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Influence of crimped connections in temperature rise tests

Paolo Emilio Roccato[1], **Luciano Bellavia**[1], **Pier Paolo Capra**[1], **Luca Cinnirella**[1], **Flavio Galliana**[1] and **Arcangela Perta**[2]

[1] Istituto Nazionale di Ricerca Metrologica (INRIM—National Institute of Metrological Research), Strada Cacce, 91, 10135 Turin, Italy
[2] Politecnico di Torino, Corso Duca degli Abruzzi 24 10129 Torino, Italy

E-mail: p.roccato@inrim.it

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Abstract

The resistance behavior of crimped connections in cables headed with crimped terminal lugs, used for rise temperature tests in the framework of the validation of electrical equipment, has been investigated. Analysis has been performed on test cables of two sections (240 mm^2 and 185 mm^2), available at the High Voltage and High Power Laboratory of the National Metrological Research Institute (INRIM). The resistance values showed a higher variability in larger section cables. The difference between the minimum and maximum value of the crimped resistance among the 240 mm^2 cables was of about one order, going from 9.6 μΩ to 82.8 μΩ. The 185 mm^2 cables, having better flexibility for their smaller section and less frequent use, and having been submitted to fewer tests, showed lower resistance variability with a variation between the maximum and minimum value of five times. The particular interest of the work is an analysis of the reliability of the crimping technique in the framework of the test activity, specifically relating to the validation of electrical devices such as circuit-breakers, switches, disconnectors, fuse-combination units and bus bar trunking systems.

Keywords: crimping, crimping resistance, terminal lug, temperature rise test, test laboratory, measurement uncertainty, validation of electrical devices

(Some figures may appear in colour only in the online journal)

1. Introduction

Crimping is a widespread technique to connect by pressure electrical contacts or wire conductors to wire terminations in electrical devices. Crimp connection reliability depends on many factors: the material, conductor size, crimp method, number of crimping profiles (with single square recess, with double recess, or hexagonal, for example), locations of crimp indents, and/or tensile strength. Some papers have explored the main factors that influence the performance of crimped connections [1–4], while other papers have investigated the current distribution in crimped connections [5], the heat transfer [6] and the temperature [7]. Other interesting papers [8, 9] have investigated, respectively, thermographic and ultrasonic techniques to evaluate crimped connections and wired connections in household appliances.

Our focus, representing the novelty and originality of the work, lies in the analysis of the effects of crimping resistances in cables headed with crimped terminal lugs involved in temperature rise tests in the framework of the validation of electrical devices. Figure 1 shows an example of crimped connections in a piece of electrical equipment. Our study could be useful for the management of devices such as circuit-breakers, switches, switch-disconnectors, fuse-combination units, power switch gear, control gear assemblies, and bus bar trunking systems (busways). The validation of electrical equipment includes the verification of temperature rises in nominal working conditions. In the case of equipment such as electrical panels and circuit breakers with nominal currents of several hundred amperes, their connections can be made with large section cables headed with crimped terminals. A temperature-rise test consists in the verification of the ability

Figure 1. Crimped connections in electrical devices.

of the device to carry the nominal current without exceeding temperature limits, imposed by the standard for the safety and durability of the devices. During the test, the cables are connected to a current supplier and to the loads to simulate the nominal conditions. In the case of low voltage, the section and the number of used cables is established by standards. The same standards, to safeguard the insulation of the cables and of the parts of the equipment during their useful life, provide, for the connections of electrical equipment, heating limits with respect to the test environment. Cables with crimped terminal lugs are therefore one of the main elements in a temperature rise test, since in the case of their being damaged or incorrectly crimped, they can lead to a dissipation of thermal power affecting or even invalidating the outcome of the test itself for the device to which they are connected. An investigation has been carried out on crimped terminal lugs, focusing our attention on the effects of crimping. This has been considered to be the point most highly subject to wear due to use and therefore to the variation in the seal of the pressed contact. Our aim was the evaluation of the electrical resistance of the crimping, with a method similar to that suggested in [10], but focusing on use in the laboratory in the test activity. This use differs from that in electrical systems and as defined in the product standards, as the cables are frequently installed on different equipment. The investigation has been performed on test cables available at the High Voltage and High Power Laboratory of the National Institute of Metrological Research (INRIM), with two different conductor sections (240 mm^2 and 185 mm^2). These cables are the most used and most subjected to wear. The choice of the cables was random, attempting only to have different types of terminal lugs and crimping method.

