Temperature Considerations for DC Relays

Relays and temperature are intertwined. When a relay is exposed to various temperatures, its operating characteristics change dependent upon the temperature. The most notable changes occur in the pick-up voltage (V_{PI}) and coil resistance (R_C). The coil winding of a relay is produced with copper wire and thus the coil resistance varies with the temperature coefficient of copper. For the temperature range that a relay will normally be exposed to, the change in copper follows the form of:

Eqn. 1

$$R_1 = R_0 \times (1 + A \times (T_1 - T_0))$$

where:

R_1 = Resistance at temperature T_1

R_0 = Resistance at temperature T_0

A = Slope of a line from a point (- 234.5,0) through the point (T_0, 1)($A = 0.003929$ at $T_0 = 20°C$)

T_1 = New temperature of interest

T_0 = Reference temperature (20°C is typically used for this value)

Now that we can calculate the coil resistance at a new temperature given a value at some known reference temperature, let us look at the pick-up voltage. For a DC relay, the magnetic force developed is proportional to the Ampere-turns developed in the coil. Since the mechanical forces are fairly constant over the normal temperature range (and the number of turns is fixed), we can also deduce that the pick-up current (I_{PI}) will be constant. If pick-up current is constant and coil resistance varies, it follows that pick-up voltage ($V_{PI} = I_{PI} \times R_C$) varies directly as the coil resistance. This leads to a simple mathematical method to determine coil resistance and pick-up voltage at any temperature if a reference point is known.

For example:

Assume that a relay has the following parameters at 20°C (T_0).

R_C = 90 Ohms

V_{PI} = 6.5 volts

Calculate the new coil resistance at 105°C (T_1)

From Eqn. 1 we find:

R_1 = $90\Omega \times (1 + 0.003929/°C \times (105°C - 20°C))$
= $90\Omega \times (1.334)$
= 120.1Ω

Eqn. 2

To find the new pick-up voltage, we replace R_1 and R_0 with V_1 and V_0 respectfully to find:

V_1 = 6.5 volts x (1.334)
= 8.67 volts

To find the factor, A, the following equation is provided:

$$A = 1 / (T_0 + 234.5)$$

For three common reference temperatures, A is as follows:

European & Asian at 20°C:	A =	0.003929
International (IEEE) at 23°C:	A =	0.003883
United States at 25°C:	A =	0.003854

It is not a critical matter which reference temperature is used. The international was selected as 23°C ($\pm$ 3°C) to encompass both of the previous standards and thus appease everyone. It is recommended that this value be used whenever specifying new products since it is not more than 1.2% from either the 20 or 25°C reference and will provide future consistency if adopting ISO countries begin to utilize it. The equivalent values can be calculated from this reference for the others. Not that almost all European specifications still use the 20°C reference while many U.S. firms are beginning to utilize the 23°C reference.

While temperature changes affect relay parameters, the power dissipated within the relay also affects the temperature in most applications. The power dissipated within the relay may be broken down into two major components. The first is heat generated in the relay coil when voltage is applied to it. This heat creates a temperature rise (or increase) in the relay coil and package. The amount of temperature rise created is dependent upon several factors such as the volume of copper wire used, insulation thickness, insulation type, bobbin material, bobbin thickness, terminal size, conductor size, and several other factors that are design related. Each of these factors will either enhance or resist the flow of generated heat out of the coil assembly and into the ambient air. For a given relay design, these factors can be summed together into a value called the "coil to ambient thermal resistance" of the relay. The dimensions of such a value are °C/Watt. The thermal resistance is analogous to the electrical resistance and the temperature rise created by coil power dissipation follows the equation:

Eqn. 3

$$T_{RC} = \theta_{CA} \times P_D$$

where:

T_{RC} = Temperature rise caused by coil dissipation

θ_{CA} = Thermal resistance from coil to ambient

P_D = Final steady-state power dissipated in coil

For normal relay temperature ranges, this relationship is nearly linear and consistent under the following conditions:

1. The relay is in still air and not subjected to significant air flow or the value of θ_{CA} was determined with an air flow identical to the end application (difficult to simulate). For pc board relays, the still air assumption is often valid because of the end product enclosure.

2. All power calculations deal with the coil resistance at the final coil temperature (T_C) attained. If only room temperature coil resistance were used, the resulting non-linearity would result in significant errors at higher temperatures.

3. The value for thermal resistance is determined from test data where the relay carried no load current.

We now have the information necessary to calculate the final coil temperature from data book parameters under no load conditions for a relay. Let us try an example.

Given the following:

T_0	=	20°C
V_0	=	V_{PI} = 6.8 volts
R_0	=	90 Ohms
V_A	=	13.5 volts (V_A = applied coil voltage)
θ_{CA}	=	40°C/W
T_A	=	85°C (T_A = ambient temperature)
I_L	=	0 Amperes (I_L = load current)

Determine the following:

1. "Cold start" pick-up voltage (with the coil previously unenergized) and coil resistance at T_A
2. Final steady-state coil temperature (T_C) and resistance for V_A
3. "Hot start" pick-up voltage (after coil energized at V_A) at T_A and V_A

First we solve Eqn. 1 for R_1 at 85°C

$$\begin{aligned} R_1 &= 90 \times (1 + 0.003929 \times (85 - 20)) \\ &= 90 \times (1.2554) \\ &= 113.0 \text{ Ohms} \end{aligned}$$

Again we find V_1 at 85°C by using the same factor

$$\begin{aligned} V_1 &= 6.8 \times (1.2554) \\ &= 8.54 \text{ volts} \end{aligned}$$

Now the difficult part, finding T_C with 13.5 volts applied to the coil.

