THERMOSTAT/LIGHTING SWITCH COOK BOOK

This cook-book will be published as a series of articles in the VT&S Bulletin describing how to construct a number of electronic thermostats and switches for lights and motors (i.e. resistive and inductive loads). The first article presented here describes the basic switching circuit which is designed around the well-known μA741 op-amp and a triac from our BT136 to BT139 range. Features of the circuit are:

- can operate in conjunction with a wide variety of sensors (LDRs and thermistors)
- can switch both resistive and inductive loads with selection of switching point for optimum performance
- supplied directly from the mains (no need for a transformer)
- simple circuit using inexpensive components
- can switch load currents up to 16 A by selection of triac
- d.c. triggering of triac to minimize interference radiation

Depending on the control element used, the circuit can be applied as:

- an automatic light switch for a garden
- a refrigerator thermostat
- a heater thermostat
- a cooler (fan) thermostat

CONTROLLING A TRIAC

Before describing the switching circuit, let's determine the best way to trigger a triac for this type of application. This can be done by either applying pulses to the gate of the triac or by d.c. triggering. If the former method is used, the triac has to be retriggered for every cycle of the load current so there must be some means of detecting the load current. Since the current and voltage for an inductive load are in quadrature, this is not an easy task. It can be done by using a system based on the TCA280 IC but such a system also requires a rather expensive interference filter. Alternatively, once the triac has been d.c. triggered, it remains conducting until the trigger current is interrupted and there is therefore no radiated interference. A negative triggering current is preferred because it can be 30% less than a positive triggering current. Although d.c. triggering consumes more energy than pulse triggering, it is the preferred method for the applications described in this series of articles.

CIRCUIT DESCRIPTION

A block diagram and a detailed circuit diagram of the basic switching circuit are given in Figs 1 and 2 respectively. Since a very sensitive triac ($I_{gt} < 10$ mA) is used as the switching element, and the remainder of the circuit consumes only about 4 mA, it is possible to derive the low voltage a.c. supply for the switch control circuitry via a capacitor (Cd) connected in series with the mains. The capacitor has an impedance of several thousand ohms at 50 Hz and, because the capacitive voltage and current are in quadrature, this arrangement leads to much less dissipation than would occur with a simple dropper resistor. Since the common mode input rejection of the op-amp is high, it can tolerate considerable ripple on its d.c. supply. Simple half-wave rectification and single capacitor smoothing of 10 V d.c. derived from a zener diode is therefore adequate for providing the power input for the switching circuitry.

The op-amp controls the gate of the triac and is connected across the output from a wheatstone bridge, one arm of which consists of the switch control element (light-dependent resistor, manually variable resistor or thermistor). This bridge sensing arrangement makes the switch independent of mains voltage fluctuations. In Fig.2, the switch control element is an NTC thermistor and the triac is controlling a heater. The circuit is therefore a thermostat in which the desired temperature is set by variable resistor R_p.

When the temperature falls below that desired, the resistance of the thermistor increases, thereby unbalancing the bridge and increasing the voltage at the inverting input of the op-amp. The output from the op-amp therefore falls and current is drawn from the gate of the triac to turn it on and allow current to flow through the heater. The optional LED in series with the triac gate indicates that the heater is on. When the temperature reaches that set by R_p; the voltage at the inverting input of the op-amp decreases and the triac is switched off. The circuit can easily be adapted to operate as a cooler (fan motor) switch by transposing $R6/R_p$ and R_{ntc} so that switching occurs when the temperature rises above that set by R_p.

When the bridge is precisely balanced, the output from the op-amp could become unstable and swing rapidly between low and high. This is prevented by using positive feedback via R_h for the op-amp, thereby causing input hysteresis as shown in Fig.4.

As previously explained, the triac is d.c. triggered and the circuit can therefore be adapted for switching inductive or resistive loads. To minimize interference radiation however, a resistive load should only be switched at the zero-crossing of the mains voltage. On the other hand, as shown in Fig.5, an inductive load should only be switched at maximum mains voltage to minimize inrush current which can be considerably greater than the normal operating current. Since the change of the characteristics of the switch control element (a thermistor in this case) will be much slower than the mains frequency, the required change of switching point can be simply established by the addition of a couple of passive components to the basic circuit.

To determine the switching point, a 650 mV 50 Hz signal is derived from the mains supply via R5 and R4 or C1 and superimposed on the 5 V d.c. reference level at the non-inverting input of the op-amp. If C1 is used, the 50 Hz signal at the non-inverting input of the op-amp will be in quadrature with the mains voltage across the triac and switching will occur at maximum mains voltage (Fig.5a) as required for an inductive load. If R4 is used, the 50 Hz signal will be in phase with the mains supply to the triac and switching will occur at the mains zero crossing (Fig.5b). This is therefore the required configuration for switching a resistive load.

COMPONENT VALUES

The next article in this series will give a step-by-step method of determining the component values for the circuit. It will also include an application for the circuit as a refrigerator thermostat.

