HEATING-UP OF CONTACTOR LINES AND TERMINALS

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Received April 27, 1972

Presented by Ass. Prof. Dr. I. SZABÓ

Introduction

Within the cladding, the connecting lines of contactors exit from the pipe which protects them, at a distance l from the terminals; there they divide and they are coupled to the corresponding phase terminals (Fig. 1). The point of bifurcation, in other terms the "crossing point" is critical from the aspect of safety against shorts [3, 4]. Its temperature t_l must not exceed the value permissible for the insulation [2, 5]. The current path away from the phase terminals leads, in several contactor types, across bimetallic thermal cut-outs operating at high temperatures. Part of the source heat Φ_b arising in the bimetallic cutout will reach the terminal, depending on the temperature difference between t_b and t_k. The heat flux reaching the connecting line is designated by Φ_k. Characteristics, $\Phi_k(t_k)$ of the thermic system of the connecting line and the transfer can be obtained by measurement or analytically. The steady state temperature t_{k0} of the terminal develops through the interaction of the

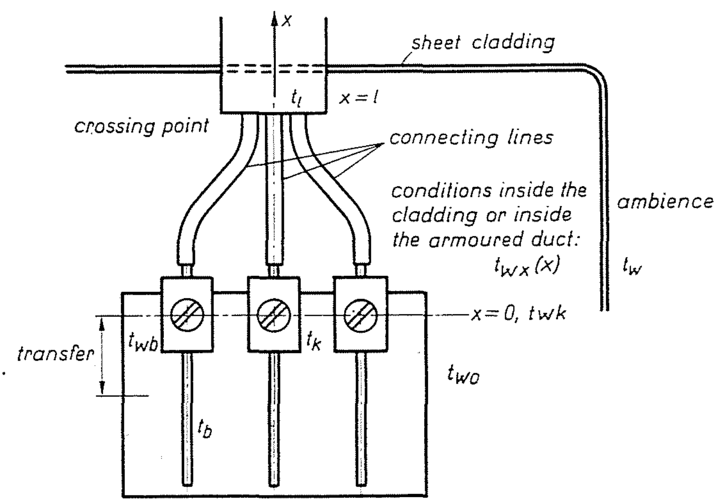

Fig. 1

"thermic system of the connecting line" and the "thermic system of the transfer", and assumes a value which satisfies both characteristic curves and which, accordingly, can be produced even graphically, as the "Point of intersection" of the characteristic curves for the two systems (Fig. 2). The t_l value can be intentionally influenced by altering the characteristic curves [1].

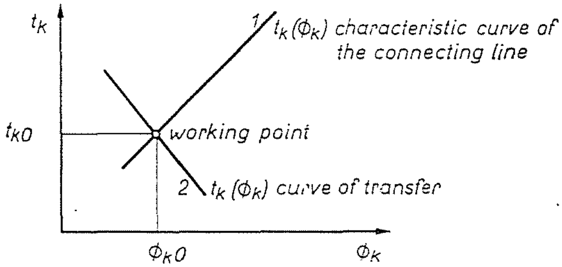

Fig. 2

The Model of the Interconnected Thermic Systems

To simulate the complicated heat source distribution of the thermic systems of transfer and connecting lines, and the environment determining the thermal boundary conditions, the following simplifying assumptions have been made:

1. The heat flux Φ_b of the transfer is concentrated to the point where a temperature t_b prevails.

2. Φ_s is the concentrated heat flux dissipated by the transfer surface.

3. The heat flux arising on the contact resistance of the hold-down terminals is Φ_t.

4. The internal source flux Φ_i of the connecting line and its heat loss Φ_3 are distributed along the line.

5. The reference temperature t_w of the space outside the cladding is constant.

6. The reference temperature of the environment of the connecting line within the cladding varies along the line $[t_{wx} = t_{wx}(x)]$.

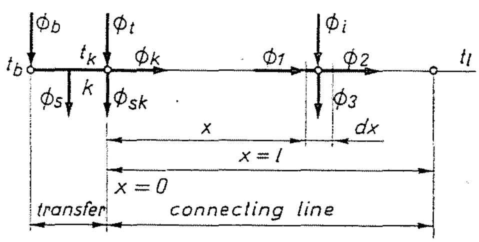

Fig. 3

7. The radial temperature variations of the connecting line are omitted.

The modelling and calculating assumptions will be dealt with in the course of the detailed discussion.

