Heating of Contacts and Terminals of Power Cables

Radisa Dimitrijevic[1], Dragan Tasic[2], Slavoljub Aleksic[3] and Nebojsa Raicevic[4]

Abstract – **Temperature rise, encountered along the power cable line due to the losses in the conductor, dielectric and contacts is of great importance in the service. Concerning the cable joints and terminations, jointing two cables by means of connector or terminating the cable by means of terminal lug represent significant phases during their installation. The nature of contacts was considered, such as their ageing in the exploitation. Calculation of temperature rise was analyzed and based on it, two numerical samples were performed. For one general case, temperature distribution in the vicinity of terminal lug was shown by means of commerically available program.**

Keywords – **Temperature rise, cable terminal lug, cable connector, temperature distribution.**

I. INTRODUCTION

Well done jointing and terminating the power cables play great role for the reliable service of cable lines in the power cable network. In these procedures, at the same places, electric and thermal fields get worse, due to interrupting the semi conducting screen of the cable and presence cable conductor or terminal lug. While the ends of semi conducting screen of the cable insulation are weak spots from point of the electric field, connectors and terminal lugs are critical from point of the thermal field.

Generally, when two metals are in touch, the contact is not made over the whole apparent surface, but only over certain number of points. These are elementary contacts [1]. Let's assume that there are *n* elementary contacts of the same radius *a*, uniformly distributed over the whole apparent surface. Then effective contact surface is:

$$S_a = n\,\pi\,a^2 \qquad (1)$$

The contact surface depends on the applied contact force, surface state and hardness of the contact metals. Electric resistivity of elementary contact consists of two components:

- Constriction resistance R_e, due to passing the current through the elementary contact and
- Film resistance R_i, relating to thin oxide layer or absorbed molecules at the interface.

The total contact resistance is the sum of metioned components, i.e:

$$R_c = R_e + R_i = \frac{\rho}{2na} + \frac{\sigma_0}{n\pi a^2} \qquad (2)$$

where ρ - specific electric resistivity of the metals and

σ_0 – surface ("tunnel") resistivity of oxide layer (depends on the nature of oxide and its thickness).

If electric conductor is very long compared to elementary contact of radius *a*, the lines of current are hyperbola and equipotential surfaces are flattened ellipsoids (Fig.1). Both hyperbola and ellipsoid are focused around the end of contact.

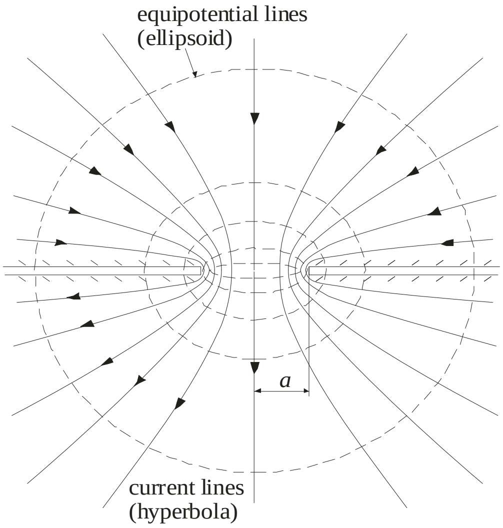

Fig. 1. Elementary contact

II. AGEING OF CONTACTS

The ageing of closed electric contacts, which are not subjected to arc effect, occurs due to reaction of the metals with the surrounding environment at contact interface [2]. This is very slow pending process, which could brings to the failure of contact under the certain undesirable circumstances. This reaction could be:

- Oxidation, due to presence of oxigen, sulphurous vapor,
- Corrosion, at bimetallic contacts, due to different electrochemical potential in the presence of higher humidity (more than 50% r.h.). Acceptable combination of metals to avoid corrosion shall have potential differences less than 350 mV.

Two simultaneous process can appear at the elementary contacts due to oxidation:

- Reduction of cross section of conducting zone,
- Increasing the thickness of oxide layer of surface resistivity σ_0.

There are other mechanisms of degradation, affecting the ageing level, but they can not be easily described by mathematical laws and therefore can not be easily analyzed. The only way to find out something about their influence is testing in laboratory.