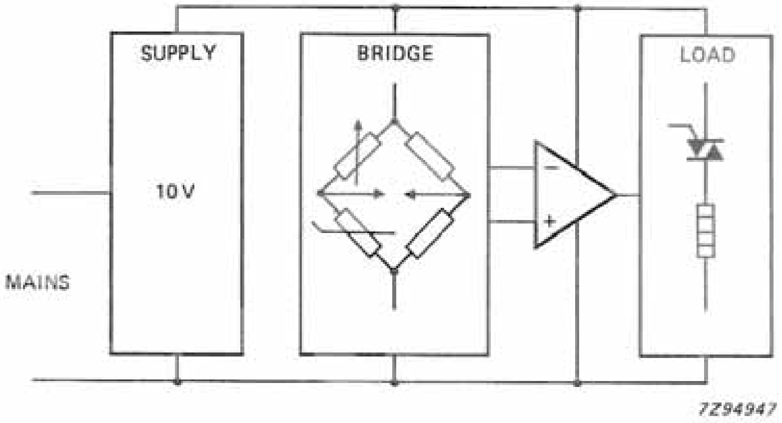


Fig.1 Block diagram of the switching circuit.

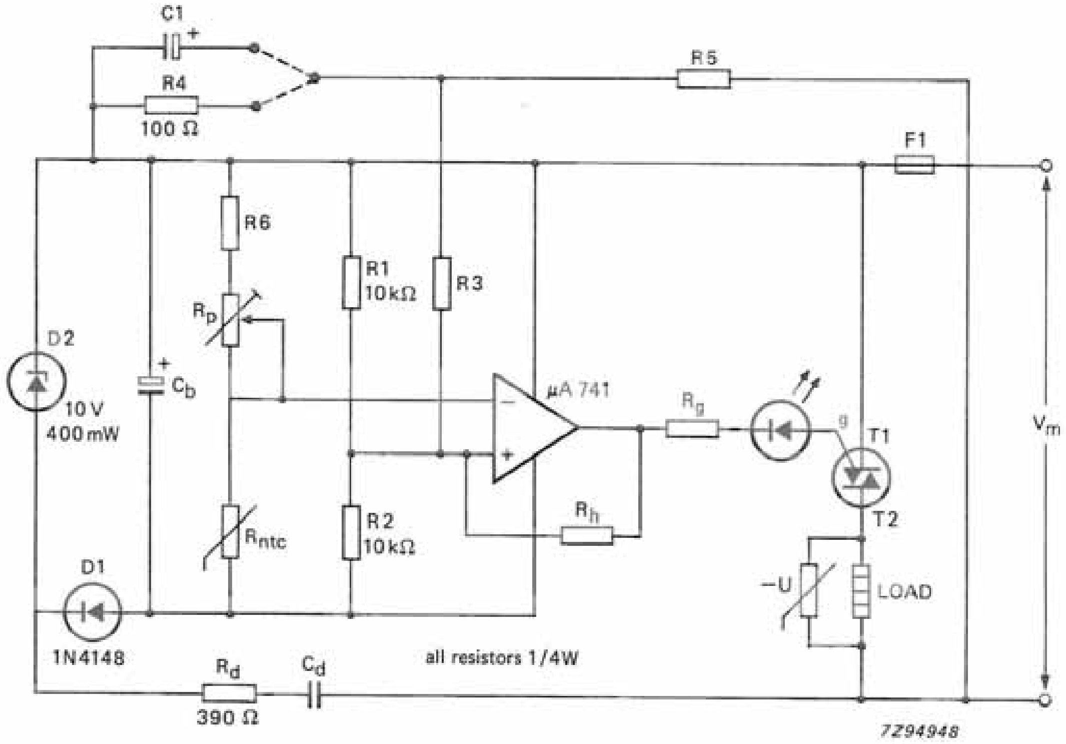


Fig.2 Detailed circuit diagram.

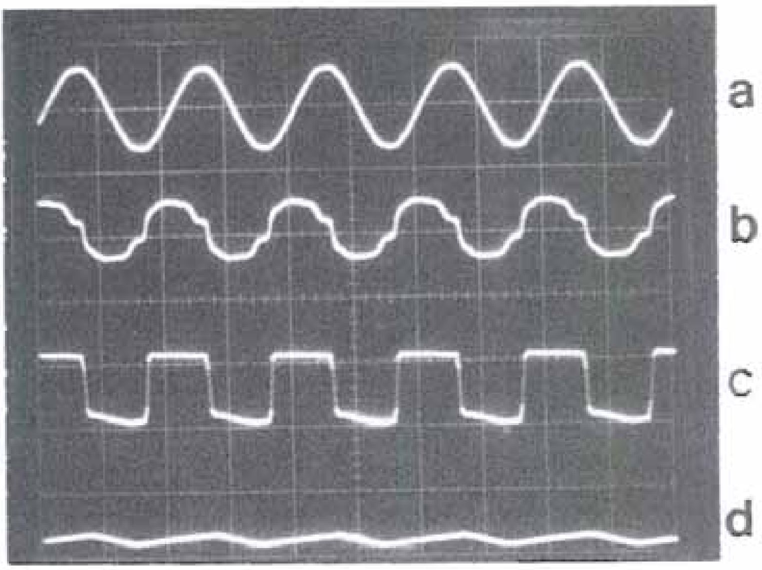


Fig.3 Waveforms in the circuit (timebase = 5 ms/div.).
(a) mains voltage (500 V/div.)
(b) junction Rd/Cd (50 V/div.)
(c) anode of D2 (10 V/div.)
(d) Cb (10 V/div.)

