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Estimation of the Heating of Crimped Connections Based on Experimental Tests

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Abstract – **In this work, some analytical formulas based on experimental tests are presented that can be used to estimate the heating of the crimped connections used in construction of electrical machines, saving the experimenter from additional, long and expensive tests. The formulas are based on the energy balance equation and combine practical results obtained from previous steady-state heating cycles for a set of 6 crimped connections of the same type, at currents close to the nominal value. There are standards that allow the estimation of the heating of the elements in the circuit at small variations of the test current. Thus, based on the heating obtained at one value of the current, the heating at another, slightly different value can be estimated, without the need for the actual experiment. For a more accurate estimation, the variation with temperature of the electrical resistances of the 6 connectors must be taken into account, which allows the extension of the estimation range. In this case, if there are two heating cycles performed at two different values of the current, estimations can also be made at other values, much different from the two. A global temperature coefficient of resistance can be deduced that can simplify the formulas while keeping the precision, serving to estimate the average heating of the connectors. The formulas have been validated for several types of crimped connections used in the construction of electrical machines.**

Cuvinte cheie: *conexiuni sertizate, încălzire, coeficient de variaţie a resistenţei cu temperatura, rezultate experimentale, maşini electrice.*

Keywords: *crimped connections, heating, temperature coefficient of resistance, experimental results, electrical machines.*

I. INTRODUCTION

Electrical machines such as motors and generators widely use crimp connections, which are permanent electrical contacts on which the reliability of the machine largely depends [1]. Crimping is a mechanical process often carried out with the help of hydraulic presses and its quality depends on a lot of factors, from the preparation of the cables and the choice of connectors, to the pressing itself.

Much research has been done over time to improve the performances of crimped connections, developing verification methods using ultrasonic inspection [2], [3] and thermography [4], analyzing the behavior at thermal shocks [5] or other factors that affect the contact resistance [6], modeling electric conduction [7] or temperature investigation for different types of crimping [8] with thermal modeling of heat transfer [9], [10]. For a quality pre-control of crimp contact, two solutions were proposed in [11] consisting in experimental determination of specific losses by calculating the initial rate of temperature or checking reaching a critical temperature using on-level thermal indicator. To reduce of contact resistance and increase the reliability of crimped connections, useful solution was proposed in [12] by using two adjacent crimp indents in opposite sides instead of one crimp indents. In a recent work [13] is studied the influence of an improper crimped connection execution on crimping validation, analyzing the limits of variation of parameters so that it will not be compromised.

International standards such as [14] and [15] establish very clear methodologies for verifying the quality of crimped connections from an electrical, thermal and mechanical point of view.

In [16], a study of the influence of experimental measurements accuracy on coefficient δ called "initial scatter" which was performed, cumulating data from 6 crimped connections of barrel of terminal lug type, with different cross sections of cables and determining the quantities with the greatest influence. The paper [17] extends the researches on crimped connections of bimetallic through connector type by analyzing two pairs of cross sections. The obtained results can help the experimenter to pay more attention to measuring more influential quantities.

In [20], some useful formulas based on experimental determinations were presented that can be used to estimate the average heating of a set of 6 crimped connections, saving the experimenter from additional, long and expensive tests. The formulas were validated for several types of crimped connections used in the electrical machines.

In this paper, the results of two case studies used in [20] are detailed, highlighting graphically the differences between the estimations of the individual heatings of the connectors, obtained with the derived formulas.

II. ELECTRICAL TESTS OF CRIMPED CONNEXIONS

The standard [14] establishes formulas for determining the connector resistance factor, initial scatter (δ) and mean scatter (β) for different types of crimping: through connector, bimetallic through connector, branch connector, barrel of terminal lug, palm of terminal lug etc. (Fig. 1).

The initial scatter coefficient (δ) provides information on the behavior of the crimped connection immediately after installation before any aging effect begins. It is considered that 6 samples are sufficient to be tested to estimate the identification of a "family" of connectors. If the resistance factors for the type of connector tested are almost equal, it can be assumed that the same design and assembly technology will lead to the same result on a conductor of the same type. The mean scatter β has the same meaning as δ but takes into account the age of the connectors, assuming long-term operation at high temperatures.

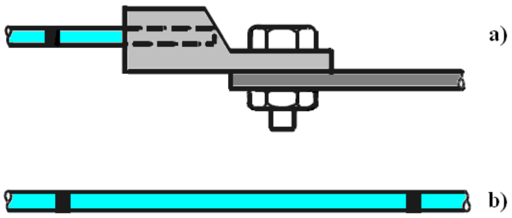

Fig. 1. Barrel of terminal lug (a) and reference conductor (b) [14].

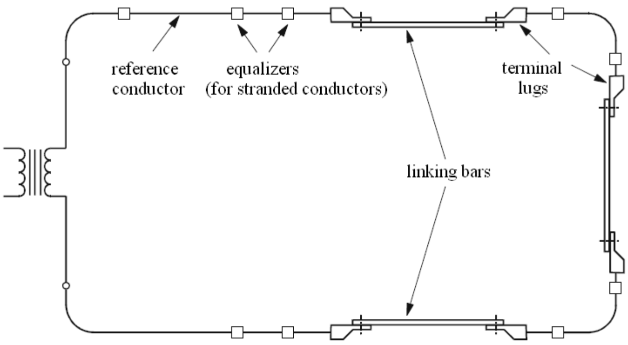

Fig. 2. Typical test circuit for barrel of terminal lugs [14].

For the experimental determinations of δ are used sets of 6 samples and reference conductors of each type involved in crimping. The measurements must make in direct current.

