Influence of the Assembly Method of Medium Voltage Mechanical Connectors on the Quality of the Electrical Connection

Mirnes Aganbegović*, Christian Reinhold, Volker Markgraf and Ralf Schell

***Abstract*— Power cables are connected with ferrules or lugs in the area of high, medium and low voltage. Nowadays, there are two main installing techniques, which are state of the art: compression or crimping and bolted mechanical connections. The bolted mechanical connectors are installed by hand with the use of a mechanical wrench. The customer demand of using impact wrenches (IW) is growing because of the higher installation comfort. However, these techniques differ from each other significantly as the quality of the connection depends on the screwing force applied by the bolt to the conductor. Therefore, a new approach by using a cordless screwdriver was investigated.**

This contribution addresses the topic of the quality of the electrical connection as a function of the assembly method used on mechanical connectors. In particular, the focus is on assembly by hand with the support of mechanical wrenches and assembly with impact wrenches. Furthermore, a method is presented that combines the advantages of both methods, whereby the disadvantages are eliminated. This involves the use of an adapter, the torque amplifier, which is part of the installation philosophy of Nexans Power Accessories.

First, the fundamentals as well as the current state of the art of connection technology are presented. This is followed by a description of the assembly methods and materials used in this work and a comparison of the electrical, mechanical and thermal properties according to IEC 61238 of the connection using the different assembly techniques. Finally, the advantages and disadvantages are compared and presented and discussed using tabular and graphical representations.

***Index Terms*—Electrical connection, mechanical screw connector, impulse-driver, wrench, torque-amplifier, connection quality, cable connector, cable joint**

I. Introduction

Nexans Power Accessories Germany GmbH is a leading company in connection technology and power cable accessories is based in Hof, Germany. The company is known as a know-how carrier in the low, medium and high voltage area all over the world. In power transmission technology, electrical connections are an important component in the supply, transport and distribution of electrical energy. The connection technology of power cables is based on the principle of screw or press technology nowadays. One mechanical connector can replace over 150 compression connectors. This multi-range capability has contributed to their widespread use. The connection must meet the high quality requirements in order to ensure a reliable operation and thus the highest possible level of operational safety. In order to demonstrate the high quality of such kind of products, the type test for mechanical connectors according to IEC 61238 1 [1] is used, in which the connection is subjected to heat-cycles and short circuits, which represent the electro-thermal testing part. Another part of this standard is the mechanical testing, where the connection is submitted to a tensile-test. The prerequisite for this test to outcome positive is that the connection already meets the highest quality requirements after installation. The quality of the connection depends on many factors especially on the quality during installation. Nevertheless, the screw force applied by the screw in the connector body to the conductor is one of the most important parameter to ensure a low resistivity and thus a high quality connection.

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II. Theoretical Basics

The connection of two metal contacts creates a contact whose (apparent) contact area A_a does not completely contribute to current transmission. In reality, only microscopically small mechanically supporting contact areas A_s are created, which represent only a fraction of the apparent contact area $A_s << A_a$ (Fig. 1) [2–4].

However, the real electrically conducting contact area A_c is even smaller. Due to a diversity of impurities like dust, oils or oxides (e.g. Al_2O_3), the electrical contact occurs only at microscopically small points where these impurity (oxide-) layers are broken through. The resulting microcontacts cause the electric current to narrow (Fig. 1b) and are described by the narrow resistivity R_n. The resistivity of the entire connection is characterized by the joint- or connection resistivity R_j. It is calculated by adding the narrow resistivity R_n, the impurity resistivity R_i and the material resistivity R_m [2–4].

$$R_j = R_n + R_i + R_m \tag{1}$$

To assess the contact quality, the so-called resistivity factor k was introduced in IEC 61238-1-3 [1], which depends on the electrical resistivity of the connection in relation to the resistivity of the cable conductor.

$$k = \frac{R_j}{R_r} \cdot \frac{l_r}{l_j} \tag{2}$$

where R_j is the resistivity of the joint, R_r is the resistivity of the reference conductor, l_r is the length of reference conductor and l_j is the length of the connector.