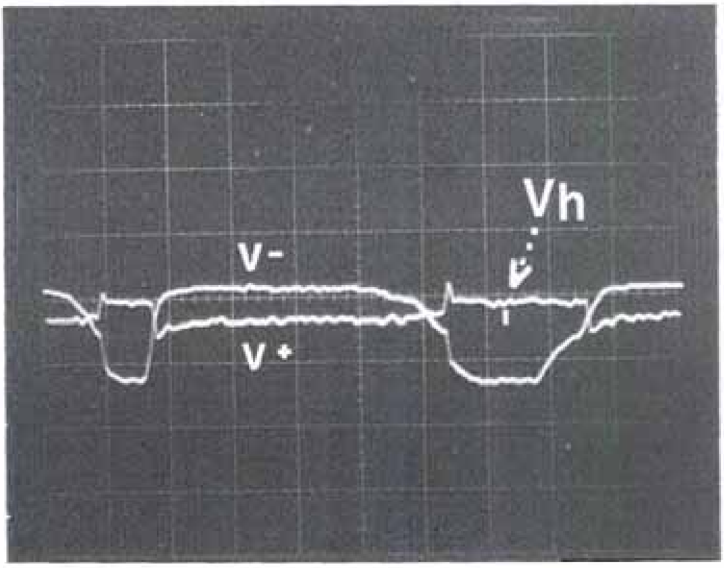
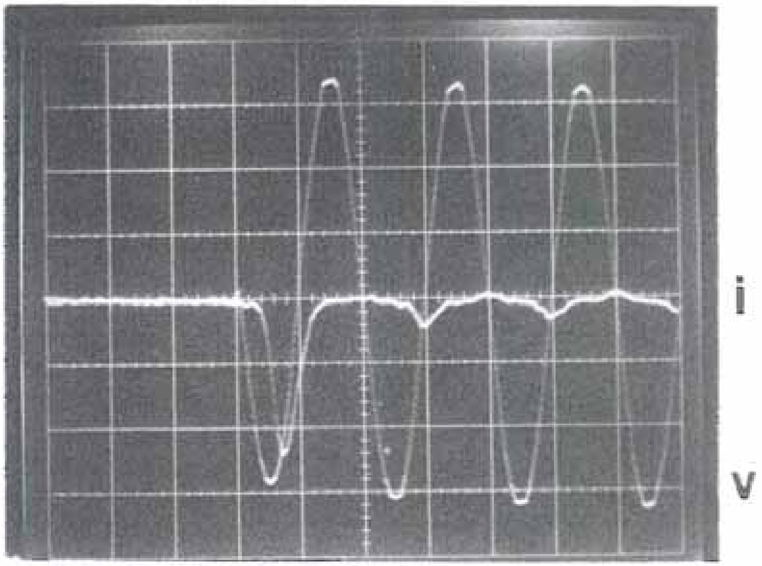
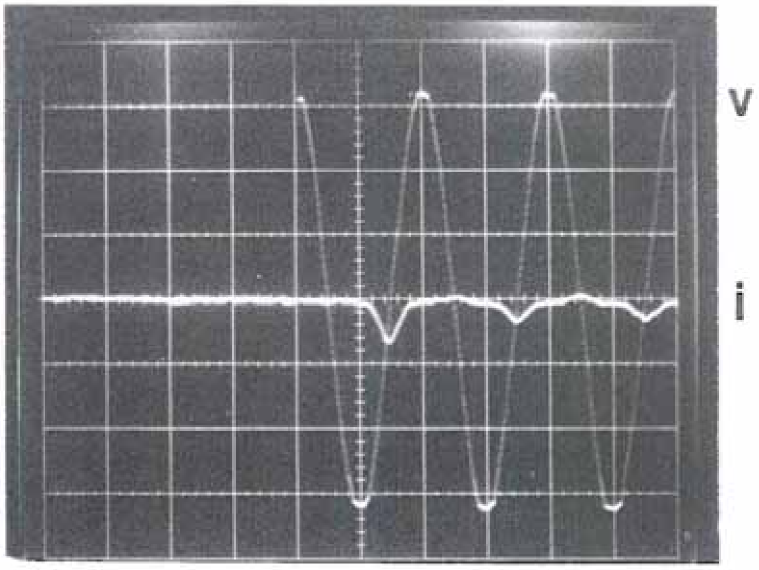


Fig.4 Input hysteresis of the op-amp (timebase 2 s/div., both channels 1 V/div.).