The influence of temperature on the resistance factor of the connector can be established after performing a large number of successive heating cycles in alternating current, by passing through the 6 samples in series (Fig. 2) with a current close to the rating one. Since during the tests high temperatures are reached both for the connectors and for the reference conductor, the use of thermoelectric thermometer is recommended for temperature measurement.

The standard provides for two preliminary heating cycles. The first cycle aims to determine the reference conductor temperature (θ_R) which will be used for subsequent heating cycles. The injected current into the test loop must be adjusted to ensure the condition 120°C ≤ θ_R ≤ 140°C at equilibrium, defined as the time when the reference conductor and connectors do not vary in temperature by more than ±2 K for 15 min.

The second heating cycle aims to determine the duration of a heating cycle by injecting a current into the test loop until the temperature of the reference conductor reaches the value θ_R for the duration t_1 and then cooling the connectors and the reference conductor to a temperature $\theta_0 \le 35$°C on duration t_2. The total period $t_1 + t_2$ constitutes the duration of a heating cycle.

A number of 1000 heating cycles is recommended [14], and after the first 250 cycles, every 75 cycles the maximum temperatures θ_{max} of the connectors and the temperature θ_{ref} of the reference conductor are recorded and then the value of the mean scatter coefficient (β) is calculated. Comparing the temperatures θ_{max} of the connectors with the simultaneously recorded temperature on the reference conductor θ_{ref} (which has a stable resistance) gives a rough idea of the "hot resistance" of each individual connector.

Being a long and expensive test, the heating test can be reduced to a single heating cycle, at current values that do not exceed the rating value, i.e. a current density of maximum 7 A/mm^2, following only the maximum temperatures θ_{max} reached of each connector, at equilibrium. Of course, in this case, the effect of the thermal stress on the crimped connections can only be ascertained in operation.

In the case of performing a single heating cycle, the manufacturer may request results regarding the maximum heating of the connectors obtained for several levels of current density, between 2 ÷ 7 A/mm^2. Based on the performed tests, empirical formulas can be derived for determining the heating of the same connectors at other current density values, thus saving the experimenter from additional tests, reducing both the cost and the duration of the tests.

The paper [20] presents useful empirically determined formulas on the basis of which the heating of the connectors can be estimated at theoretical values of the current density, different from those actually used. The formulas are experimentally validated.

The calculation is based on the equation of the energy balance in the unit of time at thermal equilibrium, which equates the Joule-Lentz losses with the heat flow transmitted to the surrounding environment by thermal convection:

$$R_i \cdot I^2 = \alpha \cdot \Delta\theta \cdot S_L = \alpha \cdot (\theta_{max\,i} - \theta_{amb}) \cdot S_L \qquad (1)$$

where I = RMS value of the current, R_i = electrical resistance of the i^{-th} connector, $i = 1 \div 6$, modeled as a conductor of cross-section S, length L and lateral surface S_L, which reaches the steady-state temperature θ_{maxi}, with global heat transfer coefficient α, at the ambient temperature θ_{amb}.

Writing the above equation for two slightly different values of the current I_1 and I_2, neglecting the temperature variation of the resistance and of the global heat transfer coefficient, we obtain:

$$\begin{cases} R_i \cdot I_1^2 = \alpha \cdot \Delta\theta_{1i} \cdot S_L = \alpha \cdot (\theta_{1max\,i} - \theta_{amb1}) \cdot S_L \\ R_i \cdot I_2^2 = \alpha \cdot \Delta\theta_{2i} \cdot S_L = \alpha \cdot (\theta_{2max\,i} - \theta_{amb2}) \cdot S_L \end{cases} \qquad (2)$$

$$\left(\frac{I_1}{I_2}\right)^2 = \frac{\Delta\theta_{1i}}{\Delta\theta_{2i}} = \frac{\theta_{1max\,i} - \theta_{amb1}}{\theta_{2max\,i} - \theta_{amb2}} \qquad (3)$$

$$\Delta\theta_{2i} = \frac{I_2^2 \cdot \Delta\theta_{1i}}{I_1^2} \qquad (4)$$

Therefore, having performed a heating test at current I_1 and θ_{amb1}, for which the maximum temperature θ_{1maxi} was obtained for connector i, respectively, the heating $\Delta\theta_{1i}$, applying formula (4) it is possible to estimate the heating $\Delta\theta_{2i}$, which would be obtained at current I_2, not much different from I_1, for the same connector, in other ambient conditions θ_{amb2}. The approximation is valid within the limits of ±5% variations of the current [18].

A global evaluation of the 6 connectors in the test loop should use information about all connectors, therefore instead of the heating of connector i at the current I_1 ($\Delta\theta_{1i}$), an average of the heatings of all connectors ($\Delta\theta_{1mean}$) at the same current I_1 can be considered [20]:

$$\Delta\theta_{1\,\text{mean}} = \frac{1}{6}\cdot\sum_{i=1}^{6}\left(\theta_{1\max i} - \theta_{\text{amb1}}\right) \tag{5}$$

from where: $$\Delta\theta_{2\,\text{mean}} = \frac{I_2^2 \cdot \Delta\theta_{1\,\text{mean}}}{I_1^2} \tag{6}$$

represents the average heating that would be obtained at current I_2 and θ_{amb2}.