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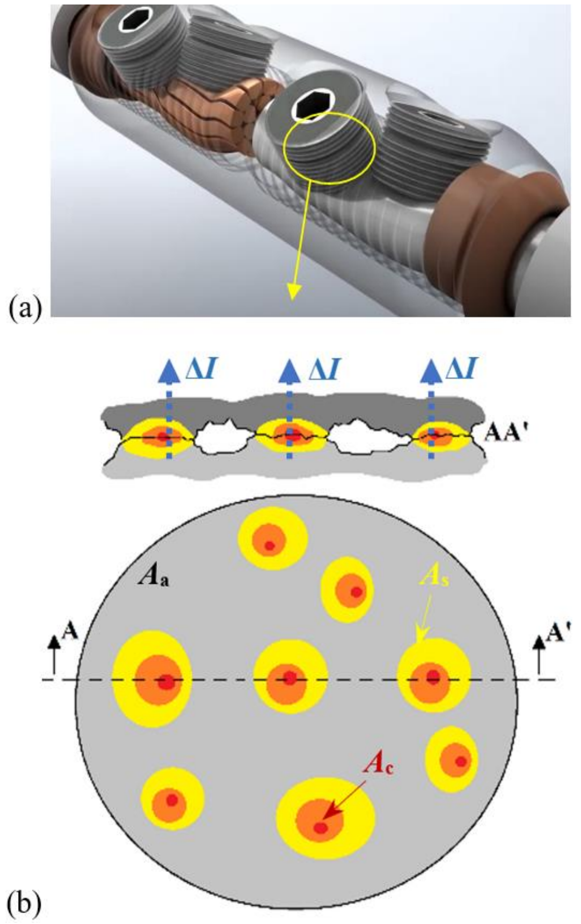

Fig. 1. (a) Mechanical connection of two cables; (b) Apparent, supporting and conducting contact areas [2–4].

A quality factor of $k = 1$ for bolted joints means that no higher power loss is generated in the joint than in the homogeneous conductor of the same length. Bolted joints with initial quality factors $k_0 < 1$ are rated as technically very good [2, 3] and lead to a long service life. In order to break the impurity layers on the conductor and to reduce the jointing resistivity, a high force has to be applied on the contact (see Fig. 2).

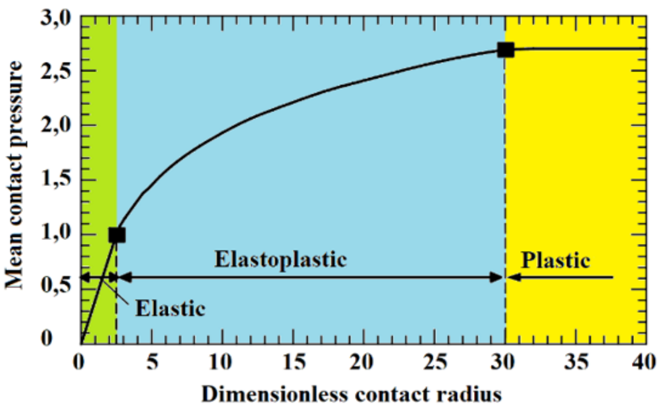

Fig. 2. Dependance of the contact pressure on the contact radius [4].

The contact resistivity is the main cause of heat losses ($P_{heat} = I^2 \cdot R$ acc. Joule`s first law) and must be as small as possible. Fig. 3 shows that with higher contact force the resistivity exponentially decreases [2]. However, with the relaxation of the contact materials the force decreases (hysteresis).

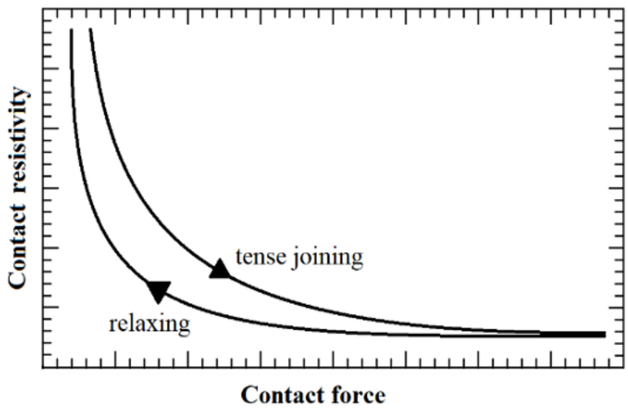

Fig. 3. Dependance of the contact resistivity on the contact force [2].

