}}}$ at 50Hz. Given that the detector stage (T3) requires a V_{BE} of $0.7V$ $(700,000\mu V)$ to activate, the internal noise floor is orders of magnitude too low to cause false triggering.

4.6 OP Analysis

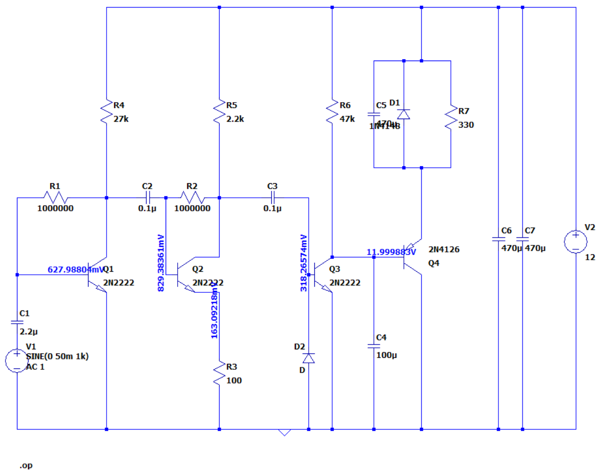

Figure 9: Schematic with op analysis command and voltages at base and emitter of Q1, Q2, Q3.

4.7 Node Voltages (DC Operating Point)

Node Label	Voltage (V)	Description
V(n001)	12.000	Supply Rail (VCC)
V(n002)	12.000	Supply Rail (VCC)
V(n008)	11.999	Supply Rail (Near Load)
V(n006)	8.412	Q2 Collector Voltage
V(n004)	2.374	Q1 Collector Voltage
V(n005)	0.829	Q2 Base Voltage
V(n003)	0.628	Q1 Base Voltage
V(n007)	0.318	Q3 Base Voltage (Detector)
V(n009)	0.163	Q2 Emitter Voltage
V(n010)	0.000	Ground (GND)

4.8 Transistor Operating Points

Transistor	I_b	I_c	I_e	State
Q1 (NPN)	1.75 μA	354.8 μA	-356.5 μA	Active
Q2 (NPN)	7.58 μA	1.62 mA	-1.63 mA	Active
Q3 (NPN)	≈ 0 A	2.5 nA	-2.5 nA	Cut-Off
Q4 (PNP)	≈ 0 A	≈ 0 A	≈ 0 A	Cut-Off

4.9 Passive Component Currents

Comp.	Current	Comp.	Current
R1	1.75 μA	C1	≈ 0 A
R2	7.58 μA	C2	≈ 0 A
R3	1.63 mA	C3	≈ 0 A
R4	356.5 μA	C4	1.20 fA
R5	1.63 mA	C5	≈ 0 A
R6	2.5 nA	C6	5.64 fA
R7	≈ 0 A	C7	5.64 fA
V1	≈ 0 A	D1	≈ 0 A
V2	-1.99 mA	D2	≈ 0 A

Analysis: The operating point analysis confirms that Q1 and Q2 are conducting significant current in the **Active Region**, ensuring they are ready to amplify signals. Conversely, Q3 and Q4 show negligible current, confirming they remain in the **Cut-Off Region** (OFF state) until a vibration signal triggers the system.

5 Discussion

The design yielded results that closely align with theoretical requirements. The AC Analysis confirmed a massive voltage gain of $68\mathrm{dB}$, allowing the detection of piezoelectric signals as low as $1\mathrm{mV}$.

The precision of the $0.65V$ threshold creates a necessary "dead zone," preventing false alarms from floor tremors. Furthermore, the stability tests (Noise and Temperature) prove that the circuit is robust enough for harsh industrial environments, such as turbine halls.

6 Conclusion

This project successfully demonstrated a low-cost, solid-state vibration monitor. The simulation data proves the system meets key performance indicators: fast response, high thermal stability, and excellent noise rejection. This design is a viable, cost-effective alternative to expensive commercial sensors for small-to-medium scale industrial applications.

7 Future Recommendations

1. **Adjustable Sensitivity:** Replacing the fixed emitter resistor with a potentiometer to allow calibration for different machine types.
2. **Latching Mechanism:** Adding a Silicon Controlled Rectifier (SCR) to ensure the machine stays off until a manual reset is performed by an operator.

8 References

- Sedra & Smith, **Microelectronic Circuits**, 7th ed.
- Analog Devices, **LTspice XVII User Guide**.