In the case of larger differences between the values of the currents I_1 and I_2, the variation of the electrical resistance R_i (or resistivity ρ_i) of the connector with temperature must also be taken into account by the coefficients $\alpha_{\text{R}i}$ [20]:

$$R_i = \frac{\rho_i \cdot L}{S} = \frac{\rho_{\text{Cu20}} \cdot \left[1 + \alpha_{\text{R}i} \cdot (\theta_{\max i} - 20^\circ\text{C})\right] \cdot L}{S} \tag{7}$$

Writing the energy balance equation for I_1 and I_2 and neglecting only the temperature variation of the global heat transfer coefficient, we obtain:

$$\begin{cases} R_{1i} \cdot I_1^2 = \alpha \cdot \Delta\theta_{1i} \cdot S_{\text{L}} = \alpha \cdot (\theta_{1\max i} - \theta_{\text{amb1}}) \cdot S_{\text{L}} \\ R_{2i} \cdot I_2^2 = \alpha \cdot \Delta\theta_{2i} \cdot S_{\text{L}} = \alpha \cdot (\theta_{2\max i} - \theta_{\text{amb2}}) \cdot S_{\text{L}} \end{cases} \tag{8}$$

$$\frac{1 + \alpha_{\text{R}i} \cdot (\theta_{1\max i} - 20^\circ\text{C})}{1 + \alpha_{\text{R}i} \cdot (\theta_{2\max i} - 20^\circ\text{C})} \cdot \left(\frac{I_1}{I_2}\right)^2 = \frac{\theta_{1\max i} - \theta_{\text{amb1}}}{\theta_{2\max i} - \theta_{\text{amb2}}} \tag{9}$$

$$\Delta\theta_{2i} = \frac{I_2^2 \cdot \Delta\theta_{1i} \cdot [1 + \alpha_{\text{R}i} \cdot (\theta_{\text{amb2}} - 20^\circ\text{C})]}{I_1^2 \cdot \left[1 + \alpha_{\text{R}i} \cdot (\theta_{1\max i} - 20^\circ\text{C})\right] - I_2^2 \cdot \alpha_{\text{R}i} \cdot \Delta\theta_{1i}} \tag{10}$$

Therefore, the heating $\Delta\theta_{2i}$ also depends on the coefficient $\alpha_{\text{R}i}$. The standard [14] indicates the value $\alpha_{\text{R}} = 0.004 \cdot \text{K}^{-1}$ for copper and aluminum conductors. In general, an electrical contact can have a value reduced by even a third of the coefficient α_{R} compared to the conductors that contributed to the formation of the contact [19]. From relation (10) it can be deduced:

$$\alpha_{\text{R}i} = \frac{I_2^2 \cdot \Delta\theta_{1i} - I_1^2 \cdot \Delta\theta_{2i}}{I_1^2 \cdot (\theta_{1\max i} - 20^\circ\text{C}) \cdot \Delta\theta_{2i} - I_2^2 \cdot (\theta_{2\max i} - 20^\circ\text{C}) \cdot \Delta\theta_{1i}} \tag{11}$$

Based on the formulas (10) and (11), having carried out two heating tests at currents I_1 and I_2 for which the maximum temperatures $\theta_{1\max i}$, respectively, $\theta_{2\max i}$ were obtained, $i = 1 \div 6$, in ambient conditions θ_{amb1}, respectively, θ_{amb2}, the heatings $\Delta\theta_{3i}$ which would be obtained at current I_3, different from I_1 and I_2, in ambient conditions θ_{amb3}, can be estimated:

$$\Delta\theta_{3i} = \frac{I_3^2 \cdot \Delta\theta_{1i} \cdot [1 + \alpha_{\text{R}i} \cdot (\theta_{\text{amb3}} - 20^\circ\text{C})]}{I_1^2 \cdot \left[1 + \alpha_{\text{R}i} \cdot (\theta_{1\max i} - 20^\circ\text{C})\right] - I_3^2 \cdot \alpha_{\text{R}i} \cdot \Delta\theta_{1i}} \tag{12}$$

The average heating of the 6 connectors at current I_3 and θ_{amb3} results:

$$\Delta\theta_{3\,\text{mean}} = \frac{1}{6}\cdot\sum_{i=1}^{6}\Delta\theta_{3i} \tag{13}$$

A global temperature coefficient of resistance α_{R} for the 6 connectors in the test loop can be obtained by replacing all individual quantities in relation (11) with their averages [20]:

$$\Delta\theta_{2\,\text{mean}} = \frac{1}{6}\cdot\sum_{i=1}^{6}\left(\theta_{2\max i} - \theta_{\text{amb2}}\right) \tag{14}$$

$$\theta_{1\max\,\text{mean}} = \frac{1}{6}\cdot\sum_{i=1}^{6}\theta_{1\max i} \tag{15}$$

$$\alpha_{\text{R}} = \frac{I_2^2 \cdot \Delta\theta_{1\,\text{mean}} - I_1^2 \cdot \Delta\theta_{2\,\text{mean}}}{\begin{bmatrix} I_1^2 \cdot (\theta_{1\max\,\text{mean}} - 20^\circ\text{C}) \cdot \Delta\theta_{2\,\text{mean}} - \\ - I_2^2 \cdot (\theta_{2\max\,\text{mean}} - 20^\circ\text{C}) \cdot \Delta\theta_{1\,\text{mean}} \end{bmatrix}} \tag{16}$$

The global coefficient α_{R} can be used in (12), replacing individual coefficients $\alpha_{\text{R}i}$, to estimate the heatings $\Delta\theta_{3i}$ [20]:

$$\Delta\theta'_{3i} = \frac{I_3^2 \cdot \Delta\theta_{1i} \cdot [1 + \alpha_{\text{R}} \cdot (\theta_{\text{amb3}} - 20^\circ\text{C})]}{I_1^2 \cdot \left[1 + \alpha_{\text{R}} \cdot (\theta_{1\max i} - 20^\circ\text{C})\right] - I_3^2 \cdot \alpha_{\text{R}} \cdot \Delta\theta_{1i}} \tag{17}$$

The average heating of the 6 connectors at current I_3 and θ_{amb3} results [20]:

$$\Delta\theta'_{3\,\text{mean}} = \frac{1}{6}\cdot\sum_{i=1}^{6}\Delta\theta'_{3i} \tag{18}$$

Relations (4), (6), (11), (12), (13), (16), (17) and (18) save the experimenter from an additional test at the I_3 value of the current, saving time and energy.