The contact force F depends strong on the screw-in torque T and on other factors e.g. friction μ, radius of the screw r and the thread pitch of the screw s and can be described as in following equation [5].

$$T = r \cdot F \cdot \left[\frac{\frac{s}{2 \cdot \pi \cdot r} + \mu}{1 - \mu \cdot \frac{s}{2 \cdot \pi \cdot r}} + \frac{2}{3} \cdot \mu \right]$$

$$\rightarrow F = \frac{T}{r \cdot \left[\frac{\frac{s}{2 \cdot \pi \cdot r} + \mu}{1 - \mu \cdot \frac{s}{2 \cdot \pi \cdot r}} + \frac{2}{3} \cdot \mu \right]} \quad (3)$$

The reduction of the friction can be achieved with grease. Also screws with smaller diameters and smaller pitch contribute to a higher contact force but on the other hand this reduces the contact area.

III. Installation Techniques

As mentioned before, to ensure a long service life of the connection, the initial quality factor should be $k_0 < 1$ [3], which is mainly influenced by the design and the installation. The main parameter to improve the contact force is a high torque.

However, these lead to problems during the manual installation, because the installer has to be able to perform the installation by hand, often in very tight trenches, which is one reason why customers tend to use machines like cordless screwdrivers or impact wrenches (IW) (Fig. 4).

The installation with the cordless screwdriver is only possible on small cross sections (up to 95 mm²) which require lower torque (<20 Nm). On bigger cable conductors (e.g., 630 mm²) the torque is even higher (≥50 Nm), which is too high for a conventional cordless electric screwdriver (40 Nm to 60 Nm) and also impossible for the installer to counter hold, which can result in injuries of the installer's wrist. More popular is the use of impact wrenches, which works with the principle of hammer and anvil. Thus, the installer can perform the installation quickly without counter holding in almost every installation space.

However, experience showed that with the manual installation by hand with a standard tool (wrench) even higher contact forces are accessible. With the use of a torque amplifier in combination with the cordless screw driver the torque in the installer's wrist can be reduced and thus the high contact quality of the installation by hand and the convenience of an impact wrench can be combined.

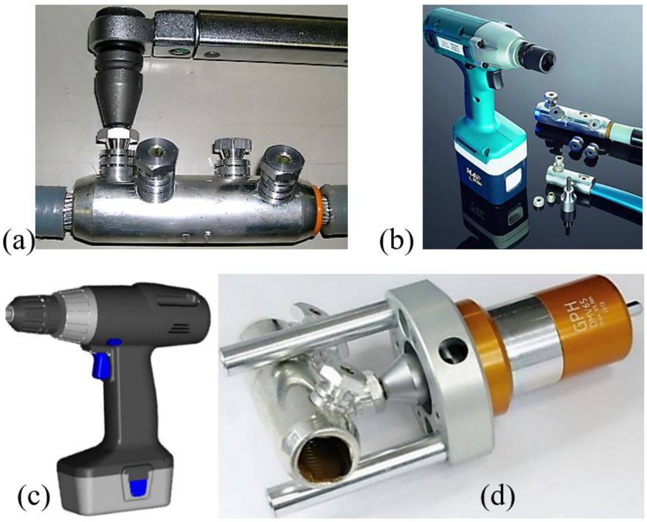

Fig. 4. Tools for installation of mechanical connectors / lugs: (a) torque wrench, (b) impact wrench, (c) cordless screwdriver, (d) torque amplifier.

IV. Test Results

In this section the used test-setups are briefly described and the experimental results are graphically presented and discussed.

A. *Clamp Test*

A tinned shear-bolt with predetermined breaking point with defined shear-off torque (see Fig. 5) was screwed into the force-measuring arrangement (see Fig. 6). The front and the thread of the screw were greased with a special contact-improving grease.