From Eqn. 3, and realizing that $T_C = T_A + T_{RC}$ and $P_D = V_A{}^2/R_C$:

Eqn. 4
$$T_C = \theta_{CA} \times V_A{}^2/R_C = T_A$$

Now we have a problem. As we have already seen, R_C changes with temperature. Since we are calculating temperature, we have two variables. The easiest approach to use here is simple iteration. Let us start by using the initial coil resistance at the ambient temperature of interest:

$$\begin{aligned} T_{C1} &= (40 \times ((13.5)^2 / 113)) + 85 \\ &= 64.5 + 85 \\ &= 149.4\,^{\circ}\text{C} \end{aligned}$$

We must now calculate a new value of R_C using T_{C1} and Eqn. 1.

$$\begin{aligned} R_{C1} &= 90 \times (1 + 0.003929 \times (149.5 - 20)) \\ &= 90 \times (1.5088) \\ &= 135.8 \text{ Ohms} \end{aligned}$$

Now using Eqn. 4 again;

$$\begin{aligned} T_{C2} &= (40 \times ((13.5)^2 / 135.8)) + 85 \\ &= 53.7 + 85 \\ &= 138.7\,°\text{C} \end{aligned}$$

Again we would calculate a new value of R_C at T_{C2} and repeat the process until a suffient accuracy is obtained. With several iterations, the answer to this example becomes:

$$T_C = 140°\text{C}$$

Now that we have the final coil temperature, we can find the coil resistance with Eqn. 1.

$$\begin{aligned} R_C &= 90 \times (1 + 0.003929 \times (140 - 20)) \\ &= 90 \times (1.4715) \\ &= 132.4 \text{ Ohms} \end{aligned}$$

The "hot start" pick-up voltage is found using the same factor:

$$\begin{aligned} V_1 &= 6.8 \times (1.4715) \\ &= 10.0 \text{ volts} \end{aligned}$$

The only remaining piece to the puzzle is how a contact load current affects the temperature of the relay coil and thus its parameters. Past

studies imply that the contact power dissipation may be treated as a separate heat source that adds heat into the relay package. Its effect on coil temperature is dependent upon many factors including package size, contact to coil distance, contact terminal size, connecting wire size, shared thermal paths, etc. Again, these factors can be lumped into a contact to coil thermal resistance. This leads to an equation similar to Eqn. 3.

Eqn. 5
$$T_{RL} = \theta_{CC} \times P_K = \theta_{CC} \times R_K\, I_L{}^2$$

where:

T_{RL} = Temperature rise in coil caused by the load current

θ_{CC} = Thermal resistance from contact to coil

P_K = Power dissipated in contacts

R_K = Contact circuit resistance

I_L = Load current flowing through the contact circuit

As an alternative possibility, and in an effort to provide a best fit curve to earlier test data, the following equation has yielded good approximations.

Eqn. 6
$$T_{RL} = K_{RL} \times I_L{}^{1.85}$$

This formula has been empirically derived from several test results and has successfully predicted final coil temperature rise caused by contact loads. The value K_{RL} can be derived from a two step temperature test. First determine temperature rise with no contact load and then measure under the same conditions with a contact load. The coil temperature rise minus the part caused by the coil power dissipation yields a T_{RL} and I_L combination that may be used to solve Eqn. 6 for K_{RL}.

The final coil temperature is then found by adding the respective components to obtain:

Eqn. 7
$$\begin{aligned} T_C &= T_A + T_{RC} + T_{RL} \\ &= T_A + \theta_{CA} \times (V_A{}^2 / R_C) + K_{RL} \times I_L{}^{1.85} \end{aligned}$$

This formula also requires solution by iteration. Since the only difference here is the added T_{RL} term, the following example is left to the reader.

All conditions the same as in the previous example except with:

I_L = 20 Amperes
K_{RL} = 0.029

The answers should be 113.0 Ohms, 8.54 volts, T_C = 146.5°C, R_1 = 134.73 Ohms, and V_1 = 10.18 volts.

The reader should now be able to determine the steady-state characteristics for any temperature and voltage combination given the appropriate relay data. It must be stressed that the values obtained here apply to DC relays operated continuously at these values. Intermittent duty (with short, i.e. less than 1 minute, "on" times and longer "off" times) may result in substantially lower temperatures. Therefore if a specific known duty cycle is given for the relay operation, testing at these conditions could yield acceptable results for final coil temperature when the continuous duty temperatures calculated here would not. The methods discussed here are applicable to standard DC relays and while the coil resistance formula will work for Polarized DC relays (one that utilizes a permanent magnet) and AC relays as well, the pick-up voltage equations will not work in such cases. With a polarized DC relay the temperature induced change in magnetic force of the magnet must be considered. This is normally such that it reverses part of the change in pick-up voltage caused by the copper wire resistance. In the case of AC relays, the inductance contributes a significant portion of the coil impedance and is related to the turns in the coil. since the inductance varies only slightly with temperature, the pick-up voltage exhibits less variation over temperature than for DC relays.