III. Case Studies

In the following, two case studies are presented in which barrel of terminal lug type crimped connections of different sections are subjected to a single heating cycle. In each test, the use of the proposed formulas is attempted and useful conclusions are drawn.

A. Case I

We consider the case of barrel of terminal lug type crimped connections of 185 mm^2 section for which the maximum temperatures of the connectors are requested during steady-state heating tests with current densities of 2, 3 and 4 A/mm^2, corresponding to the currents I_1 = 370 A, I_2 = 555 A and I_3 = 740 A. After carrying out the tests, overtemperatures ($\Delta\theta_i = \theta_{\max i} - \theta_{\text{amb}}$) were obtained at thermal equilibrium for ambient temperatures θ_{amb1} = 27.2°C, θ_{amb2} = 27.2°C, respectively, θ_{amb3} = 28°C, and they are noted in Table I.

In the second test, a current of 560 A was used, which corresponds to a current density of 3.027 A/mm^2. For a correct reporting, it is necessary to estimate the values at 555 A using formulas (4) and (6), since the difference between the test currents is not too big (variation 0.89%). The estimation results are presented in Table II. In Table III and Table IV are presented the estimations with formulas (12), (13), respectively, (17), (18) with a better precision.

In Fig. 3 are shown the overtemperatures measured in the real tests, the estimations with (4), highlighted to the value 555 A and the range of applicability allowed by the

TABLE I.
OVERTEMPERATURES MEASURED IN REAL TESTS FOR 370 A, 560 A, 740 A [20]

Current [A]	$\Delta\theta_i$ [K]						$\Delta\theta_{mean}$ [K]
	1	2	3	4	5	6	
370	15.9	16.5	16.0	16.7	16.0	16.1	16.20
560	38.5	38.1	37.7	37.6	37.1	38.7	37.95
740	66.3	67.5	66.6	67.9	66.4	69.4	67.35

TABLE II.
OVERTEMPERATURES ESTIMATED WITH (4), (6) FOR 555 A BASED ON RESULTS FOR 560 A [20]

I_2 [A] / based on I_1 [A]	$\Delta\theta_i$ [K] (4)						$\Delta\theta_{mean}$ [K] (6)
	1	2	3	4	5	6	
555 / 560	37.8	37.4	37.0	36.9	36.4	38.0	37.275

TABLE III.
OVERTEMPERATURES ESTIMATED WITH (11), (12), (13), FOR 555 A AND 560 A BASED ON RESULTS FOR 370 A AND 740 A

I_3 [A] / based on I_1, I_2 [A]	$\Delta\theta_i$ [K] (11), (12)						$\Delta\theta_{mean}$ [K] (13)
	1	2	3	4	5	6	
555 / 370, 740	36.4	37.5	36.6	37.8	36.5	37.3	37.022
560 / 370, 740	37.1	38.2	37.3	38.5	37.2	38.0	37.711

TABLE IV.
OVERTEMPERATURES ESTIMATED WITH (16), (17), (18) FOR 555 A AND 560 A BASED ON RESULTS FOR 370 A AND 740 A

I_3 [A] / based on I_1, I_2 [A]	$\Delta\theta_i$ [K] (16), (17)						$\Delta\theta_{mean}$ [K] (18)
	1	2	3	4	5	6	
555 / 370, 740	36.5	37.1	36.6	37.3	36.5	38.1	37.025
560 / 370, 740	37.1	37.8	37.3	38.0	37.2	38.8	37.714

TABLE V.
ESTIMATION ERRORS OF (12), (13), (17), (18) COMPARED TO THE VALUES MEASURED IN REAL TEST FOR 560 A

Formulas	Errors ε_i [%]						ε_{mean} [%] (13), (18)
	1	2	3	4	5	6	
(12)	-3.74	0.15	-1.15	2.45	0.33	-1.70	-0.63
(17)	-3.54	-0.8	-1.05	1.11	0.25	0.35	-0.62

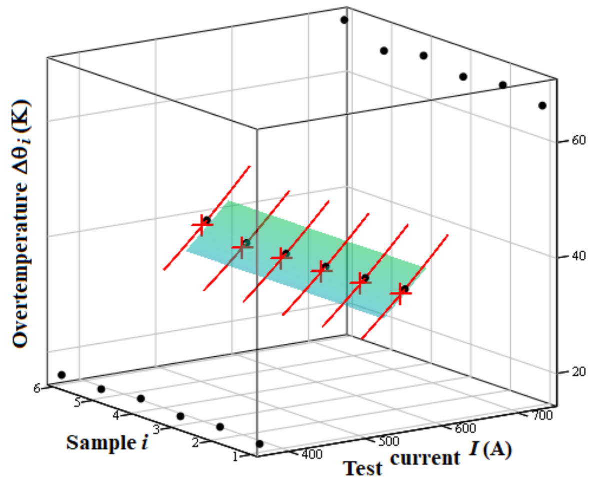

Fig. 3. Overtemperatures measured in real tests (black), estimated with (4) (red), highlighted to the value 555 A and the range of applicability (rainbow), for the case I.

standard [18]. In Fig. 4 and Fig. 5 are shown the estimations with (11), (12), respectively, (17), (18) highlighted to the same value and the range of applicability, visibly extended compared to the previous one.