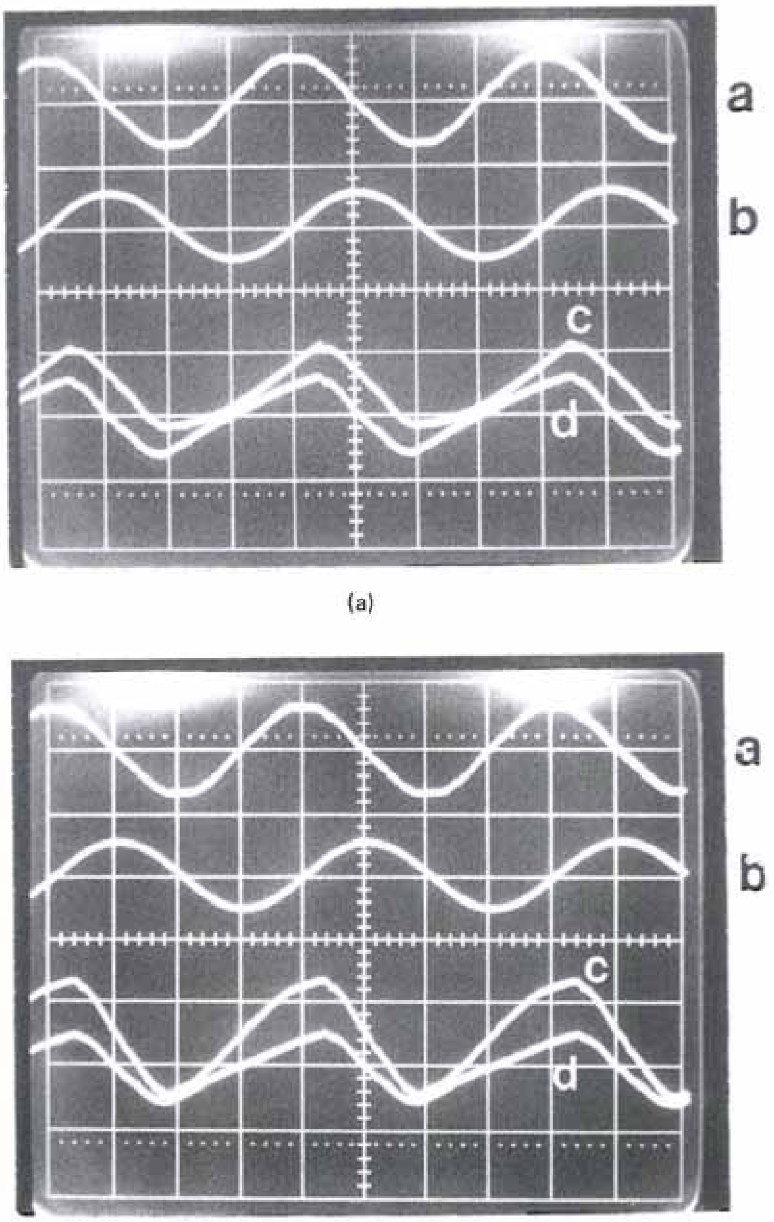


(a)



(b)

Fig.5 Switching an inductive load (timebase 10 ms/div., voltage 100 V/div., current 0,9 A/div.).
(a) at maximum mains voltage
(b) at mains zero-crossing



(a)

(b)

Fig.6 Switching with R4 or C1 in circuit (timebase 5 ms/div.). Waveform a at junction R4/C5 (1 V/div.), waveform b at junction C1/R5 (1 V/div.), waveform c at non-inverting input of op-amp (0,5 V/div.), waveform d at inverting input of op-amp (0,5 V/div.).
(a) switching at mains zero crossing (R4 in circuit)
(b) switching at mains negative-going peaks (C1 in circuit)

THE THERMO-/LIGHT-SWITCH COOK-BOOK
PART II

This is the second in the VT&S cookbook series of articles. The first article described a basic switching circuit designed around the µA741 op-amp. This article gives a step-by-step method of determining the component values for the circuit of Fig. 1. It also includes an application for the circuit as a refrigerator thermostat. Future articles will use the same basic steps to configure the circuit for other applications.

STEP 1 **Selecting circuit components**

By answering the following questions, you can determine all the relevant parameters so that the circuit design is applicable to all the 'cookbook recipes' in this series.

(a) Must the load be switched on above (coolers) or below (heaters) a certain temperature?
(b) Is the load inductive or resistive? (In the basic switching circuit shown in Part 1 of this series, R4 is connected in circuit for inductive loads and C1 is connected for resistive loads)
(c) What is the maximum load current (I_{ld}) to be switched?
(d) Is an adjustable temperature required or is a fixed temperature sufficient?
(e) If an adjustable temperature (T_{max}, T_{min}) is required what is the range?
If a fixed temperature (T_f) is required what is it?
(f) How large is the temperature hysteresis (T_h) to be?
(g) What is the mains voltage (V_m)?

When all these questions have been answered, you can determine the required component values.