The scheme of the distribution of the source and absorber currents in the model is shown in Fig. 3.

The equations of the characteristic curves

Dissect the system in Figure 3 at K and examine the characteristics first of the connecting line and then of the transfer.

a) *The characteristics of the connecting line*

Let the balance of the heat fluxes for the section dx of line l, cut out at point x be written as:

$$\Phi_1 + \Phi_i = \Phi_2 + \Phi_3 \tag{1}$$

where

$$\Phi_1 = - \lambda A \left.\frac{dt_x}{dx}\right|_x \tag{1a}$$

$$\Phi_2 = - \lambda A \left.\frac{dt_x}{dx}\right|_{x+dx} \tag{1b}$$

$$\Phi_i = f_{hb} A \, dx \tag{1c}$$

and where f_{hb} [W/m^3] is the *Joule* source intensity in the connecting line at the working current intensity; and

$$\Phi_3 = \alpha_x S(t_x - t^0_{wx})_x \, dx \tag{1d}$$

the heat flux dissipated to the environment across the surface of a wire of circumference S, under the conditions of compound heat transfer coefficient α_x [W/m^2 deg]. Heat transfer coefficient α_x and ambient temperature t^0_{wx} vary along the line. To obtain a simple solution of the differential equation involved by the thermal balance, the effect of the variations in α_x is considered with a correction t^0_{wx} for the actual ambient temperature ($\alpha_x \; t^0_{wx} = \alpha \, t_{wx}$), viz. for $\alpha =$ constant the "apparent" ambient temperature $t_{wx}(x)$ will be used in the calculations. The function $t_{wx}(x)$ was assumed on the basis of experiments:

$$t_{wx} = a_3 + a_1 \, e^{-a_2 x} \, . \tag{2}$$

This function helps to obtain a continuous value for the environment of the line leaving the cladding and passing along the armoured duct, tending, for $x \to \infty$, towards $t_{w\infty}$.

At the point $x = l$ the "apparent" reference temperature $t_{wx} = t_{wl}$ can be assumed to be equal to the wall temperature of the cladding. At point $x \to \infty$, $t_{wx} \to t_{w\infty}$, $t_{w\infty}$ denoting the "apparent" inside wall temperature of the armoured duct surrounding the line.

After substitutions, the equation of balance (2) can be written in the following form:

$$\frac{1}{dx}\left[\frac{dt_x}{dx}\bigg|_{x+dx} - \frac{dt_x}{dx}\bigg|_{x}\right] + \frac{f_{hb}}{\lambda} - \frac{\alpha S}{\lambda A}(t_x - t^0_{wx})_x = 0\,. \tag{3}$$

Simplifying (3), taking (1) into consideration and introducing the notations:

$$B_1 = -\frac{\alpha S}{\lambda A}, \tag{3a}$$

$$B_2 = -\frac{f_{hb}}{\lambda} + a_3 B_1, \tag{3b}$$

$$B_3 = a_1 B_1 \tag{3c}$$

it may be written that

$$\frac{d^2 t_x}{dx^2} + B_1 t_x = B_2 + B_3 e^{-a_2 x}. \tag{4}$$

The general resolution of (4) is known [6]:

$$t_x = \frac{B_2}{B_1} + \frac{B_3}{B_1 + a_2^2} e^{-a_2 x} + M_1 e^{x\sqrt{-B_1}} + M_2 e^{-x\sqrt{-B_1}}. \tag{5}$$

The boundary conditions are as follows:

1. At the point $x = \infty$, from (5) and (1):

$$\frac{B_2}{B_1} = t_{x\infty} \tag{6a}$$

$$M_1 = 0 \tag{6b}$$

$$a_3 = t_{w\infty}\,. \tag{6c}$$

2. $x = 0$

$$t_x = t_k = t_{x\infty} + \frac{B_3}{B_1 + a_2^2} + M_2\,, \tag{7}$$

whence

$$M_2 = t_k - t_{x\infty} - \frac{B_3}{B_1 + a_2^2}, \tag{7a}$$

Furthermore, from (1):

$$a_1 = t_{w0} - t_{w\infty}, \tag{8}$$

and as the equation defining Φ_k:

$$\Phi_k = -\lambda A \left.\frac{dt_x}{dx}\right|_{x=0}. \tag{9}$$

3. $x = l$

$$t_{wx} = t_{wl},$$

$$a_2 = \frac{1}{l} \ln \frac{t_{w0} - t_{w\infty}}{t_{wl} - t_{w\infty}}. \tag{10}$$