---

[1] Radisa Dimitrijevic is with the Institute FKS, Marka Kraljevica bb, 35000 Nis, Serbia, E-mail: radisa.dimitrijevic@fks.co.rs

[2] Dragan Tasic, [3] Slavoljub Aleksic and [4] Nebojsa Raicevic are with the Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Nis, Serbia, E-mail: dragan.tasic@elfak.ni.ac.rs; slavoljub.aleksic@elfak.ni.ac.rs; nebojsa.raicevic@elfak.ni.ac.rs

III. INFLUENCE OF TEMPERATURE RISE

Generally, when the contact is exposed to oxidation in the air and the temperature rise overcomes permissible value, accelerated ageing of contact occurs. Its shelf life shall be multiplied by ageing factor K_{th}.

In more general case, when both temperature rise of ambient and temperature rise of inner contacts act simultaneously, the following assumptions are adopted:

- Temperature rise is proportional to current by exponent between 1,5 and 2, depending on emissivity of the surface (for cooling by radiation and natural convection, average value of 1,67 can be used, but for radiation and forced convection, average value 2);
- Shelf life of contact is reduced by half, if ambient temperature rise ΔT_i is increased by 6,5 K;
- Shelf life of contact is reduced by half, if average temperature θ_e of medium, surrounding the contact, is increased by 8,5 K.

The ageing factor K_{th} can be expressed by:

$$K_{th} = 2^{\left(\frac{\theta_e - \theta_{an}}{8.5} + \frac{\Delta T_i - \Delta T_n}{6.5}\right)} \tag{3}$$

where

θ_{an} (T_{an}) – standard temperature of surrounding air (^{0}C) or (K);

ΔT_n – contact temperature rise, relating to surrounding medium (average values in K).

Analysis indicates, that effect of ageing in short term can not be compensated, if the contacts are subjected to reduced load and lower temperature under the similar terms.

IV. CALCULATION OF TEMPERATURE RISE OF CONDUCTORS AND CONTACTS

The changing of temperature along two conductors, connected in point O is shown in the Fig.2.

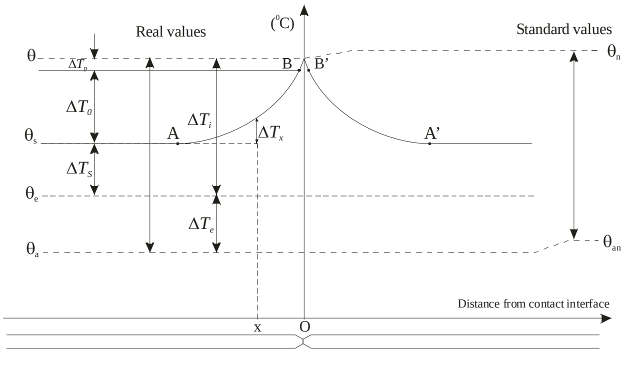

Fig. 2. The changing of temperature along two conductors

Maximum temperature θ represents the following addition:

$$\theta = \theta_a + \Delta T_e + \Delta T_s + \Delta T_0 + \Delta T_p \tag{4}$$

where : θ_a – the temperature of outside ambient (accepted 40^{0}C). If termination is inside an enclosure, θ_a is the temperature of the air outside enclosure;

ΔT_e – the temperature rise of the air surrounding contact or terminal, in relation to ambient temperature;

ΔT_s – real temperature rise without contact. Contacts and conductors are usually cooled by radiation or natural convection [2];

ΔT_0 – temperature rise in the vicinity of contact, caused by Joule effect at resistance of contact;

ΔT_p – additional temperature rise at elementary contacts.

A. Temperature rise ΔT_s relating to ambient temperature T_e

It is calculated by expression:

$$\Delta T_s = \frac{\left[\left(T_e + \Delta T_s - 273.15\right)\alpha + 1\right] R_0 I^2 + r\,\varphi_s S_r}{Bl\left[\sigma\varepsilon\frac{\left(T_e + \Delta T_s\right)^4 - T_e^4}{\Delta T_s} + \frac{\lambda}{D_h} N_u\right]} \tag{5}$$

where: α – temperature coefficient of conductor;

R_0 – longitudinal resistance of conductor at 0^{0}C;

I – current;

r –coefficient of receiption of sun radiation $0 \le r \le 1$;

φ_s – thermal flux;

S_r – surface of conductor, receiving thermal flux φ_s;