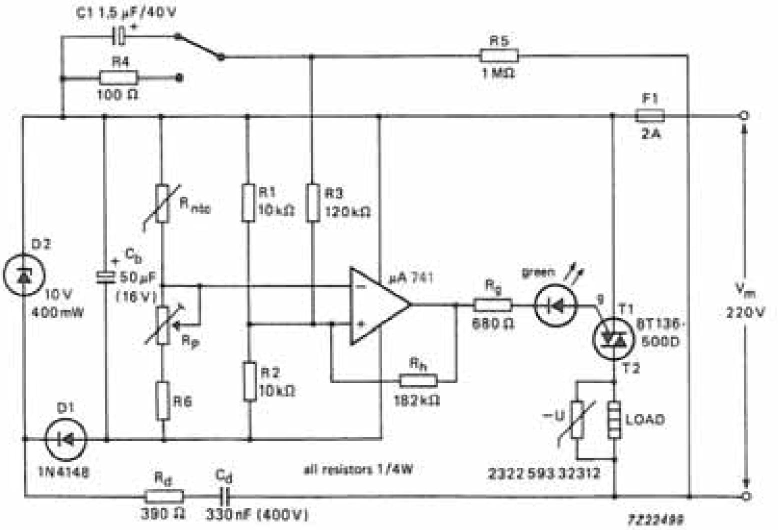


Fig. 1 Circuit diagram for refrigerator thermostat.

STEP 2 **Selection of the triac**

As already stated in part I, the triac has to be sensitive and capable of switching the required load current. The table below shows suitable types:

Load current to be switched I_{ld} (A)	Triac type number	I_g (mA)	V_{gt} (V)
<4	BT136-500D	− 5	1.5
4 to 8	BT137-500D	− 5	1.5
8 to 12	BT138E	−10	1.5
12 to 16	BT139E	−10	1.5

V_{gt} is the voltage between the gate and terminal T_1 when gate current is applied.

STEP 3 **Selection of R_g and LED**

The output voltage range of the µA741 op-amp in the circuit of Fig. 1 is +10 V to +4 V. The +4 V is the negative saturation voltage of the µA741, referred to as V_{sat}. The LED may be considered unnecessary, but if used it has a voltage V_1 across it when forward biased (V_1 = 1.4 V for a red LED or V_1 = 2.1 V for a green LED).

Resistor R_g limits the gate current (I_g) to the triac. Its value can be calculated from:

$$R_g = \frac{(10V - V_{sat} - (V_1 + V_{gt}))}{I_g}\ (\Omega) \qquad \text{Equation (1)}$$

(where $V_1 = 0$ if the LED is omitted).

Practical values for R_g are:

I_g (mA)	Value of R_g (Ω)		
	with red LED	with green LED	without LED
− 5	820	680	1.1 k
−10	390	360	560

STEP 4 **Selection of R1 and R2**

Equal value resistors R1 and R2 in series form the reference arm of the Wheatstone bridge and so determine the reference voltage (half the supply voltage = 5 V) at the non-inverting input of the µA741 op-amp. Since R1 and R2 are equal, the wheatstone bridge balances when the resistance of the NTC temperature sensor (thermistor) at a certain temperature equals the series resistance of R_p and R6 (5 V at the inverting input of the op-amp). In the circuit in Fig. 2 of Part I, the load is switched on when the temperature drops below a certain level (heating). By transposing the thermistor and the series R6 and R_p resistors, the load is switched on when the temperature is too high (cooling).

STEP 5 **Choice of thermistor**

The choice of thermistor is determined by the required operating temperature of the thermal switch, since dissipation is proportional to $1/R_{thermistor}$. Dissipation factor (δ) in mW/K, gives the relationship between the power dissipated in the thermistor and its subsequent rise in temperature. It is preferable to choose a thermistor with a high resistance, because at high temperatures especially, the resistance of thermistors becomes quite low, resulting in self-heating by up to 5 K. Generally this can be taken into consideration in the circuit design. The dissipation in the thermistor can be calculated as follows:

$$P = \frac{V^2}{R}\ (W)$$

where R is the thermistor resistance value at the maximum temperature.

At the switching point, $R_{thermistor} = R_6 + R_p$, so the voltage drop over $R_{thermistor}$ = 1/2 supply voltage = 5 V. Therefore dissipation is

$$P = \frac{(0.5\,V_{supply})^2}{R} = \frac{V^2_{supply}}{4R}\ (W) \qquad \text{Equation (2)}$$

and self-heating temperature $T = \dfrac{1000\,P}{\delta}$ (K)

therefore $T = \dfrac{1000}{\delta} \cdot \dfrac{V^2_{supply}}{4R}$ (K)

$$\text{so } T = \frac{250\,V^2_{supply}}{\delta R} \qquad \text{Equation (3)}$$

If this is acceptable continue with Step 6; if not, choose a thermistor with a higher resistance value.

STEP 6 **Selection of R6 and R_p**

(a) If the circuit is intended to switch at an adjustable temperature in the range T_{min} to T_{max}, then determine the resistance of the thermistor at these two temperatures, say, $R(T_{min})$ and $R(T_{max})$ by reference to the data handbook C11 or by direct measurement. Then:

$$R6 = 0.9\,R(T_{max})\ (\Omega) \qquad \text{Equation (4)}$$

$$\text{and } R_p = (R(T_{min}) - R(T_{max})) + 0.1\,R(T_{max}) + 0.1\,R(T_{min})\ (\Omega) \qquad \text{Equation (5)}$$

If R_p is a logarithmic potentiometer, temperature will be proportional to its shaft angle.

