DESIGN AND SIMULATION OF A TEMPERATURE-CONTROLLED FAN

Author: Chetna
Course : B.Tech (Microelectronics and VLSI design), Second Year
Institution: NIT Kurukshetra

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1. ABSTRACT

This project presents the design and LTspice simulation of an automatic temperature-controlled cooling system. The circuit uses an operational amplifier (Op-Amp) configured as a voltage comparator in conjunction with an NTC thermistor to achieve automated thermal management. The simulation demonstrates a precise switching threshold at 38°C, ensuring that the fan operates only when the temperature exceeds the desired limit. This controlled operation improves power efficiency and enhances system longevity by reducing unnecessary fan usage.

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2. CIRCUIT COMPONENTS

- Operational Amplifier (U1): Configured as a voltage comparator.
- NTC Thermistor (Rth): 10 kΩ temperature sensor with β = 3950.
- NPN Transistor (Q1): 2N2222 used as a low-side switch to drive the load (fan).
- Flyback Diode (D1): 1N4007 used to protect the transistor from inductive voltage spikes generated by the fan.
- Resistors:
  - R1 = 4.7 kΩ (forms a voltage divider with the thermistor)
  - R2 = 8 kΩ (part of the reference divider)
  - R3 = 10 kΩ (part of the reference divider)
  - R4 = 1 kΩ (base resistor for the transistor)
- Load: 12 V DC fan modeled as resistor R5 in LTspice.
- Power Supply: 12 V DC source.

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3. THEORY OF OPERATION

3.1 Sensing and Reference Logic

The circuit uses two voltage dividers to define the switching behavior of the comparator.

1. **Variable Temperature-Dependent Voltage (Vtemp)**
   - The thermistor (Rth) and resistor R1 form a voltage divider.
   - As temperature increases, the resistance of the NTC thermistor decreases.
   - This variation in resistance changes the voltage at the non-inverting (+) input of the Op-Amp.
2. **Reference Voltage (Vref)**
   - A fixed reference voltage is generated using resistors R2 and R3 as a voltage divider connected to the 12 V supply.
   - The reference voltage is given by:

$$V_{ref} = 12 \times \frac{R3}{R2 + R3}$$

Substituting the component values:

$$V_{ref} = 12 \times \frac{10\text{k}\Omega}{8\text{k}\Omega + 10\text{k}\Omega} \approx 6.67\text{ V}$$

   - This reference voltage remains constant for a stable switching threshold.

3.2 Switching Mechanism

The Op-Amp (U1) is configured as a comparator that compares Vtemp with Vref.

- When the ambient temperature is below the threshold (38°C), the thermistor resistance is relatively high, resulting in a Vtemp that does not exceed 6.67 V.
- In this condition, the Op-Amp output remains LOW, keeping the transistor Q1 in the cutoff region, and the fan stays OFF.
- As the temperature rises and reaches the threshold value, the thermistor resistance decreases sufficiently such that Vtemp crosses the 6.67 V reference.
- At this point, the Op-Amp output switches to a HIGH state (approximately 12 V).
- The HIGH output drives the base of the transistor Q1 through resistor R4, turning Q1 ON in saturation mode and activating the 12 V DC fan connected in series with it.

- The flyback diode D1 across the fan provides a safe path for the inductive back EMF when the transistor turns OFF, protecting the switching device.

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4. PERFORMANCE ANALYSIS

4.1 Thermal Stability

The LTspice simulation confirms that the temperature-controlled fan circuit exhibits precise and stable switching behavior.

- The output voltage of the Op-Amp shows a sharp transition from 0 V (LOW) to approximately 12 V (HIGH) at around 38°C.
- This near-instantaneous switching characteristic ensures that the cooling fan turns ON exactly when required, providing immediate cooling action.
- By triggering at a well-defined threshold, the system prevents the protected equipment from reaching potentially harmful temperature levels.

4.2 Power Efficiency

The design significantly improves power efficiency by operating the fan only when necessary.

- **OFF State ($T < 38°C$):**
  - The fan remains inactive and draws negligible power from the supply.
  - Only the small bias currents of the Op-Amp and the voltage divider networks contribute to power consumption.
- **ON State ($T \geq 38°C$):**
  - The fan turns ON and consumes power to provide active cooling.
  - Since the fan operates only under thermally critical conditions, the average power consumption over time is reduced.
- **Energy Savings:**
  - Compared to a continuously running fan, this demand-based control can potentially save around 70–80% of the cooling power, depending on ambient temperature variations and duty cycle of operation.
  - This makes the circuit suitable for low-power and energy-conscious applications.

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5. CONCLUSION

The LTspice-based design and simulation of the temperature-controlled fan system validate the effectiveness of using an Op-Amp comparator and NTC thermistor for automatic thermal management. The circuit achieves a precise switching threshold at 38°C, ensuring reliable and timely activation of the cooling fan. By allowing the fan to operate only when necessary, the design offers an efficient and low-cost solution that enhances both power savings and system reliability. This approach is well-suited for integration into electronic equipment, power supplies, and embedded systems requiring autonomous temperature control.