B – external periphery of conductor, emitting heat;

l – length of conductor; average distance between elementary contacts;

σ – Stefan-Boltzman constant $5.67 \cdot 10^{-8}$ (Wm^{-2}K^{-4});

ε – total emissivity of conductor;

λ – thermal conductivity of surrounding medium;

D_h – diameter of conductor, leading to contact or total height of section conductor (m);

N_u , G_r , P_r , R_E – Nusselt number;

B. Temperature rise ΔT_0 of conductor in the vicinity of contact or terminal, cooled by radiation and natural convection

Additional temperature rise of contact or terminal, which is cooled by radiation and natural convection, is expressed by:

$$\Delta T_0 = \left(W\sqrt{\frac{\delta + 1}{2\lambda_c S\gamma B}}\right)^{\frac{2}{\delta+1}} \tag{6}$$

where: W – dissipation at the contacts;

δ – exponent of ΔT in expression $\varphi = \gamma\Delta T^{\delta}$;

λ_c – thermal conductivity of conductor;

S – cross section of conductor;

γ – constant relating to emission.

C. Temperature rise T_p of elementary contacts

Finally, there is additional temperature rise at the elementary contacts due to opening the thermal flux lines from their boundary surface. This rise is small and can be expressed by:

$$\Delta T_p = \frac{I^2}{2\pi^2 n^2 \lambda_c}\left(\frac{\rho}{4a^2} + \frac{\sigma_0}{a^3}\right) \tag{7}$$

where a, n are radius and number of elementary contacts and coefficient $n_k = 2{,}5 \cdot 10^{-5}$ [1].

V. NUMERICAL EXAMPLES

A. Example

Indoor cable termination is installed in bay of power plant. Temperature rise of contacts during the short term overload is $\Delta T_i = 65^0$C, while ambient (enclosure) temperature $\theta_e = 40^0$C. Calculate the effect of ageing contacts, if standard temperature of surrounding air $\theta_a = 20^0$C, and maximum permissible standard temperature rise of contact $\Delta T_n = 50^0$C.

Solution. From Eq.3 ageing factor will be:

$$K_{th} = 25.3 \text{ h}$$

It means, that 1 hour service in the new worse condition during the short term overload at higher ambient temperature will shorten shelf life of cable termination by 25,3 hours. If ambient temperature increases by $8{,}5^0$C above standard 20^0C, and temperature rise of contact by $6{,}5^0$C above maximum permissible 50^0C relating to ambient temperature, then ageing of contacts will occur.

B. Example

Cable line of three cables A2XSY 1×150/25 mm^2 12/20 kV in trefoil formation is laid in air and terminated with outdoor terminations. Fitting is performed by bimetallic terminal lugs. Calculate maximum temperature of contact, if the cable terminal is cooled by radiation an natural convection.

Cable data:

- Nominal current carrying capacity for trefoil formation and laying in the air I=322 A (calculated value);
- Thermal coefficient of resistivity at 0^0C $\alpha_{0\,\mathrm{Cu}} = 4{,}265\cdot10^{-3}$ K^{-1} and $\alpha_{0\,\mathrm{Al}} = 4{,}383\cdot10^{-3}$ K^{-1} [1];
- Specific resistance at 0^0C for copper $\rho_{0\,\mathrm{Cu}} = 1{,}5881\cdot10^{-8}$ Ωm and for aluminium $\rho_{0\,\mathrm{Al}} = 2{,}6\cdot10^{-8}$ Ωm [1];
- Thermal conductivity at 20^0C $\lambda_{c\,\mathrm{Cu}} = 387$ W/mK i $\lambda_{c\,\mathrm{Al}} = 203$ W/mK [1];
- Physical properties of air at 20^0C – density $M = 1{,}205$ kg/m^3; compressibility $\beta = 3{,}4\cdot10^{-3}$ K^{-1}; specific heat $C_p = 1006{,}3$ J/kg K; thermal conductivity $\lambda = 0{,}02585$ W/mK; dynamic viscosity $\mu_d = 1{,}822\cdot10^{-5}$ Pa s [1];
- The remaining physical properties and constants – emissivity of outer cable sheath $\varepsilon = 0.95$ [3]; $g = 9{,}81$ m/s^2; cross section $S = 150\cdot10^{-6}$ m^2; periphery $B = 0{,}11$ m; cable diameter $D_h = 0{,}035$ m; specific surface of cable cooling $S_c = \pi D_h\ l$ m^2; average temperature of surrounding air $T_e = 293{,}15$ K; coefficient of receiption of sun radiation $0 < r < 1$ accepted $r = 0{,}5$; thermal flux $\varphi_s = \gamma \Delta T^{\delta}$ W/m^2, where $\gamma = 5.9$ and $\delta = 1{,}2$; resistance of aluminium conductor $R_0 = \rho_{0\,\mathrm{Al}} \cdot l/S = 2{,}6\cdot10^{-8}\cdot1/150\cdot10^{-6}\,\Omega$ na 0^0 C [1];
- Specific resistivity at 20^0C $\rho_{\mathrm{Cu}} = 1{,}8\cdot10^{-8}$ Ωm and $\rho_{\mathrm{Al}} = 3{,}06\cdot10^{-8}$ Ωm; tunnel resistivity of contact surface $\sigma_{0\mathrm{Cu}} = 5\cdot10^{-12}$ Ωm^2 and $\sigma_{0\,\mathrm{Al}} = 10^{-11}$ Ωm^2; $n_k = 2{,}5\cdot10^{-5}$; hardness $H_{Cu} = 5{,}5\cdot10^8$ Pa and $H_{Al} = 3\cdot10^8$ Pa; $N_{u\,Cu} = 0{,}05$ and $N_{u\,Al} = 0{,}07$; evenness coefficient $\xi = 0.15$ and $F = 50$ N [1].

Maximum contact temperature θ according to Eq.4 is:

$$\theta = \theta_a + \Delta T_e + \Delta T_s + \Delta T_0 + \Delta T_p$$

It is adopted $\theta_a = 40^0$C and $\Delta T_e = 5^0$C. Temperature rise of air ΔT_e, surrounding the contact (terminal), compared to ambient temperature is estimated to be 5^0C. Higher values should not be expected, because the contact is in the open space and is cooled by radiation and natural convection, so that these temperatures are very close.

In the case of natural convection, a value of temperature rise of horizontal "infinite" long single core cable, related to ambient temperature can be obtained from Eq. 5, after several iterations:

$$\Delta T_s = 23{,}2 \text{ K}$$

Contact resistance at the point of compression of aluminium conductor and aluminium part of bimetallic terminal lug (Eq.2) will be as follows:

$$R_c = 9{,}01\cdot10^{-6}\ \Omega$$

and at the point of tightening its copper part:

$$R_c = 8{,}26\cdot10^{-6}\ \Omega$$

Total power dissipation towards the conductor, taking into account both transient contact resistances amounts:

$$W = \frac{1}{2} R_{c\,\mathrm{Cu}} I^2 + \frac{1}{2} R_{c\,\mathrm{Al}} I^2 = 0{,}9 \text{ W}$$

Additional temperature rise of contact, cooling by radiation and natural convection will be (Eq.6):

$$\Delta T_0 = 24 \text{ K}$$

Finally, additional temperature rise at the elementary contacts due to openning the thermal flux lines from their boundary surface will be (Eq.7):

$$\Delta T_p = \frac{I^2}{2\pi^2 n^2 \lambda_c}\left(\frac{\rho}{4a^2} + \frac{\sigma_0}{a^3}\right) = 0{,}4 \text{ K}$$

Now, total maximum temperature of contact θ amounts:

$$\theta = \theta_a + \Delta T_e + \Delta T_s + \Delta T_0 + \Delta T_p = 92{,}6^0\,\mathrm{C}$$

Taking into account that maximum permissible temperature of contact is 90^0C (because of XLPE insulation and other similar materials, overlapping the conductor, close to contact), the temperature rise $2{,}6^0$C, obtained in calculation, will not cause its ageing, because this overheating is not continuous. As noted in Example 1, ageing of contact will occur, if average annual ambient temperature will be increased by $8{,}5^0$C above standard one (20^0C) or if temperature rise of contact would be by $6{,}5^0$C above maximum permissible temperature rise related to ambient temperature (50^0C).