(b) If the circuit is intended to switch the load on or off at a fixed temperature T_f, then determine the resistance of the thermistor $R(T_f)$ at T_f. Then:

$$R6 = 0.9\,R(T_f)\ (\Omega) \qquad \text{Equation (6)}$$

and

$$R_p = 0.2\,R(T_f)\ (\Omega) \qquad \text{Equation (7)}$$

In this case R_p should be a linear potentiometer and is only used to compensate for component tolerances.

STEP 7 **Selection of R_h**

It can be shown from the appendix that the relationship between temperature variation and the variation of the voltage at the inverting input of the op-amp at a supply voltage of 10 V DC is given by:

$$\left|\frac{dV}{dT}\right| = \frac{10\,B}{4\,T_f^2}\ (\text{V/K}) \qquad \text{Equation (8)}$$

where B is a constant of the thermistor (refer to data handbook C11), and T_f is the required switching temperature of the thermal switch.

So, with temperature hysteresis (T_h), the voltage hysteresis V_h at the inverting input becomes:

$$V_h = \frac{10\,B\,T_h}{4\,T_f^2}\ (\text{V}) \qquad \text{Equation (9)}$$

If the circuit is intended for switching at one temperature T_f, the hysteresis will be constant. For an adjustable switching temperature range T_{min} to T_{max}, the hysteresis will change by a factor

$$f = \frac{T_{max}^2}{T_{min}^2} \quad \text{with } T_{max} \text{ and } T_{min} \text{ expressed in Kelvin.} \qquad \text{Equation (10)}$$

For example, over the temperature range 60°C (333 K) to 180°C (453 K) f will be 1.8 which means that the temperature hysteresis at the maximum temperature will be 1/1.8 = 0.55 of that at the minimum temperature.

For the variable temperature circuit T_f is defined as

$$T_f = \frac{T_{min} + T_{max}}{2}\ (\text{K}) \qquad \text{Equation (11)}$$

However, in practice, approximately 20% of the voltage hysteresis at the non-inverting input of the op-amp will be used to determine the initial switch-on. So V_h is approximately:

$$V_h = \frac{12\,B\,T_h}{4T_f^2}\ (\text{V/K}) \qquad \text{Equation (12)}$$

A hysteresis voltage V_h via feedback resistor R_h is produced as the output of the op-amp switches between 10 V (supply voltage) and V_{sat}. And if R3 >> R1 and R2 then

$$\frac{R_1(V_{DC} - V_{sat})}{R_1 + 2\,R_h} = \frac{12\,B\,T_h}{4\,T_f^2}$$

so, for V DC = 10 V and $V_{sat} = 4$ V,

$$R_h = \frac{R_1}{2} \cdot \left(\frac{2\,T_f^2}{B\,T_h} - 1 \right)\ (\Omega) \qquad \text{Equation (13)}$$

STEP 8 **Selection of R5 and R3**

The values of R4/C1 and R5 are chosen so that the amplitude of the signal at the junction of R3/R5 is approximately 0.65 V. Typical values for R5 when R4 is fixed at 100 Ω and C1 fixed at 1.5 μF are given in the following tables:

(a) resistive load switching at maximum voltage

Mains voltage (V_{RMS})	R5 (Ω)
110	24
220	47
240	51
380	82

(b) capacitive load switching at zero-crossing.

Mains voltage (V_{RMS})	R5 (MΩ)
110	0.5
220	1
240	1.1
380	1.8

(c) Value of R3
R3 is used to produce a ripple voltage which is added to the non-inverting input of the op-amp, and which is about 20% of the hysteresis voltage V_h.

$$\text{so, } R3 = \frac{R_1}{2} \cdot \left(\frac{1.3\, T_f^2}{BT_h} - 1 \right) (\Omega) \qquad \text{Equation (14)}$$

STEP 9 **An estimation of the supply current I_s**

The 10 V power supply must deliver:

(a) Supply current to op-amp	2.0 mA
(b) Current in reference arm of Wheatstone bridge (see STEP 4)	0.5 mA
(c) Gate current of triac (see STEP 2) (5 mA or 10 mA)	mA
(d) Max. current in measurement arm of Wheatstone bridge (see STEPS 5, 6) $\left(\frac{10}{R(T_{max}) + R_6 + R_p} \right)$	mA
Total I_s =	mA

STEP 10 **Selection of C_b**

The lower the value of C_b the less expensive the circuit becomes. However, decreasing the value of C_b increases the supply voltage ripple. The op-amp can tolerate a voltage ripple of 2 V so (at a ripple frequency of 50 Hz):

$$C_b = \frac{I_s \cdot \frac{1}{2} \cdot \frac{1}{\mathrm{fmains}}}{V_r} =$$

$$\frac{I_s \cdot 0.01}{2} \text{ (F)}$$

where I_s = supply current and V_r = ripple voltage across C_b. Typical values of C_b are from 50 to 100 μF at a working voltage of at least 16 V.