Since three real heating tests were performed, the results of the second test can be used to validate the estimations using the purposed formulas. Thus, in Table V are done the errors ε of (12), (13), respectively, (17), (18) compared to the values measured in the real heating test for 560 A:

$$\varepsilon_i = \frac{\Delta\theta_{3i} - \Delta\theta_{3i}\big|_{560A}}{\Delta\theta_{3i}\big|_{560A}} \cdot 100\% \tag{19}$$

$$\varepsilon_{mean} = \frac{\Delta\theta_{3mean} - \Delta\theta_{3mean}\big|_{560A}}{\Delta\theta_{3mean}\big|_{560A}} \cdot 100\% \tag{20}$$

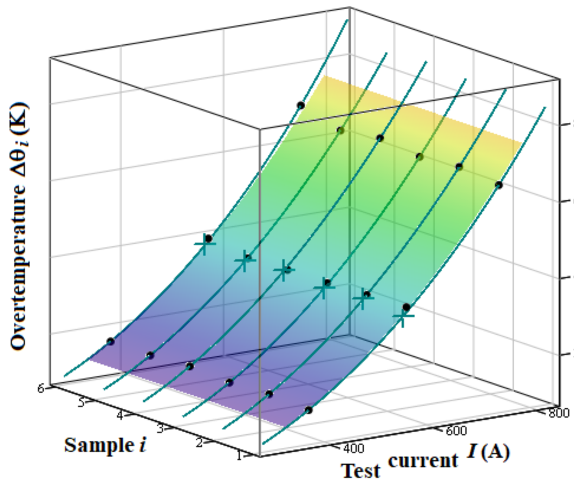

Fig. 4. Overtemperatures measured in real tests (black), estimated with (11) and (12) (green) and highlighted to the value 555 A and the range of applicability (rainbow), for the case I.

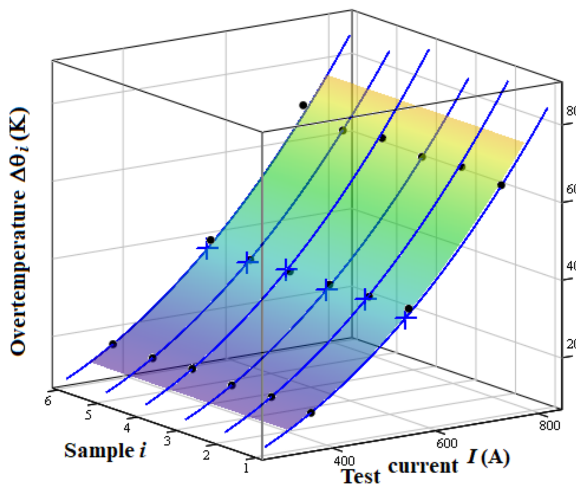

Fig. 5. Overtemperatures measured in real tests (black), estimated with (16) and (17) (blue) and highlighted to the value 555 A and the range of applicability (rainbow), for the case I.

The data show a good agreement with the real experiment, with average errors of –0.63% for (13) and –0.62 % for (18). Also, it can be observed that the two formulas offer results close to each other. In Fig. 6 and Fig. 7 are highlighted the estimations with (11), (12), respectively, (17), (18) to the 560A.

The global temperature coefficient of resistance determined with (16) is $\alpha_R = 0.0007711639\ K^{-1}$. There is a decrease of 80.72% compared to the value of 0.004 K^{-1} [14].

In Fig. 8 are plotted the mean overtemperatures defined by relations (6) and (18) [20]. The points corresponding to the three real tests are also placed on the graph. The estimation of 37.714 K obtained with (18) at 560 A differs by 0.62% from the average real value 37.950 K. It is observed that the accuracy is quite good, although the current variations from 370 A to 560 A, or from 740 A to 560 A are 51.35%, respectively, –24.32%, i.e. much higher than ±5% [18]. At 555 A, an average heating of 37.275 K is estimated with (6) and of 37.025 K with (18), with an error between them of 0.67%. Obviously, the value obtained with (18) is much more precise.

B. *Case II*

We consider the case of barrel of terminal lug type crimped connections of 245 mm^2 section for which the maximum temperatures of the connectors are requested during steady-state heating tests with current densities of 4 and 5 A/mm^2, corresponding to the currents I_1 = 980 A and I_2 = 1225 A. After carrying out the tests, overtemperatures were obtained at thermal equilibrium for ambient temperature $\theta_{amb1} = \theta_{amb2}$ = 19°C and they are noted in Table VI.

In the two tests, currents of 1005 A and 1140 A were used, which corresponds to current densities of 4.103 A/mm^2 and 4.654 A/mm^2. For a correct reporting, it is necessary to estimate the values at 980 A and 1125 A.

As the variations of the currents from 1005 A to 980 A (–2.49%), respectively from 1140 A to 1125 A (1.32%) fall within the limits of ±5% [18], we can use formulas (4) and (6) and the estimation results are presented in Tables VII. For a greater precision, the use of formulas (12), (13) or (17), (18) led to the results shown in Tables VIII-IX.