Substituting the derivative of (5) into (9) we get

$$\Phi_k = \lambda A \frac{a_2 B_3}{B_1 + a_2^2} + \lambda A M_2 \sqrt{-B_1}. \tag{11}$$

Substituting from (7a) and resolving for t_k:

$$t_k = \frac{\Phi_k}{\lambda A \sqrt{-B_1}} + t_{x\infty} + \frac{B_3}{B_1 + a_2^2} \left(1 - \frac{a_2}{\sqrt{-B_1}}\right). \tag{12}$$

(12) is the equation of the characteristic curve of the connecting line.

The temperature of the connecting line at the point of intersection $x = l$, according to (5), (6a) and (7a):

$$t_l = t_{x\infty} + \frac{B_3}{B_1 + a_2^2} e^{-a_2 l} + \left(t_k - t_{x\infty} - \frac{B_3}{B_1 + a_2^2}\right) e^{-l\sqrt{-B_1}}. \tag{13}$$

Rearranging (13) it will be evident that the condition

$$\sqrt{-B_1} = a_2$$

trivially satisfies the equation. For the last member of Equ. (13), according to the L'Hospital rule:

$$\lim_{a_2 \to \sqrt{-B_1}} B_3 \frac{e^{-a_2 l} - e^{-l\sqrt{-B_1}}}{B_1 + a_2^2} = -B_3 \frac{l e^{-l\sqrt{-B_1}}}{2\sqrt{-B_1}}$$

which, (3c) taken into consideration, reduces (13) into:

$$t_l = t_{x\infty} + \left(t_k - t_{x\infty} + \frac{a_1 l \sqrt{-B_1}}{2}\right) e^{-l\sqrt{-B_1}}. \tag{13a}$$

Also the equation of the characteristic curve can be brought into a simplified form:

$$t_k = \frac{\Phi_k}{\lambda A\sqrt{-B_1}} + t_{x\infty} + \frac{a_1}{2}\,. \tag{12a}$$

b) *The characteristic curve of the transfer*

The balance of the thermal fluxes for the length of the "transfer":

$$\Phi_i + \Phi_b = \Phi_s + \Phi_{sk} + \Phi_k\,, \tag{14}$$

where

$$\Phi_s = A^* \alpha_0 (t_{m.} - t_{wb}) \tag{14a}$$

$$t_{m.} = 0.5(t_b + t_k) \tag{14b}$$

A^* designating the heat transmitting surface of the transfer and
α_0 the combined heat transfer coefficient on the transfer,

$$\Phi_{sk} = A_k \alpha_{0k} (t_k - t_{wk}) \tag{14c}$$

A_k is the heat transmitting surface of the terminal board and the hold-down screw
α_{0k} the combined heat transfer coefficient referred to the terminal
t_{wk} the reference temperature of the combined heat transfer from the terminal.

As per (14), the actual heat flux reaching the terminal is decisively affected by the evolution of Φ_s (see also Fig. 3).

Assume the value of Φ_s to be proportional to the temperature $t_{m.}$:

$$\Phi_s = B_0 \cdot t_{m.} \tag{15}$$

If so, then in the case of

$$t_b = t_k = t_{m.}\,, \text{ i.e.} \tag{15a}$$

$$\Phi_b = \Phi_s \tag{15b}$$

and

$$\Phi_k + \Phi_{sk} = 0 \tag{15c}$$

(which means that Φ_k can reach the terminal from the environment or from the connecting line only), then

$$B_0 = \frac{\Phi_b}{t_b} \tag{16}$$

B_0 will be obviously influenced by factors depending on the construction; this will be evident from (14a) and (15):

$$B_0 = A^* \alpha_0 \left(1 - \frac{t_{wb}}{t_{m.}}\right) . \tag{17}$$

Although $t_{wb}/t_{m.}$ is not constant, in the small range of examined t_k values it may be regarded to be so.