STEP 11 **Selection of C_d**

The dropper capacitor c_d has to supply capacitor C_b and the rest of the circuit during the positive half cycle of the mains supply. During this time it must supply all the current required for a full cycle of the mains supply. The value of C_d can be calculated as follows;

$$Z_c = \frac{V_m}{2I_s} \text{ but also } Z_c = \frac{1}{\omega C_d}$$

so:

$$\frac{V_m}{2I_s} = \frac{1}{\omega C_d}; \frac{V_m}{2I_s} = \frac{1}{2\pi f C_d}$$

$$\frac{V_m}{I_s} \approx \frac{1}{3fC_d} = \frac{1}{150 \cdot C_d}$$

$$\text{so: } C_d = \frac{I_s}{V_m \cdot 150} \text{ (F)}$$

where V_m = RMS voltage of the mains supply

Typical values for C_d are:

Mains voltage (V_{RMS})	Value of C_d	
	I_{ld} = 0 to 8 A	I_{ld} = 8 to 16 A
110	560 nF 300 V	860 nF 300 V
220	330 nF 400 V	470 nF 400 V
240	270 nF 400 V	390 nF 400 V
380	180 nF 600 V	270 nF 600 V

For safety reasons, C_d should be of good quality, therefore the MKT-P type is recommended.

APPENDIX

If the resistance of a thermistor is approximated by:

$$R = Ae^{B/T} \qquad \text{(i)}$$

then the temperature coefficient 'a' may be derived from:

$$a = \frac{1}{R} \cdot \frac{dR}{dT} = -\frac{B}{T^2} \qquad \text{(ii)}$$

so:

$$\frac{dR(T)}{dT} = -R(T) \cdot \frac{B}{T^2} \ (\Omega/K) \qquad \text{(iii)}$$

If the thermistor is used in a voltage divider branch with another resistor R, fed from a supply voltge V_i with a branch voltage V, then:

$$V = \frac{R(T)}{R+R(T)} \cdot V_i \text{ volts} \qquad \text{(iv)}$$

so:

$$\frac{dV}{dT} = \frac{\frac{dR(T)}{dT} \cdot (R+R(T))V_i - R(T) \cdot \frac{dR(T)}{dT} \cdot V_i}{(R+R(T))^2}$$

so:

$$\frac{V_i \cdot R \cdot \frac{dR(T)}{dT}}{(R+R(T))^2} = \frac{V_i}{4R} \cdot \frac{dR(T)}{dT} \overset{\text{with (iii)}}{=} -\frac{BV_i}{4T_f^2} \ (V/K) \qquad \text{(v)}$$

EXAMPLE

A Refrigerator Thermostat

Figure 1 shows the switching circuit configured as a refrigerator thermostat. This circuit only applies to this example; slight configuration differences will appear in the circuit for different applications in future articles. However the step-by-step methods for determining the component values will be applicable to all examples using the cookbook.

Step 1
- a. The load has to be switched on when the temperature rises above a certain level.
- b. The circuit has to switch a resistive load.
- c. The maximum load current is 2 A.
- d. The temperature must be adjustable.
- e. $T_{min} = -5°C$, the data sheet gives $R(-5) = 42066\ \Omega$ (Step 4)
  $T_{max} = \ 5°C$, the data sheet gives $R(\ 5) = 25312\ \Omega$ (Step 4)
- f. $T_h = 1°C$
- g. The mains voltage (V_m) = 220 V.

Step 2 Because the load current is smaller than 4 A, the triac can be a BT136-500D ($I_g = -5$ mA).

Step 3 A green LED indicator is used, so $R_g = 680\ \Omega$

Step 4 The thermistor is exchanged with the series combination of R_p and R6.

Step 5 A type 2322-645-03103 thermistor is chosen (temp. tol. ± 4 K).

The self-heating is calculated from:

$$T = \frac{V^2}{4\,\delta\, R(T_{max})} \ (K) \qquad (\text{where } \delta = W/K)$$

$$\text{therefore, } T = \frac{100}{4 \cdot 0.0085 \cdot 25312} = 0.1 \text{ K}$$

which is considered acceptable.

Step 6 Both R6 and R_p are calculated by using equations 4 and 5.
R6 = 22780 (practical value 22 KΩ)
R_p = 23491 (practical value 47 KΩ)

Step 7 $f = (278^2) = 1.1$ which is acceptable
$T_f = 273$ KΩ so R_h can be calculated to 182 KΩ

Step 8 C1 = 1.5 µF, R5 = 1 MΩ and R3 can be calculated as follows:

$$R3 = \frac{10\,000}{2} \cdot \frac{(1.3 \cdot 273^2}{3965 \cdot 1} - 1) = 117\ \text{K}\Omega$$

so use a 120 KΩ type.

Step 9 Current consumption

op-amp	= 2.0 mA
gate current	= 5.0 mA
current in reference branch	= 0.5 mA
current in measuring branch	= 0.2 mA
TOTAL	= 7.7 mA

Step 10
$$C_b = \frac{7.7 \cdot 10^{-3} \cdot 0.01}{2} = 39\mu F$$

so use a 47 µF, 16 V type.