1.1. The High Voltage and High Power Laboratory (LATFC)

The LATFC laboratory deals with high voltages and high power. LATFC is involved in research in the electro-technical field, calibration and in verification services of electrical equipment, through temperature rise, short-circuit, voltage measurement and dielectric tests. It develops and maintains the standard setups for calibration of sources, sensors and measurement systems in high voltage and high power fields. LATFC customers are mainly calibration, testing, industrial laboratories, and manufacturers of high voltage and high power devices.

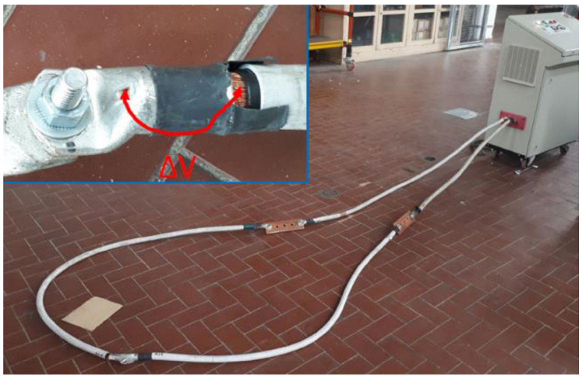

Figure 2. Measurement layout and detail of the measurement points for the voltage drop.

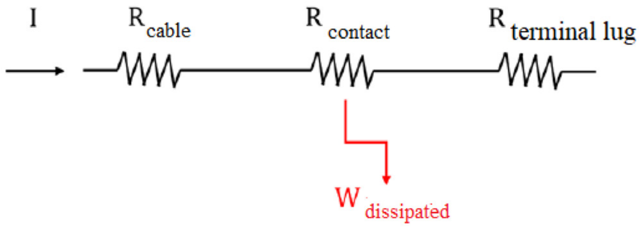

Figure 3. Resistive equivalent circuit of a section of a crimped connection. R_{contact} is the film resistance.

2. Measurement procedure

The cables involved in the tests have been connected, in series with each other, to a stabilized direct current generator. Initially they have been supplied with reduced current, for about an hour, to stabilize the thermal effects. The cables have then been measured at currents of 217 A and 107 A, respectively, for the 240 mm^2 and 185 mm^2 section cables. These values allow limiting heating effects and, at the same time, allow reliable measurements in conditions of thermal stabilization among the various terminal lugs. Thirty terminal lugs for the higher section cables and 18 terminal lugs for the lower section cables have been examined. The test layout is shown in figure 2. The crimp resistance has been evaluated as the ratio of the voltage of an equivalent resistance circuit (figure 3) and of a known supplied current I. In figure 3, the contact resistance is the resistance of the interface between two separable bodies. The voltage has been measured between the end of the pressed collar, in the area of the inspection hole, and the beginning of the corded conductor, paying attention to minimize the local effects of voltage drop.

The crimping resistance is given by the sum of the constraint and of the film resistances (figure 3). The constriction resistance is due to the coupling of two surfaces occurring only through their asperities that touch each other, while the resistance of the films is linked to the generation of surface films on the materials. In figure 3 the resistance components are as follows:

- R_{cable} is the equivalent resistance of the conductor inside the crimped lug;

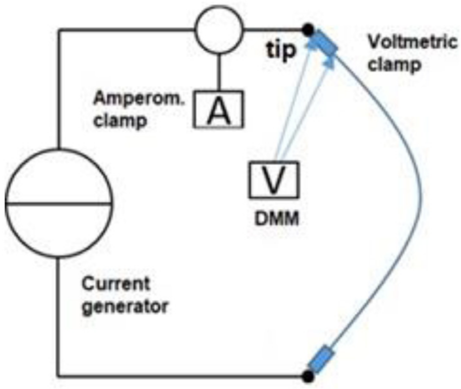

Figure 4. Simplified measurement scheme with employed instruments and devices.