VI. TEMPERATURE DISTRIBUTION IN THE VICINITY OF CONTACT OF CABLE TERMINATION

Generally, in the case of indoor mounting, cable termination is connected through terminal lug or connector to the copper bus bar. The terminal lug or connector is fixed with the screws by the force, which is prescribed.

The warmest place is contact between terminal connector and bus bar, which is usually cooled by radiation and natural convection. Approximate temperature distribution is shown in Fig.3. Some simplifications were applied. The influence of other terminations in the same enclosure is neglected and only one section of the metal enclosure around the fitting the cable termination is analyzed. Fig.3 is not scaled.

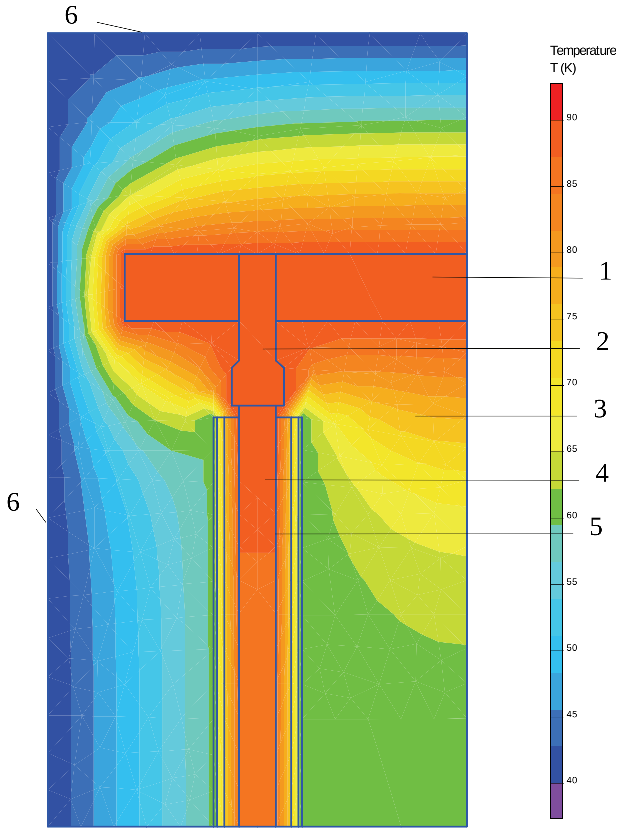

Fig. 3. Temperature distribution in the vicinity of contact of cable termination in the metal enclosure.

Legend: 1 – copper bus bar; 2 – terminal connector; 3 – surrounding air; 4 – aluminium conductor; 5 – XLPE insulation; 6 – enclosure.

The values of thermal conductivity, used in calculation, are shown in the Table I [4]. Finite temperatures, which were adopted in calculation, are 90^0C for the contact surface and 40^0C for surface of metal enclosure. Applied method was based on finite element method.

TABLE I
VALUES OF THERMAL CONDUCTIVITY

Block	Copper contact and bus bar	Aluminium conductor	XLPE insulation	Air
Thermal conductivity λ (W/mK)	387	210	0.25	0.0258

VII. CONCLUSION

Temporary monitoring of contact temperature at the place of fitting the cable indoor termination in the metal enclosure is important for safe service of the cable line. Each overheating the contact in some period can cause its ageing and cannot be compensated by subsequent cooling (decreasing the load current). As seen in numerical examples, analytical calculation of temperature is very complex and obtained results are not reliable. Therefore, some numerical method can be applied in the case of more complex configuration. Knowing the thermal conductivity of applied materials and geometry of analyzed domain, the temperature distribution can easily be obtained.

For the best reliable results, infra red camera shall be applied

REFERENCES

[1] IEC 60943 Guidance concerning the permissible temperature rise for the part of electrical equipment, in particular for terminals

[2] D.Tasić, Termički aspekti strujne opteretljivosti provodnika nadzemnih elektroenergetskih vodova, Edicija Monografije, Elektronski fakultet, Niš, 2002.

[3] L.Heinhold: Kabel und Leitungen für Starkstrom, Siemens Aktiengesellschaft, 4. überarbeitete Aufulage 1987.

[4] R.Dimitrijević, G.Jovović: Thermal field in premoulded 110 kV cable joint, R 2.04 JUKO CIGRE XVI Conference about power cables, Commitee 21, Soko Banja 27.-31.5. 2000.