Step 11
$$C_d = \frac{7.7 \cdot 10^{-3}}{220 \cdot 150} = 233\ \text{nF}$$

so use a 330 nF/400 V type.

Triac mounting instructions

Although the triac is a fairly good switch, a small voltage drop across it causes power to be dissipated in the form of heat. This power dissipation is a function of the current that flows through the triac and can be estimated by:

$$P = 1.33 \cdot I_{ld} (W)$$

The maximum allowable junction temperature is 120°C. The thermal resistance from junction to ambient in free air is 60 K/W, so the maximum load current can be derived from:

$$I_{ld}(max) = \frac{120 - T_{amb}}{60} (A)$$

(t_{amb} = ambient temperature in degrees C)

From this equation it is clear that the maximum load current for a triac in free air is about 1.5 A. So, the triac has to be mounted on a heatsink if the current exceeds 1.5 A. Mounting by means of a spring clip is the best method, because it offers good thermal contact under the crystal area.

The thermal resistance of the heatsink as a function of the controlled current for a triac mounted with a spring clip, heatsink compound and mica insulator is:

$$R_{th} = \frac{120 - T_{amb}}{1.33 \cdot I_{ld}} - 2.6\ (K/W)$$

Figure 2 shows a printed circuit board which has been developed to accommodate many different circuit configurations, including thermo- and light-switches.

Notes

a) For heater applications, connect the thermistor to terminals 1 and 2. For cooling applications, connect the thermistor to terminals 2 and 3.

b) There are four position options for R6. In Fig. 2 R6 is mounted for a cooling circuit application. By placing R6 in the alternative position the circuit can be used for a heater. R6 can also be placed to the left or right of the potentiometer. either of these positions will determine the potentiometer's shaft orientation e.g. with R6 in position R6a, turning the potentiometer's shaft to the left corresponds to a higher temperature setting.

c) Space for an optional resistor parallel to the potentiometer. The resistor position chosen will depend on the potentiometer's orientation.

d) Space for an optional resistor parallel to the thermistor. The resistor position chosen will depend on whether the thermo-switch application is heating or cooling.

e) This alternative position for R_g can be used if the LED indicator is omitted.

f) If the mains supply is connected to pin 6 the circuit includes fuse F1.

g) If the triac is mounted perpendicular to the printed circuit board, the board may be cut here.

h) For a light-switch application, connect the LDR to terminals 2 and 4. Resistor R7 is used only for this application.

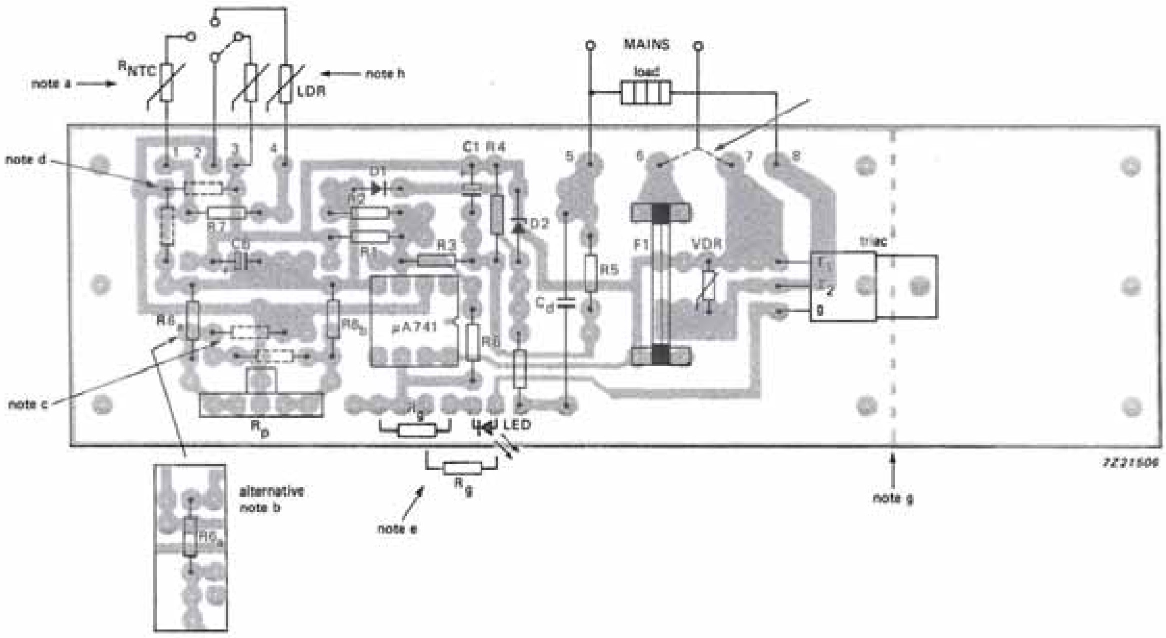


Fig. 2 Printed circuit board for thermo-switch application.