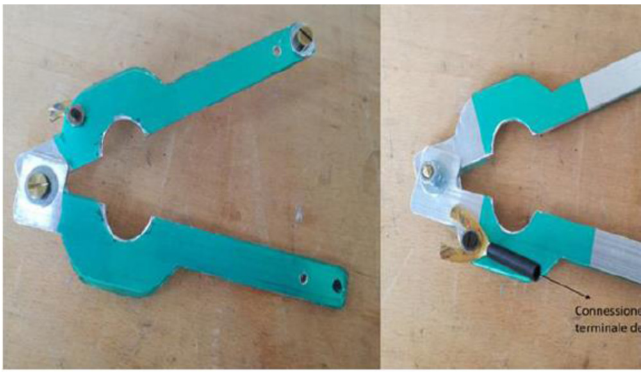

Figure 5. Voltmetric measuring clamp.

- R_{contact} is the equivalent resistance of the crimped contact due to the coupling between the two irregular surfaces; and
- $R_{\text{terminal lug}}$ is the equivalent resistance of the lug over the crimped zone.

2.1. Measurement setup

To carry out the resistance measurements (scheme in figure 4) on the terminals lugs fixed on the conductor end, the following instruments were used:

- Current generator (O.S.A.T. Elettronica), max voltage 8 V and a max current 1200 A.
- Low voltage cable CEI FG7R-O 0;6/1 kV 1 × 240 mm^2 CEI 20-2 with a length of about 2 m.
- Copper bars with a cross-section of 600 mm^2.
- Fluke 355 current clamp meter.
- Digital multimeter (DMM) HP 34401A.
- Voltmetric clamp.
- Thermocouples.
- Fluke 54 thermometer ii.

A voltmetric clamp, acting as auxiliary device, was built in aluminum at the LATFC (figure 5). Its shape is that of a 'nut-cracker' pivoted at the end. The diameter of the clamp closing

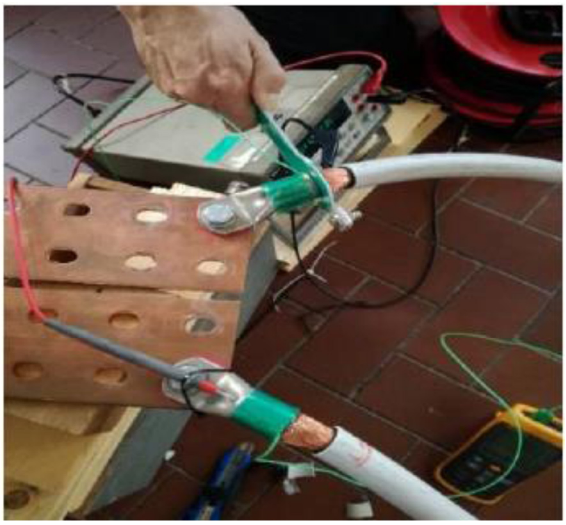

Figure 6. View of the setup to evaluate the uncertainty component due to the measurement reproducibility due to the voltmetric clamp.

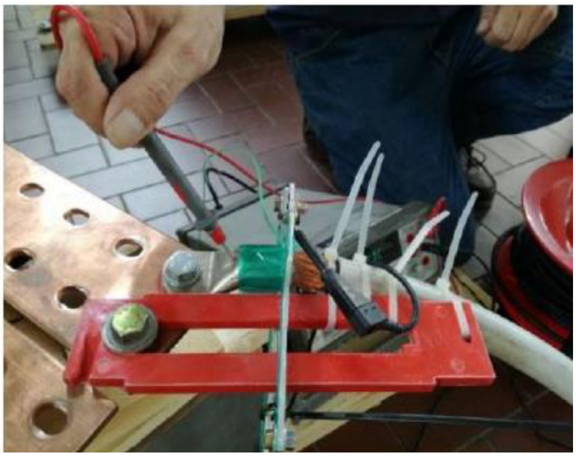

Figure 7. View of the setup to evaluate the measurement reproducibility due to the tip.