Substituting (14b), (15) and (16) into (14) we obtain the equation of the characteristic curve of the transfer:

$$t_k = t_b \left(1 - \frac{2\Phi_{sk}}{\Phi_b} - \frac{2(\Phi_k - \Phi_t)}{\Phi_b}\right) . \tag{18}$$

Practical

The characteristic curves of the VMK TL-25 type contactor were determined by the following empirical system of values, in the range:
$\alpha = 14$ [W/m^2 °C], a $120 < t_k < 140$ °C; $t_w = 35$ °C; $k_\infty = 7{,}8$ [W/m^2 °C], the heat transmission coefficient between the line and the environment at a temperature t_w (with $\Phi_h = k_\infty S(t_{x\infty} - t_w)$),

$$t_{x\infty} = t_w + \frac{f_{hb} A}{S \cdot k_\infty} ,$$

$$t_{w\infty} = t_{x\infty} - \frac{f_{hb} A}{S \cdot \alpha} .$$

Neglecting the temperature variations on the insulation of the wire:

$$\Phi_h = \alpha S(t_{x\infty} - t_{w\infty})$$

$$t_{wl} = t_w + \frac{\Phi_0}{A_t \alpha_t} ,$$

$\alpha_t = 5{,}4$ [W/m^2 °C] is the coefficient of natural heat transfer by convection on the external surface A_t of the cladding, and

Φ_0 (W) the total dissipated heat flux of the switch;

$$l = 100 \text{ mm.}$$

From (3a), (14) and (10)

$$\frac{t_{w0} - t_{w\infty}}{t_{wl} - t_{w\infty}} = e^{l\sqrt{-\frac{\alpha S}{\lambda A}}},$$

$$a_1 = t_{w0} - t_{w_\infty} .$$

The above relationships determine the value system of the environment.

a) In determining the characteristics of the connecting line, the calculations were performed for three different wire cross-sections A and for two Φ_k values, using the relationships (12a) and (13a). For the results see Table 1. It has been proved by experiments that the connecting lines dissipate heat to a decisive degree (over 80 per cent) by radiation.

Table 1

Temperature pattern of connecting lines

$t_w = 35$ °C; $\alpha = 14$ [W/m² °C]; $k_\infty = 7.8$ [W/m² °C]

	A [mm²]	f_{hb} [W/m³]	a_2	t [°C]	t_k [°C]		t_{wx} [°C]		
					$\Phi_k =$ = 0.55 [W]	$\Phi_k =$ = 1.25 [W]	$x = 0$	$x = l$	$x \to \infty$
1	2.5	$2.34 \cdot 10^6$	13.8	95	132	185	50	58.5	61.5
2	4.0	$9.1 \cdot 10^5$	11.6	67.8	114	154.5	78.1	58	49.6
3	6.0	$4.15 \cdot 10^5$	9.95	55.4	97.7	129	78.7	57	44.1

Accordingly, the $\alpha = 14$ [W/m² °C] cannot be readily applied to the parts of the characteristic curves $t_k\,(\Phi_k)_A$ at different temperatures. Therefore, the characteristics had to be corrected by $\alpha = 13$ and $\alpha = 15$ [W/m² °C] in the ranges $100 < t_k < 120$ and $140 < t_k < 160$ °C, respectively. The curves obtained this way are plotted in Fig. 4, together with the isotherms $t_l =$ = constant.

b) To calculate the curves of the transfer, again on the basis of measurements, the following system of data was used:

$$t_b = 235 \text{ °C};\ \Phi_b = 5.3 \text{ W};\ \Phi_{sk} = 0.61 \text{ W}\ (\Phi_t = 0),$$

therefore, according to (18), the equation of the characteristic curve is

$$t_k = 181 - 89\Phi_k. \tag{19}$$

The very good agreement between the characteristic curves calculated with (19) and recorded — (see 1a and 1b in Fig 5 resp.) — indicates that the