On the force sensor prepared metal inserts (plate-samples) from aluminium and steel were placed to simulate the conductor. Thus two different hardness of the conductor samples were used and compared. The plate shape was chosen as the conductor in order to neglect the impact of wire movement during the test. This could influence the results thus the comparison would be more difficult. The screw was installed only by hand until first contact was made with the sample. Afterwards, the screw was tightened with the respective tool until the screw sheared off and the result was read from the measuring device. The shear-off torque was constant in all tests. The results are shown in Fig. 7a.

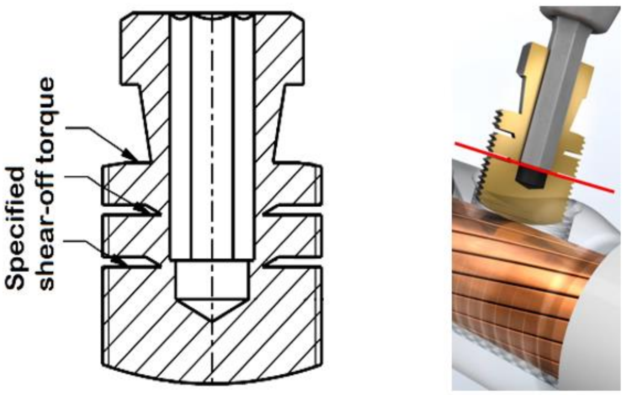

Fig. 5. Shear-off screw with predetermined breaking points.

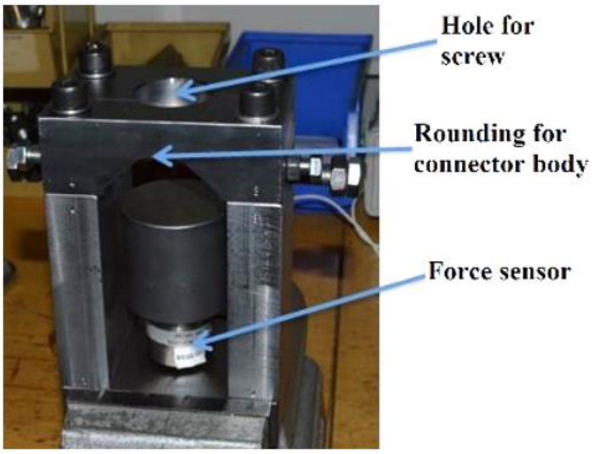

Fig. 6. Contact force measuring arrangement.

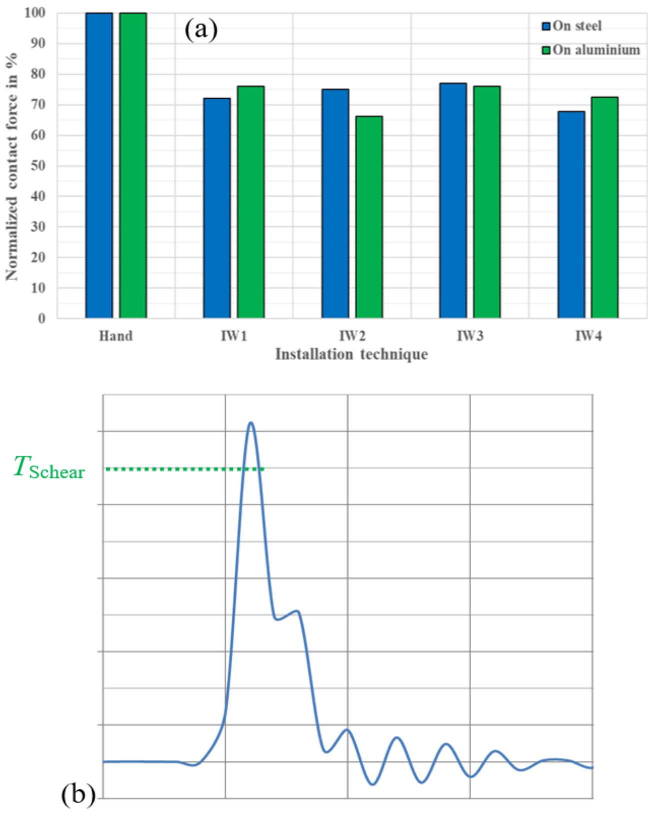

Fig. 7. (a) Comparison of contact forces achieved with different installation techniques; (b) Single pulse with transient behaviour.