Table 1. R_{crimp}, uncertainty budget.

Component	Type	(%)	ν
Measurement reproducibility due to the voltmetric clamp	A	1.1	29
Measurement reproducibility due to the tip	A	0.2	29
DMM accuracy	B	0.5	∞
Voltage noise	A	0.1	29
Current clamp accuracy	B	0.8	∞
Standard uncertainty		**1.5**	92
Expanded uncertainty (2σ)		**2.9**	

area around the conductor was chosen to allow the use of the clamp even when the cable is subjected to any mechanical stress that could cause a slight swelling of the conductor. Table 1 shows an example of uncertainty budget for a measurement of the crimping resistance. The voltmetric clamp was built to have a stable equipotential point on the conductor to carry out the measurements. The use of a clamp has been chosen

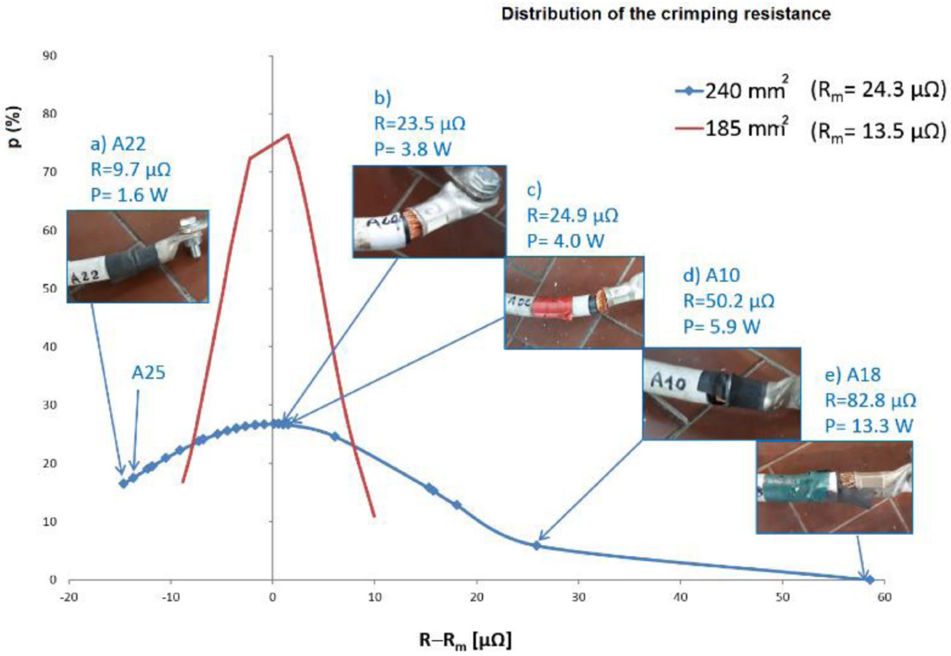

Figure 8. Value probability distributions of the crimping resistance for the examined cables and photos of some terminal lugs with indication of their crimping resistance and dissipated power. (a) A22, $R = 9.7$ μΩ, $P = 1.6$ W. (b) $R = 23.5$ μΩ, $P = 3.8$ W. (c) $R = 24.9$ μΩ, $P = 4.0$ W. (d) A10, $R = 50.2$ μΩ, $P = 5.9$ W. (e) A18, $R = 82.8$ μΩ, $P = 13.3$ W.

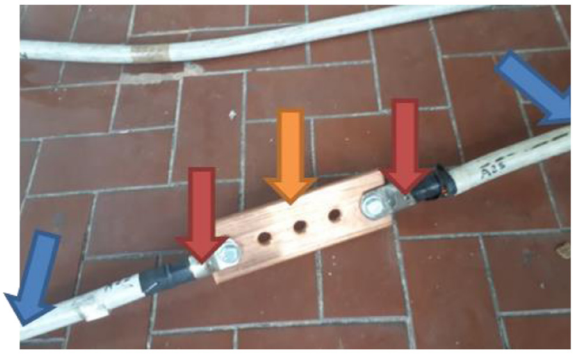

Figure 9. Temperature rise on the terminal lugs (red arrows, at the end of copper bar), at the center of the cable (blue arrows, on the edge of the figure), at the center of the copper bar/simulacrum (orange arrow, in the middle of the figure). The surface was not cleaned as the surface of the bar, being very glossy, hardly oxidizes. A bar normally used in electrical panels was involved, without cleaning it to carry out a measure close to real-world use.