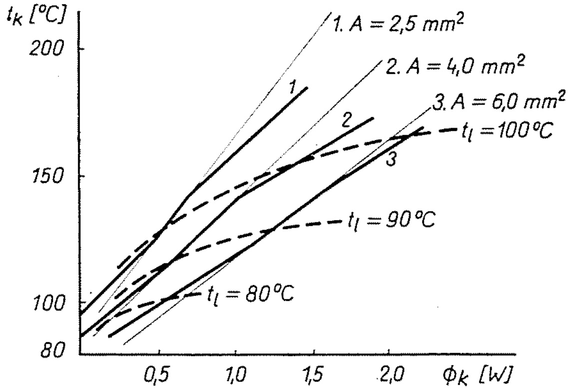

Fig. 4

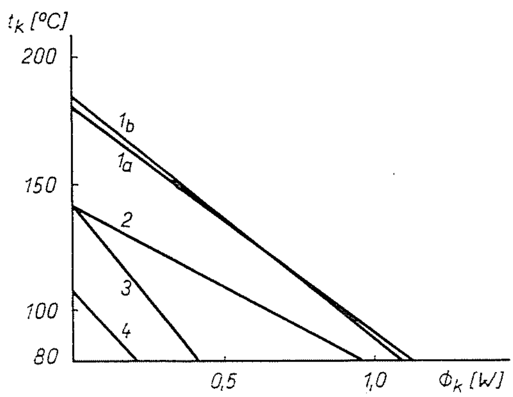

Fig. 5

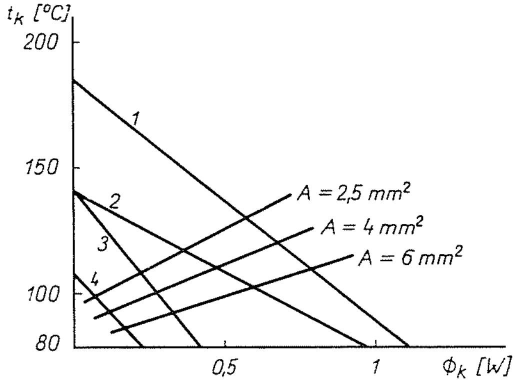

Fig. 6

simplifying assumptions are permissible. The characteristic curve of the transfer can be modified by changing t_b and Φ_b which are both dependent on the construction. This means that modification is possible through a structural interference. Curves 2, 3 and 4 in Fig 5 pertain to the coherent values $\Phi_b = 5.3$ W and $t_b = 180$ °C; $\Phi_b = 3$ W and $t_b = 235$ °C; and $\Phi_b = 3$ W and $t_b = 180$ °C, respectively.

In steady state operation at 25 Amp rated current, the actual temperatures t_k and t_l can be established by the superposition of the characteristic curves according to Figs 4 and 5, and by the examination of the working point *P*, Fig. 6 (see also Fig. 2). The working points and the temperatures t_l of the relevant crossings are compiled in Table 2.

Table 2

Steady state values of t_k and t_l at 25 Amp rated current for different values of A, Φ_b and t_b

Mark	Φ_b [W]	t_b [°C]	t_k [°C]			t_l [°C]		
			$A = 2.5$ [mm²]	$A = 4.0$ [mm²]	$A = 6.0$ [mm²]	$A = 2.5$ [mm²]	$A = 4.0$ [mm²]	$A = 6.0$ [mm²]
1	5.3	235.0	132.0	121.5	110.5	103.0	91.0	82.0
2	5.3	180.0	117.5	110.0	102.5	99.0	86.0	78.0
3	3.0	235.0	109.0	100.0	93.0	98.0	84.0	78.0
4	3.0	180.0	99.5	92.0	86.0	96.0	83.5	78.0

1. The temperature t_l is determined by the interaction of the thermic systems of the connecting line and the transfer. From this point of view t_l may be regarded to be a characteristic of the contactor.

2. Upon increasing the cross-section of the connecting lines, both t_k and t_l will considerably diminish.

3. The Φ_b and t_b values of the transfer have a marked influence on the terminal temperature t_k and a lesser influence on the crossing temperature t_l.

Acknowledgement

Authors wish to express their thanks to VBKM for the kind assistance given them in their work and to its kind permission to publish the results.

Summary

The safety of contactors against shorts requires the working temperature of the connecting lines not to exceed the degree permissible for the insulation. The temperature conditions of the connecting lines depend not only on their own heat sources and thermal conductivity but also on the heat fluxes transferred in different solid elements by conduction

(henceforth named: "transfer") from other sources to the terminal. Lines and transfer, therefore, will be examined as an integral system. Steady state temperature conditions are determined by their interaction, in the form of a solution which corresponds to their thermal characteristics (the point of intersection of the characteristic curves). The temperature conditions can be influenced by the intentional modification of the thermal characteristics.

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