The contact forces were normalized to the contact force achieved by hand with the standard wrench. It is clearly visible that by installation with the wrench by hand an approx. 30 % higher contact force could be achieved than with the IW. The result was not affected by the brand of the IW because all IW's show similar results. Also the hardness of the insert didn't seem to impact the result because the installation by hand showed higher contact forces on aluminium and on steel. A possible explanation for this could be the torque impulses generated by the IW's (see Fig. 7b). At the peak the torque is higher than the shear-off torque of the screw. Because of the short impulse duration of few milliseconds, the low friction and the elasticity of the material, high contact forces can be reached. But the material fatigue after dozens of pulses could be the reason for the earlier shear-off, which results in the lower contact force.

B. Resistivity Factor

One of the most important parameters to evaluate the quality of an electric connection is the resistivity factor [1]. In the following an electrical test was performed with 200 heat cycles on 12 samples. Six were installed with the IW and six by hand with a wrench. All other parameters like conductor, connector body and screws, were identical. The results of the *k*-factor can be seen in Fig. 8.

Already the initial *k*-factor of the by hand installed connectors was by approx. 11 % lower than by IW installed connectors. From the results in Fig. 8a is clear, that the *k*-factor increased after 200 heat cycles for all 12 connectors.

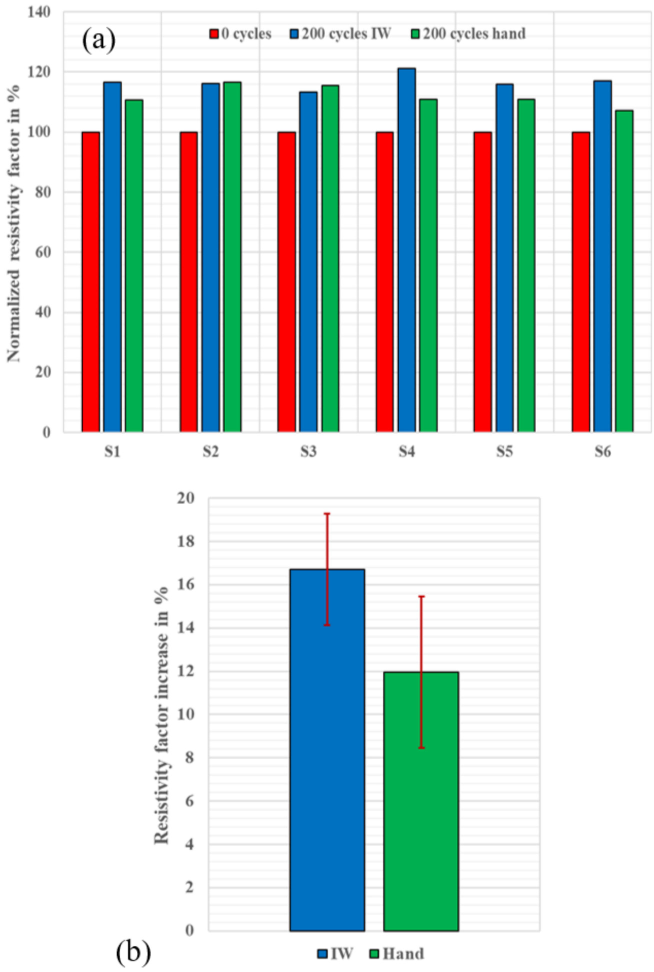

Fig. 8. (a) Normalized resistivity factors before and after 200 heat cycles; (b) Increase of resistivity factor after 200 heat cycles.

This is normal and can be explained with the relaxation of the material, which is also described as the formation time. However, a difference between the installation can be seen (see Fig. 8b). The *k*-factor of the by hand installed connectors have increased by 4.8 % less than by IW installed connectors.

C. Torque Amplifier

The thermo-electric heat cycle tests are very time consuming (several months, depending on the square section of the cable conductor). Because the *k*-factor depends directly on the contact force for the most part, to assess the quality of the connection the clamp-test was performed on aluminium plates (99.5 %) by hand (with conventional wrench), with an impact wrench (IW) and with the cordless screwdriver in combination with the torque amplifier (T-Amp) (Fig. 7).