over that of an equalizer as suggested by [10], as the equalizer tends to block the movements to which the conductor could be subjected. In addition, the clamp is easily removable and could be a suitable device to use during the measurement of the crimping resistance for periodic evaluation of the deterioration status of terminal lugs.

2.2. Measurement procedure

The measurement procedure consisted in the following steps:

- connection of the cables with terminal lugs with torque lock of (30 ± 5) Nm (torque tolerance);
- supplying with constant current for pre-heating;

Table 2. Temperature rise on the crimped-terminal lugs, on the cables and on the bars.

Lug ID	ΔT crimp	ΔT cable	ΔT bar
A10	37 K	10 K	32 K
A18	39 K	10 K	
A22	19 K	11 K	15 K
A25	17 K	9 K	

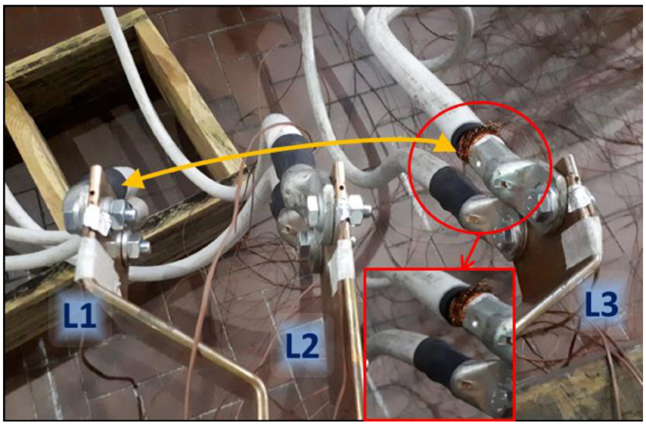

Figure 10. Comparison of measurements on a device with inversion of the damaged cable, in the red-square detail, # measurement in table 3.

- waiting for thermal stability evaluated by means thermocouples on the terminal lugs;
- current measurement;
- measurement of the voltage drop; and
- calculation of the resistance.

Table 3. Comparison between the rise temperature test exchanging the cable with damaged crimping between the phases L_1 and L_3 of a device.

First case			
Phase	L_1	L_2	L_3
I	1256 A	1267 A	1260 A
ΔT	54 K	61 K	67 K#
Second case			
Phase	L_1	L_2	L_3
I	1256 A	1268 A	1256 A
ΔT	65 K#	64 K	57 K

2.3. Measurement uncertainty

A resistance estimate is obtained from the readings of the DMM, which measures the voltage drop between the inspection hole of the terminal lug and the start of the corded conductor, and of an amperometric clamp meter. The main contributions to uncertainty are due to the following:

- DMM accuracy;
- voltage measurements noise;
- amperometric clamp meter accuracy;
- measurement reproducibility due to the voltmetric clamp; and
- measurement reproducibility of the measurements due to the tip.

The last two points are very important as these two characterizations allow the consideration of two additional uncertainty components, taking into account that in the measurements both the voltmetric clamp and the tip might not always be placed in an equal position for each cable. Therefore, a characterization of how possible different positioning of these two devices affects the total uncertainty was made. An evaluation of the measurement reproducibility due to the voltmetric clamp was obtained by locking the tip on the inspection hole of the terminal and making 30 readings of the voltage drop between the inspection hole and the start of the collar of the other terminal. The clamp was removed after each measurement (figure 6).

An evaluation of the measurement reproducibility due to the tip was obtained by locking the clamp on the beginning of the corded conductor and placing the tip on the inspection hole evaluating the voltage drop on the collar of the terminal (figure 7). Again, 30 measurements were performed. The tip was removed after each measurement.