In Fig. 9 are shown the overtemperatures measured in the real tests, the estimations with (4), highlighted to the value 980 A and 1125 A and the ranges of applicability allowed by the standard [18]. In Fig. 10 and Fig. 11 are shown the estimations with (11), (12), respectively, (17), (18) highlighted to the same values and the range of applicability, visibly extended compared to the previous ones, like in case I.

The global temperature coefficient of resistance determined with (16) is $\alpha_R = 0.0031139147\ K^{-1}$. There is a decrease of 22.15% compared to the value of 0.004 K^{-1} [14].

In Fig. 12 are plotted the mean overtemperatures defined by relations (6) and (18) [20]. The points corresponding to the two real tests are also drawn.

At 980 A, an average heating of 71.742 K is estimated with (6) and of 70.922 K with (18), with an error between them of 1.06%.

At 1125 A, an average heating of 101.394 K is estimated with (6) and of 100.540 K with (18), with an error between them of 0.85%. As before, the values obtained with (16) are much more precise.

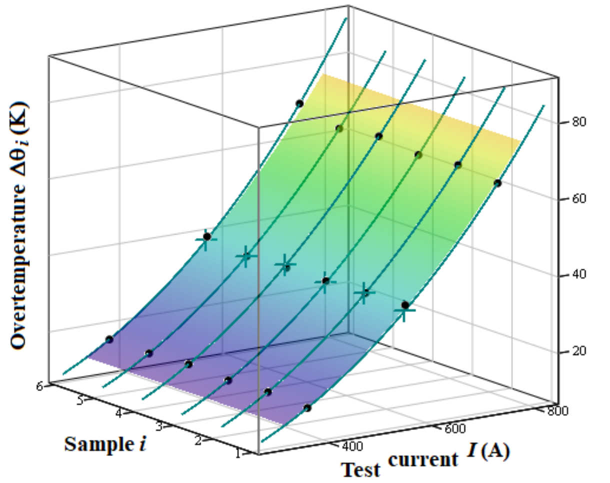

Fig. 6. Overtemperatures measured in real tests (black), estimated with (11) and (12) (green) and highlighted to the value 560 A and the range of applicability (rainbow), for the case I.

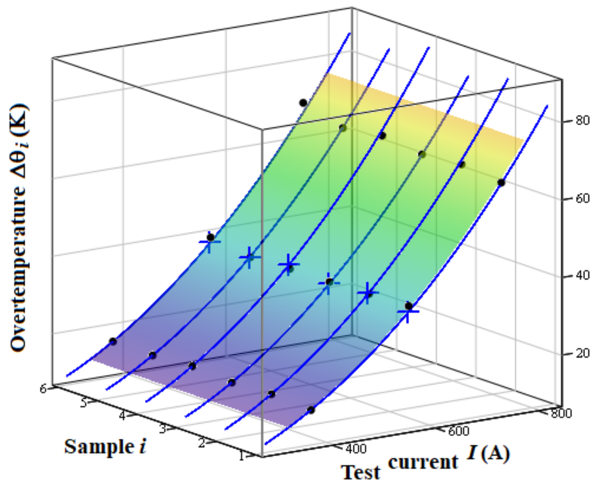

Fig. 7. Overtemperatures measured in real tests (black), estimated with (16) and (17) (blue and highlighted to the value 560 A and the range of applicability (rainbow), for the case I.

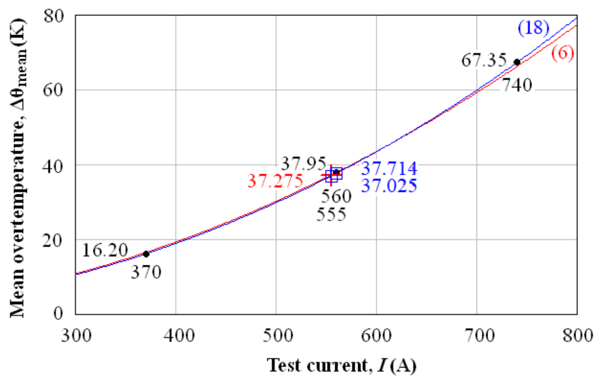

Fig. 8. Mean overtemperatures measured in real tests (black), estimated with (6) (red) and (18) (blue) [20].

TABLE VI.
OVERTEMPERATURES MEASURED IN REAL TESTS FOR 1005 A, 1140 A [20]

Current [A]	$\Delta\theta_i$ [K]						$\Delta\theta_{mean}$ [K]
	1	2	3	4	5	6	
1005	75.6	76.1	75.2	76.1	74.9	74.8	75.450
1140	103.4	104.1	104.2	104.9	103.8	104.3	104.117

TABLE VII.
OVERTEMPERATURES ESTIMATED WITH (4), (6).FOR 980 A AND 1125 A BASED ON RESULTS FOR 1005 A, RESPECTIVELY, 1140 A [20]

I_2 [A] / based on I_1 [A]	$\Delta\theta_i$ [K] (4)						$\Delta\theta_{mean}$ [K] (6)
	1	2	3	4	5	6	
980 / 1005	71.9	72.4	71.5	72.4	71.2	71.1	71.742
1125/1140	100.7	101.4	101.5	102.2	101.1	101.6	101.394

TABLE VIII.
OVERTEMPERATURES ESTIMATED WITH (11), (12), (13), FOR 980 A AND 1125 A BASED ON RESULTS FOR 1005 A AND 1140 A