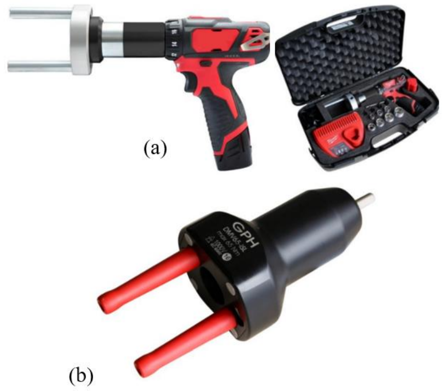

Fig. 7. (a) Torque amplifier with cordless electric screwdriver; (b) Insulated torque amplifier.

With the use of the aluminium plate instead of an stranded conductor with a specific number of wires (strands), the deviation of the results because of moving strands during installation was reduced.

The experiment was repeated for each installation method at least three times. The results can be seen in Fig. 8.

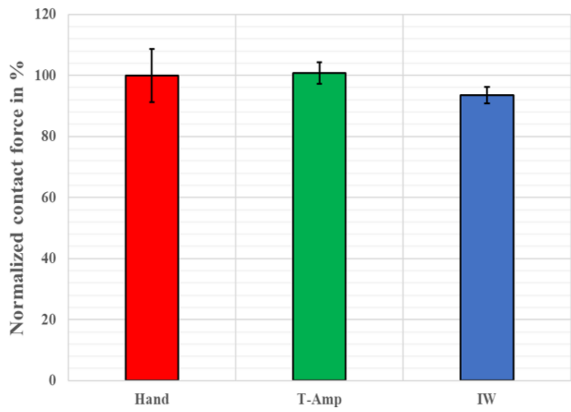

Fig. 8. Normalized contact force.

From the results in Fig. 8 it can be stated, that the contact force generated with the torque amplifier is higher as with an impact wrench. In fact, the generated contact force is as high as installed by hand using a wrench. Therefore, it can be stated, that the quality of the contact by installation with the torque amplifier is at least as good as by installation by hand (wrench).

After the installation the contact force was measured again after 60 s of relaxation time (see Fig. 9).

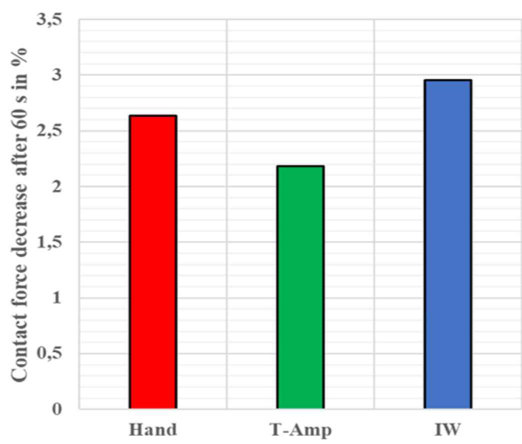

Fig. 9. Decrease of contact force after 60 seconds.

Another important aspect of the quality of a connection is maintaining the force, thus the contact resistivity doesn't increase (see Fig. 1b). As shown in Fig. 9, the contact force decrease by installing with the torque amplifier is the lowest (approx. 25 % lower than by installing with the impulse wrench).

V. Conclusion

According to the test results the installation of mechanical connectors with the three methods (Manual, T-Amp and IW) generate high quality connections. However, the installation by hand with a wrench is very good quality and highly regarded from experience and slightly better than the installation by impact wrench, the use of which is becoming more and more in demand in the field because of its convenience. With the usage of the torque amplifier, a conventional cordless screwdriver can be also used. Thus, the highest quality of connection regarding contact force from installation by hand and the comfort of an impact wrench are combined.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mirnes Aganbegovic performed the experimental tests, evaluated the results, wrote this contribution and presented the results on CPESE 2022 in Kyoto, Japan. Christian Reinhold and Volker Markgraf were involved in the tests and helped writing this paper. Ralf Shell supervised this project and helped writing this paper. All authors had approved the final version.

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Ralf Schell studied mechanical engineering in Cologne and started his career in the field of fluid technology. He has held various positions in the automotive sector and since 2016, he has been head of the connection technology segment at Nexans Power Accessories in Hof, Germany.