3. Measurement results

The measurement results are shown in figure 8. This figure shows the distributions of the crimping resistances with respect to their difference versus the mean value (μΩ) for cables of two sections and available in our laboratory. The results show higher variability (evaluated as standard deviation) for the 240 mm^2 section cables due to their wider employment, due to the test requests at high current, but also because of their greater installation difficulty, being difficult to place the terminal lug on the connection bars. For these cables, the difference between the minimum and maximum value spans from 9.6 μΩ to 82.8 μΩ. The external appearance of the terminal lugs, in fact, observing figure 8(e)), shows higher resistance values, and a very marked color change of the corded conductor. Nevertheless, this does not show external differences in comparison with (b) or (c), which were also ruined; in a dual way, there are no particular differences between (a) and (d), although having a remarkably different resistance value. The 185 mm^2 cables, submitted to a lower number of tests and with greater flexibility due to their smaller section, shows a lower variability of their resistance values with a variation between the maximum and minimum resistance value of five times. For some values, the dissipated power in the crimp has been also calculated for the nominal current value of 400 A for the 240 mm^2 section cables and shown in figure 8. The effect of heating is not negligible, in particular on devices of small dimensions.

4. Thermal effects

The thermal effects as the temperature rises, with the same setup used for the resistance measurements (figure 2), were evaluated, placing the two cables with worst terminal lugs on a connection simulacrum, while the two cables with best terminal lugs were placed on another simulacrum (figure 9). The test was carried out in free air at 21 °C. The focus was on the comparison between the two terminal lug pairs rather than on the value of the temperature rise. The measurements were performed at 404 A at ambient temperature. The results are shown in table 2.

The results of this measure show how the effect of damaged terminal lugs can lead to a significant increase of the temperature rise – about double – on the bar set as a simulacrum. To verify that the cables do not affect the temperature rise, the surface temperature of their insulating material was measured at the center of the conductors, obtaining similar values both with worst and best terminal lugs. The measurements were made by drilling a small hole in the cable terminal and inserting a thermocouple, or, for the insulators, with a manual contact probe, still based on a thermocouple. Trying to evaluate the crimping effects in conditions closer to daily application, the results of a temperature rise test performed on a simulacrum of an electrical device have been compared, placing a cable with damaged crimping alternatively on the two external phases (L_1 and L_3), leaving unchanged the other conditions, including the measurement points (figure 10).

The result of the test, shown in table 3, is an inversion of the maximum temperature condition between the two phases.

5. Conclusions

Terminal lugs crimping resistance measurements, on cables available in our laboratory, were made. Despite our terminal lugs being employed in more favorable conditions than those 'in the field', a relative variation of the crimping resistances among all the tested terminal lugs on the order of 37% for the 185 mm^2 section cables and more than 61% for the 240 mm^2 section cables were detected. In addition, we detected an increase of the contact temperature of almost double between a terminal lug with safe crimping and another with damaged crimping. Some obtained values may be critical for some equipment and affect the outcome of a temperature rise test. Due to these results and to the increasing availability of better equipment, it has become important to study and propose new methods to check crimped connections, to determine the cables' use or to highlight the need to redo the connection. Another important aim should be the evaluation of the dependency of crimped resistances from mechanical and thermal stresses to establish which are the most reliable crimping profiles, and if crimping itself is a reliable technique to guarantee the correctness of temperature rise tests, in comparison with the soldering technique. This should be an important issue because soldering is a more expensive and time-consuming technique than crimping. Another aim could be combining electrical and ultrasound measurements and microscope analysis with a thermo-camera, referring only to the crimping area. In this way we could solve many problems for electrical laboratories. In addition, a further aim will be the evaluation of the electrical and mechanical life of a crimped connection used during temperature rise test. This should be necessary to identify a suitable and reliable method or procedure to manage the cable used in test laboratories to improve the repeatability and the reproducibility of the tests. All these conditions are necessary for tests performed according to [11].

ORCID iDs

Paolo Emilio Roccato https://orcid.org/0000-0002-0939-3360

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