I_3 [A] / based on I_1, I_2 [A]	$\Delta\theta_i$ [K] (11), (12)						$\Delta\theta_{mean}$ [K] (13)
	1	2	3	4	5	6	
980 / 1005, 1140	71.2	71.6	70.6	71.6	70.4	70.2	70.9
1125 / 1005, 1140	100.0	100.6	100.6	101.3	100.2	100.6	100.5

TABLE IX.
OVERTEMPERATURES ESTIMATED WITH (16), (17), (18) FOR 980 A AND 1125 A BASED ON RESULTS FOR 1005 A AND 1140 A [20]

I_3 [A] / based on I_1, I_2 [A]	$\Delta\theta_i$ [K] (16), (17)						$\Delta\theta_{mean}$ [K] (18)
	1	2	3	4	5	6	
980 / 1005, 1140	71.1	71.5	70.7	71.5	70.4	70.3	70.922
1125 / 1005, 1140	99.9	100.5	100.6	101.3	100.2	100.7	100.540

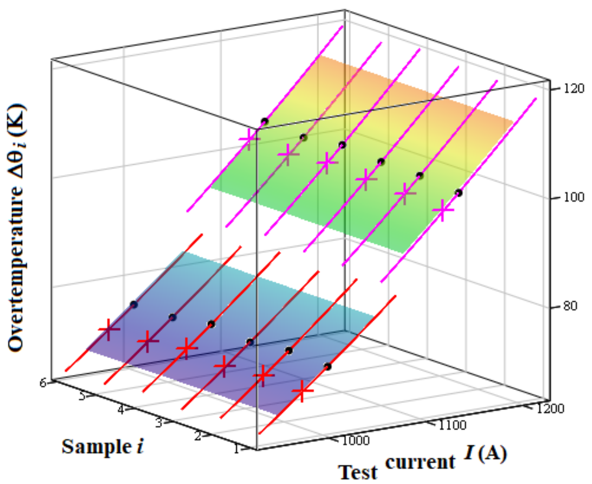

Fig. 9. Overtemperatures measured in real tests (black), estimated with (4) around the values 1005 A (red) and 1140 A (magenta) and highlighted to the value 980 A, respectively, 1125 A and the ranges of applicability (rainbow), for the case II.

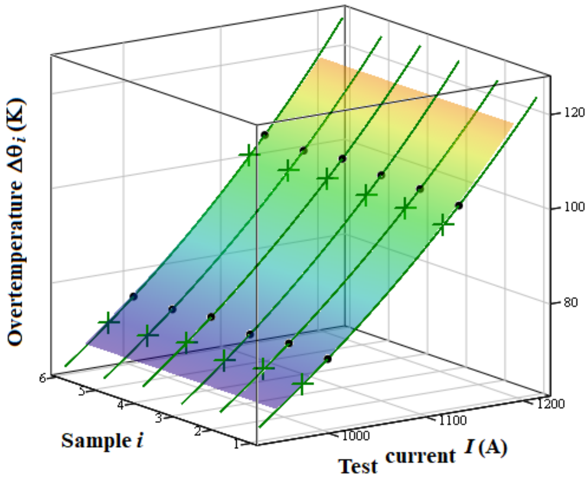

Fig. 10. Overtemperatures measured in real tests (black), estimated with (11) and (12) (green) and highlighted to the value 980 A, respectively, 1125 A and the range of applicability (rainbow), for the case II.

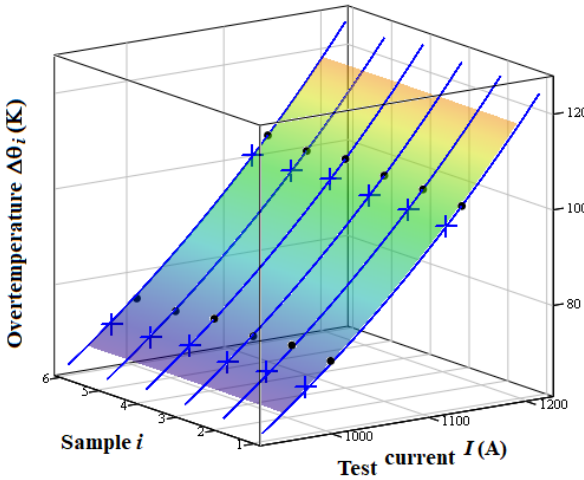

Fig. 11. Overtemperatures measured in real tests (black), estimated with (16) and (17) (blue) and highlighted to the value 980 A, respectively, 1125 A and the range of applicability (rainbow), for the case II.

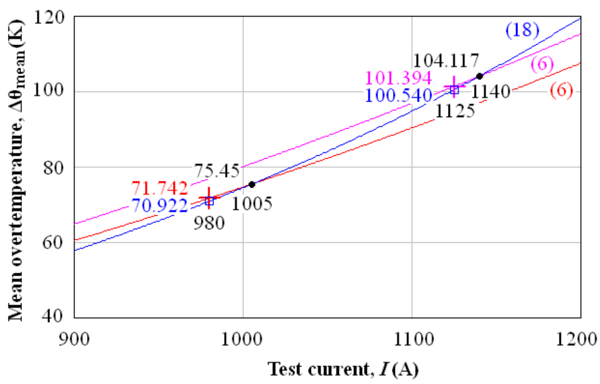

Fig. 12. Mean overtemperatures measured in real tests (black), estimated with (6) around the values 1005 A (red) and 1140 A (magenta) and highlighted to the value 980 A, respectively, 1125 A, estimated with (18) (blue) and highlighted to the same values, for the case II [20].

IV. CONCLUSIONS

The paper draws attention to some useful formulas for estimating the heating of crimped connections based on the experimental results obtained from previous tests. Some of the formulas can be applied to small variations of the test current (±5%), allowing estimations at a certain current if there are practical results for a close current. Other formulas, which take into account the temperature variation of the resistance of the connectors, allow the extension of the estimation range (>5%), being able to make estimations at very different currents, based on known practical results for two different values of the current. In this case, a global temperature coefficient of resistance α_R can be deduced that can be used to estimate the average heating.

The formulas were tested with a fairly good precision on concrete cases of crimped connections used in the construction of electric machines. Values of the coefficients α_R lower values than those of the component conductors were determined, which is in accordance with the theory of electrical contacts.

The use of the proposed formulas can save the experimenter from additional tests, leading to a saving of energy and time.

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REFERENCES

[1] BS EN 60352-2:2006, Solderless connections, Part 2: crimped connections – general requirements, test methods and practical guidance, 2006.

[2] E. Cramer, F. Daniel Perey, and T. William Yost, "Wire crimp connectors verification using ultrasonic inspection," IV Conferencia Panameri-cana de END Buenos Aires, Octobre, 2007.

[3] K. Elliott Cramer, F. Daniel Perey, and T. William Yost, "Wire crimp connectors verification using ultrasonic inspection," IV Conferencia Panamericana de END, Buenos Aires, pp. 1-11, 2007.

[4] M. Finc, T. Kek, and J. Grum, "Use of thermography and ultrasonic inspection for evaluation of crimped wire connection quality," 18thWorld Conference on nondestructive testing, Durban, South Africa, 2012.

[5] D.R. Liu, T. Bracket, and S. McCarthy, "Contact resistance comparison of good and bad crimp joints with tinned wires under thermal shock", Electrical Contacts, Proceedings of the Forty-Seventh IEEE Holm Conference, pp. 35-43, 2001.

[6] M. Mohd Ruzlin, A. H. Huzainie Shafi, and A.G. Ahmad Basri, "Study of cable crimping factors affecting contact resistance of medium voltage cable ferrule and lug," 22nd International Conference of electricity distribution, Stockholm, Suedia, 2013.

[7] G. Rosazza Prin, T. Courtin, and L. Boyer, "A new method to investigate electrical conduction in crimp joints. Influence of the compaction ratio and electrical model," Electrical Contacts, Proceedings of the Forty-Eighth IEEE Holm Conference, pp. 246 – 251, 2002.

[8] C.-F. Ocoleanu, A.-I. Dolan, G.A. Cividjian, and S. Teodorescu, "Temperature investigations in two type of crimped connection using experimental determinations," International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering, Vol. 8, No. 10, pp. 1633-1636, 2014, International Conference on Thermal Engineering, Barcelona, Spain, 2014.

[9] C.-F. Ocoleanu, I. Popa, A.-I. Dolan, and V. Ivanov, "Magneto-Thermal Model for Crimped Connections," Annals of the University of Craiova, Series: Electrical Engineering, No. 38, pp. 56-61, Universitaria Publishing House, 2014.

[10] C.-F. Ocoleanu, I. Popa, A.-I. Dolan, and V. Ivanov, "Crimped Connections Heat Transfer Coefficient Law Determination Using Experimental and Numerical Results," Proceedings of the XII-th IEEE International Conference on Applied and Theoretical Electricity - ICATE 2014, pp. 1-4, Craiova, Romania, October 23-25, 2014.

[11] C.-F. Ocoleanu, G.A. Cividjian, and Gh. Manolea, "Solutions for quality pre-control of crimp contacts used in electric power systems and electrical machines," 3nd International Symposium On Environment Friendly Energies And Applications, pp. 1-6, 2014.

[12] C.-F. Ocoleanu, G.A. Cividjian, and Gh. Manolea, "Technological solution for increasing the quality of crimped connections," 2015 IEEE 1st International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI), Sept. 16-18, pp. 1-6, 2015.

[13] C.-F. Ocoleanu, and A.-I. Dolan, "Experimental and Statistical Study of Connector Resistance Factor Influence on Crimping Validation Process," 7-th International Conference on Renewable Energy Research and Applications - ICRERA 2018, Paris, France, Oct 14-17, pp.174-178, 2018.

[14] BS EN 61238-1:2003, Compression and mechanical connectors for power cables for rated voltages up to 36 kV – Part 1: test methods and requirements, 2003.

[15] B945-05, Standard Guide for Specification and Quality Assurance for the Electrical Contact of Crimped Wire Terminations.

[16] A.-I. Dolan, and C.-F. Ocoleanu, "Influence of Experimental Measurements Accuracy on Connector Resistance Factor for Crimped Connections," XVI-th IEEE International Conference on Applied and Theoretical Electricity – ICATE 2021, Craiova, Romania, May 27-29, 2021, pp. 1-5, 2021.

[17] A.-I. Dolan, and C.-F. Ocoleanu, "Impact of Experimental Measurements Accuracy on Validation Process of Crimped Connections," Annals of the University of Craiova, Series: Electrical Engineering, No. 45, pp. 16-23, Universitaria Publishing House, 2021.

[18] IEC 60034-4, Rotating electrical machines - Part4: Methods for determining synchronous machine quantities from tests, 2008.

[19] I. Popa, Electrical equipments - Theoretical bases (In Romanian), Universitaria Publishing House, 2017.

[20] A.-I. Dolan, "Useful Experiment Based Formulas for Estimating the Heating of Crimped Connections," Proceedings of the XIV-th IEEE International Conference on Electromechanical and Power Systems – SIELMEN 2023, October 11-13, pp. 1-5, Craiova-Chişinău, 2023.